HEAT FLOW AND METABOLIC REACTION DURING DRY ICE COOLING

BY

PAISAN TECHAPATANARAT

B.Eng., Chulalongkorn University, Thailand, 1973.

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements of the degree

MASTER OF SCIENCE

Department of Industrial Engineering

Kansas State University

Manhattan, Kansas

1976

Approved

Major Professor

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Introduction

There are many situations in industry where a man is expected to perform a task in a heat stress environment. Man has been able to survive and work in such environment for a limited period because he had in his possession an excellent thermoregulatory system. In many situations, it is not practical to cool the entire environment. Personal cooling is an economical and effective means of reducing heat storage and extending the time in a heat stress environment.

Various methods of personal cooling have been tried at Kansas State University. Duncan (1969) successfully tried a water cooled headdress. Sharma (1970) used an air cooled helmet and a vortex tube to reduce the heat stress. Gandhok (1970) got comparable results with a PVC jacket supplied with cold air from a vortex tube. Byrnes (1970) found a Jacket to be more effective than a hood from physiological viewpoint. Konz, Duncan and Masud (1975) studied a dry ice cooling garment and found the advantage of dry ice cooling over water cooling and air cooling system was that the dry ice cooling utilizes the thermal efficiency of conduction cooling, has no moving parts, and has no tether (as with a power cord or air hose), so there is no restraint on the user's mobility.

Duncan (1975) studied the effects of changing the dry ice cooling garment variables of dry ice surface area facing the subjects and thermal conductance of the insulation between dry ice and subjects.

Two surprises were found in Duncan's experiment. First there was a significant increase in oxygen consumption (from a mean of 313 to 387 Kcal/hr) when subjects wore the dry ice cooling garment. He believed that this increase was not due to shivering as the subjects stated that they never perceived any shivering. His hypothesis was a non-shivering thermogenesis or chemical thermogenesis had taken place. Another surprise was that there was no significant effect of the insulation of the dry ice pocket on dry ice sublimation rate. It had been predicted that the large air bubble insulation would offer more resistance to heat flow than the small air bubble insulation. But the mean sublimation rate per slab was 0.861 gm/min with the large air bubble insulation (5 gcal/sec-^{o}C-cm^{2}x10^{-5}) and 0.852 gm/min with the small air bubble insulation (17 gcal/sec-^{o}C-cm^{2}x10^{-5}). Duncan did not measure insulation values but calculated them.

Duncan's finding was that the dry ice sublimation in the top compartments (1.904 gm/min/slab) was significantly faster than the lower compartment (1.190 gm/min/slab). When the dry ice sublimed, the carbon dioxide gas from the upper compartment flowed down due to its weight (1.5 times heavier than air). This increased the concentration of carbon dioxide around the lower compartments, thus lowering the sublimation rate of dry ice in the lower compartments.

This thesis presents a more detailed investigation of the excess oxygen consumption rate, pocket insulation, and pocket orientation.

Literature Review

The 'non-shivering thermogenesis' or 'chemical thermogenesis', which Duncan (1975) described as a cause of the increase of the oxygen consumption rate during dry ice cooling, is a cold induced non-shivering heat production which is mediated by the sympathetic nerve.

Jansky (1971) evaluated the previous studies, based on organ blood flow and on extraction of oxygen from the blood in

1. skeleton muscle tissue
2. visceral organs
3. brown adipose tissue

1. <u>Skeleton muscle tissue</u>

Depocas (1958) demonstrated that functional evisceration (restriction of blood flow to abdominal organs) of cold acclimated, curarized rats did not prevent the metabolic increase in the cold. He observed that the oxygen consumption of leg muscles more than doubled during exposure to cold as did the total metabolism. This finding indicated as important role of skeleton muscles in non-shivering thermogenesis. He estimated that hte metabolic contribution of skeletal muscle to non-shivering thermogenesis is unlikely to exceed 50% of the total non-shivering thermogenesis, and that it might be even less (Jansky and Hart, 1968).

2. <u>Visceral organs</u>

Measurement of liver metabolism of small animals under in vivo conditions is technically difficult owing to the complicated vascularisation of this organ. In order to get at least some informations about liver heat production, Jansky performed several experiments on isolated rat liver perfused with rat blood, before and after injection of a high concentration of noradrenaline into circulation. Experiments have shown that the liver can play a certain role in cold thermogenesis, since the metabolism of the perfused rat liver can be markedly enhanced by increased blood flow and blood oxygenation. It was not expected that the liver metabolic contribution to non-shivering thermogenesis could exceed 25% (Jansky, 1971).

The intestine is also a potential heat producer in cold exposed animals. Experiments were carried out based on A-V differences in blood oxygen content. Rats were exposed to cold and their metabolism doubled. These results, although preliminary, have shown that the A-V differences in oxygen content were not changed in cold exposed animals while the blood flow increased by 55%. Oxygen consumption of the intestine thus increased by 64%. This internal metabolic increase represented less than 10% of total non-shivering thermogenesis.

The metabolism of the kidney also was measured in curarized, cold acclimated rats exposed to cold or injected by noradrenaline (Jansky, 1963).

No attempt has been made to evaluate the role of small body organs. However, considering their small body mass, their thermogenesis potential probably will be negligible.

3. <u>Brown adipose tissue</u>

Within the class mamalia, occurence of brown fat has been reported in many species distributed through seven orders: Chiroptera, Insectivora, Rodentia, Lagomorpha, Artiodactyla, Carnivola and Primates (Smith and Horwitz, 1969). Distribution of brown fat in the human has recently checked by Aherne and Hull (1966) on a large series of autopsy material (394 cases). Brown adipose tissue was found at the following sites:

(a) An interscapular mass lies in a thin diamond shape sheet between the shoulder blades. It is separated from the subcutaneous white adipose tissue by a discontinuous fibrous layer. When replete with fat it has a yellowish brown color; depleted it is much darker. It has a fine lobular structure.

(b) Many smaller brown adipose tissue masses are present around the muscle and blood vessels of the neck. The main mass follows the course of the internal jugular vein and common carotid artery.

(c) Extensions from the adipose tissue of the neck pass under the clavicles to rather large deposits in the axillae.

(d) Further extensions accompany the great vessels entering the thoracic inlet. From these, fine fingers of brown adipose tissue spread out from the midline with each intercostal artery. Similar deposits lie among the internal mammary vessels. Many discrete, moderately large masses lie in the mediastinum between the oesophagus and the trachea.

(e) In the abdomen discrete masses of brown adipose tissue accompany the aorta and lie in relation to many structures on the posterior abdominal wall such as the pancreas, autonomic ganglia and cromaffin tissue. By far the largest abdominal mass envelops the kidneys and adrenals.

Smith (1961) suggested that the brown adipose tissue might produce heat in cold exposed animals. Hein and Hull (1966) have shown on new born rabbits that the amount of oxygen in the incoming blood may cover 2/3 non-shivering thermogenesis. In the adult rats, on the other hand, Imai, Horwitz and Smith (1968) indicated that brown adipose tissue can participate by 8% in total heat production in cold. Jansky (1968) indicated that, based on blood flow and the maximum oxygen supply to brown adipose tissue, a relatively small thermogenesis significance of this tissue, not exceeding 6% in total non-shivering thermogenesis.

In addition, Jansky (1968) found that the metabolic capacity of the brown fat is not directly related to non-shivering thermogenesis and the level of cold acclimation.

Problem

Duncan (1975) showed that personal cooling with dry ice is effective in reducing physiological strain associated with working in conditions of high thermal stress and metabolic activity. But it suffered from a draw back that the oxygen consumption rate increased significantly. An attempt to investigate the excess of the oxygen consumption rate was made by measuring shivering by means of the integrated EMG muscle activity under the dry ice pockets.

The back pocket orientation was changed from vertical to horizontal (Figure 1). This will provide the better flow of carbon dioxide gas around the lower compartment. An increase of sublimation rate as well as uniformity of sublimation rate among slabs was expected.

Three levels of insulation (Figure 2) also were used as an experimental variable to determine a more definite relationship between the sublimation rate of dry ice and levels of insulation by using three thicknesses of insulation instead of two as in Duncan's experiment.

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

THIS IS AS RECEIVED FROM CUSTOMER.

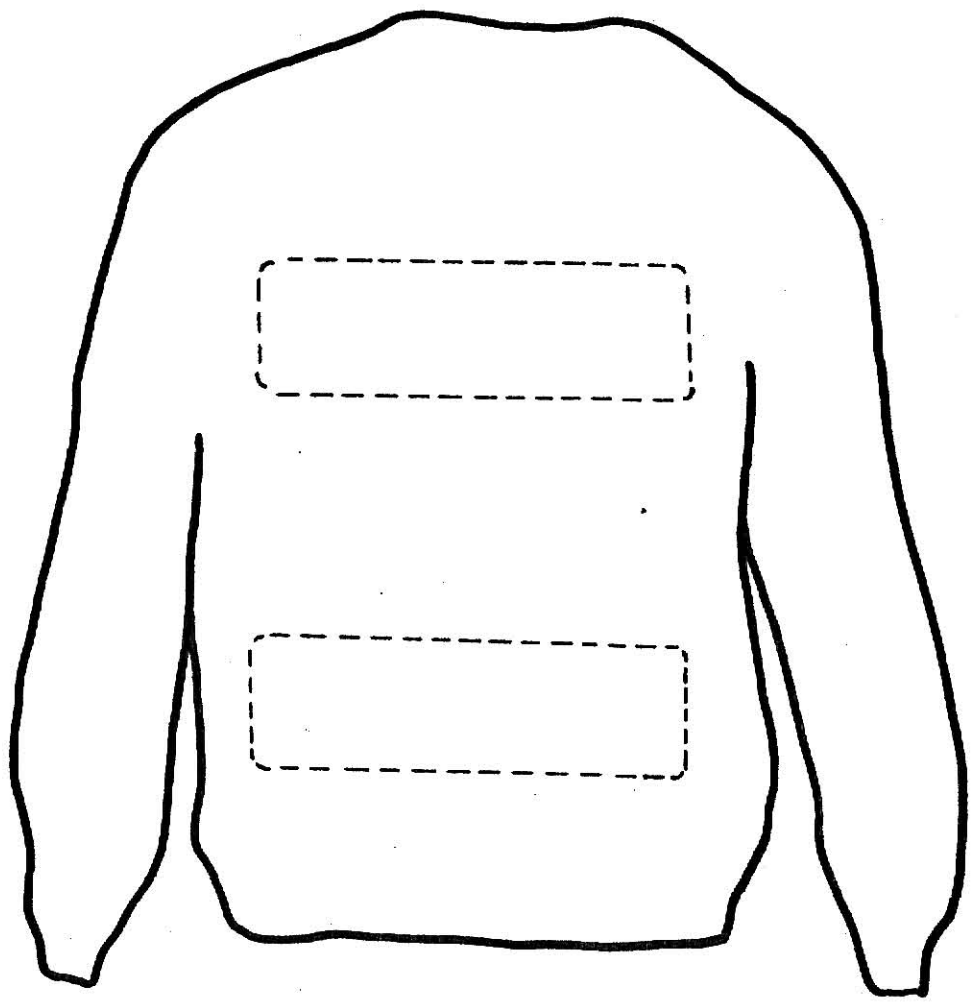

Figure 1. Horizontal Back Pocket Orientation.

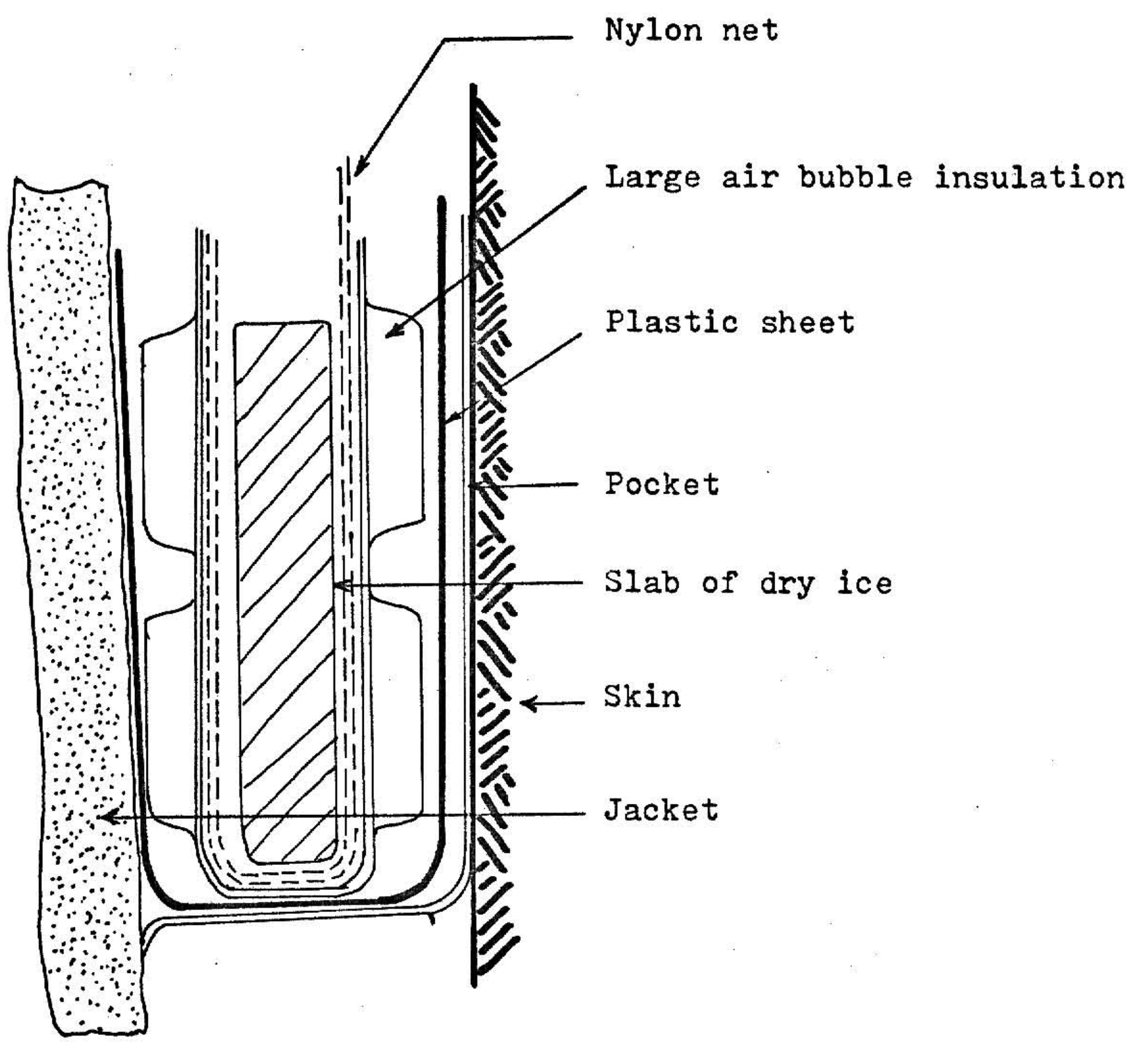

Figure 2. Insulation Inside the Dry Ice Pocket.

Method

Task

Each subject pedaled on a Monark bicycle ergometer at a constant speed of 60 rpm and ergometer load of one kilopond for 60 minutes in an environment chamber, controlled at 35°C dry bulb, 31.6°C wet bulb and 70% relative humidity.

Subjects

Three healthy males were used for subjects in this study. Each was paid a total of $40 for completion of five experimental sessions. All three were selected to be alike as possible. Table 1 gives characteristics of the subjects. The VO_2 maximum of 64 seems far too high. Although no computational errors could be discovered, 40 seems a more reasonable value(based on a subjective estimate).

Experimental design

The experimental design was divided into three stages. The first stage (control session) was conducted with the subjects not wearing the cooling garment. The second stage consisted of three sessions which evaluated the garment at three levels of insulation. The sequence of insulation was:

	Session			
Subject	1	2	3	
1	L	M	H	L = low insulation

Table 1. Characteristics of the Subjects.

	Subject 1	Subject 2	Subject 3
Age (years)	29	27	23
Weight (kg)	66	61	63
Height (cm)	169	169	173
Surface Area (m^2)	1.87	1.81	1.86
Skinfold Thickness (mm)			
1 Triceps	20	12	9
2 Pectoral	17	14	6
3 Abdominal	27	17	12
Percent of Body Fat	20	15	10
Blood Pressure (mm Hg)			
Systolic	130	127	125
Diastolic	84	80	82
VO_2 (ml/min/kg)	33	64*	48

$$\text{Surface Area} = .208 + .945((7.184*10^{-3})(\text{Height in cm})^{.725}(\text{Weight in kg})^{.425}),$$ (Mitchell,1971)

$$\text{Percent Body Fat} = 100\left(\frac{5.548}{\text{Specific Gravity}} - 5.044\right),$$ (Consolazio, et al.,1963)

$$\text{Specific Gravity} = 1.1017 - 2.82*10^{-4}(\text{Abdominal skinfold,mm}) - 7.36*10^{-4}(\text{Pectoral skinfold,mm}) - 8.33*10^{-4}(\text{Tricep skinfold,mm})$$

* The VO_2 maximum of 64 seems far too high. Although no computational errors could be discovered, 40 seems a more reasonable value(based on subjective estimate).

Subject	1	2	3	
2	H	L	M	M = medium insulation
3	M	H	L	H = high insulation

The third stage was a repeat of the first stage (control session).

Procedure

Each experiment session began when the surface ECG and EMG electrodes were attached and held in position by applying 'Collodium' (a chemical solution) around and over the 1" by 1" gauze which covered each electrode. Then they were covered with crossing strips of surgical tape and then 'New-Skin' applied over the tape touching the skin. This application method insured a water tight seal around the electrodes and guaranteed a good electrical signal throughout the periods when the skin was covered with sweat. Then a rectal thermister probe was inserted 13 cm. On the days that the subjects wore a dry ice cooling garment, slabs of dry ice (12 cm wide, 12 cm long and 1.6 cm thick) were weighed and placed in the pocket with the proper insulation while the sensors were attached to the subject.

The subject entered the conditioned environmental chamber and started pedalling. Oxygen consumption rate, rectal temperature and heart rate were recorded at the starting time (0^+ minute). Oxygen consumption rate was measured for two minutes every ten minutes. Heart rate and rectal temperature were measured every five minutes.

After pedalling for 60 minutes, the subject left the chamber and sat on a chair for ten minutes. Slabs of dry ice from the garment were weighed again. After the subject sat outside the chamber for ten minutes, all the sensors were removed and the session was over.

Measurements

Slabs of dry ice were weighed with a Hanson spring scale model 1440 (the least scale division equals one gram). Oxygen consumption rate was measured for two minutes every ten minutes with a Collins 9-liter respirometer. Integrated EMG and heart rate were recorded with a Bechman recorder, coupled with an EMG coupler (model 9852) and a Cardiotachometer (model 9857). Two surface electrodes were placed around the neck and the other two around the waist under the right front pocket; see Figure 3.

The integrated EMG coupler is an electronic device which can produce, when the EMG or any other potentials are fed into the coupler, an arbitary quantitative figure derived from the amplitude frequency and spike shape. Bigland and Lippold (1954) showed that integrated potential varied directly with the strength of the contraction of the muscle. It was also found that the detailed situation of recording electrodes (distance between electrodes, subcutaneous or intramuscular insertion) changes the value of electrical activity. Therefore the position of

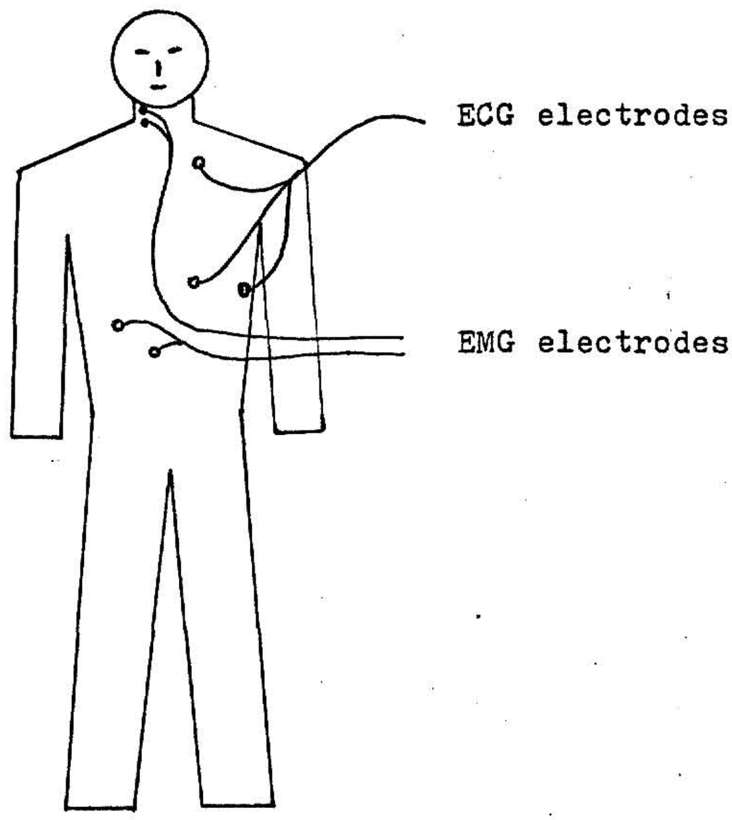

Figure 3 Sensor Locations

the electrodes were marked in the first session of every subject to keep the same position in the latter sessions (Mejsnar, 1971).

Rectal temperature was measured, mainly for safety purposes, with a YSI 401 rectal thermister probe inserted 13 cm. The dry bulb and wet bulb temperatures within the Sherer-Gillett (model CER 812) environmental chamber were measured with a self made psychometer using a YSI 423 thermister as the temperature measurement device.

The thermal conductance values of the insulation were measured by putting a slab of dry ice inside the insulation and measuring the heat flow with a heat flow meter, and the temperature at the external surface of the insulation with a digital thermometer. And then, the thermal conductance was calculated from:

$$U = \frac{Q}{t}$$

U = thermal conductance, gcal/sec-^{o}C-cm^{2}x10^{-5}

Q = heat flow, gcal/sec-cm^{2}x10^{-3}

t = external surface temperature - sublimation temperature of dry ice (-78.5^{o}C)

The thermal conductance values were:

Low insulation (air bubble insulation which equals to Duncan's high insulation) = 11.57 gcal/sec-^{o}C-cm^{2}x10^{-5}

Medium insulation (air bubble and rubber sheet) = 7.36 gcal/sec-^{o}C-cm^{2}x10^{-5}

High insulation (air bubble, rubber and plastic sheet) = 5.02 gcal/sec-^{o}C-cm^{2}x10^{-5}

Instrumentation

The garment was made of a quilted nylon outer shell (nylon facing the polyester fill) and blended cotton inner shell. There were four inside pockets, two vertical in the front and two horizontal at the back. Each was 45 cm long, 18 cm wide and 5 cm deep. The pockets opened at the top and were closed with the Velcro fasteners. Each pocket contained a removable plastic air bubble material liner. Inside the liner, slabs of dry ice were placed inside a nylon net which was divided into three compartments. The long-sleeves were made of a light, permeable, loose-weave nylon. Elastic was sewn around the bottom edge (waist) of the garment and at the wrist of the sleeves. The garment was fastened in the front by means of Velcro fasteners running vertically down its center. On experimental days without a cooling garment, each subject was clothed in tennis shoes and socks, boxer shorts, slacks and a long sleeved, cotton-twill shirt. On days when a cooling garment was worn, the same clothing was worn plus a dry ice cooling garment but without the long sleeved shirt.

Results

The results were analyzed using the Wilcoxon Matched Pair Signed-Rank Test (Siegel, 1956) and a computer analysis of variance program to search for significance among the main effects.

Sublimation Rate

The sublimation rate (gm/min) of each slab of dry ice was determined by subtracting the final weight from the initial weight and dividing by the interval time in minutes between the two weighings.

The analysis of variance of sublimation rate was made from the computer model

SUBLIM = S(I)+I(J)+P(K)+C(KL)+E(IJKLM)

SUBLIM = Sublimation rate of each slab, gm/min

S(I) = Subjects, I=3

I(J) = Insulation levels, J=3

P(K) = Pocket location, K=4

- -Right front
- -Left front
- -Upper back
- -Lower back

C(KL) = Slabs, KL=4*3=12

(C(KL) is nested in P(K))

Table 2 shows the result of the analysis of variance. A Duncan's New Multiple Range Test was used to find the significant difference between the means of the four effects.

Table 2. Analysis of Variance of Dry Ice Sublimation Rate.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Subjects (S)	8	0.538	0.269	31.15 **
Insulation (I)	2	0.171	0.085	9.87 **
Pocket location (P)	3	0.065	0.021	2.50
Compartments (C)	8	0.975	0.122	14.10 **
Error	92	0.795	0.009	
Total	107	2.543		

** $p < .01$

Table 3 and 4 show the mean dry ice sublimation rate of each effect (Subjects, Insulations, Pocket locations and Compartments). Figure 4, 5 and 6 show the mean sublimation rate on levels of insulation, compartments on back pockets and front pockets respectively.

Figure 4 shows a trend that the low insulation gave a lower mean sublimation rate which was not expected. A possible explanation is that when the low insulation was used, the skin temperature under the dry ice pocket dropped which restricted the blood flow under the skin due to contraction of the capillaries. This reduced the heat flow from skin to dry ice, therefore the sublimation rate of dry ice was lowered.

Heart rate

The heart rate was measured every five minutes over the 60 minutes exposure. The mean heart rate was 138 beats/minute when subjects wore a cooling jacket; that was significantly lower than the 148 beats/minute for the no-cooling condition. Thus, wearing the jacket reduced the strain on the heart an average of 558 beats during the 60 minutes exposure. Figure 7 shows the mean heart rate for the cooling and no-cooling condition. Heart rate was not significantly changed by levels of insulation of the dry ice pocket.

Figure 8 shows that the mean heart rate dropped significantly ($p < .01$) when the subject was breathing the oxygen from the respirometer at 0, 10, 20, ..., 60 minutes. There was

Table 3. Mean Dry Ice Sublimation Rate (gm/min) for Subjects, Insulation Levels and Pocket Locations.

Subject	Dry Ice Sublimation Rate (gm/min)
1	1.010
3	0.866
2	0.855
Insulation level	
Medium (7)	0.955
Low (11)	0.916
High (5)	0.859
Pocket location	
Upper-back	0.941
Lower-back	0.926
Right-front	0.896
Left-front	0.877

Table 4. Mean Dry Ice Sublimation Rate (gm/min) for the Twelve Pocket Compartments.

Pocket Compartment	Dry Ice Sublimation Rate (gm/min)
Right-Front-Top	1.046
Left-Front-Top	1.045
Upper-Back-Right	1.034
Lower-Back-Right	1.019
Upper-Back-Left	0.927
Lower-Back-Left	0.923
Lower-Back-Middle	0.864
Upper-Back-Middle	0.831
Right-Front-Middle	0.830
Right-Front-Bottom	0.812
Left-Front-Bottom	0.795
Left-Front-Middle	0.794

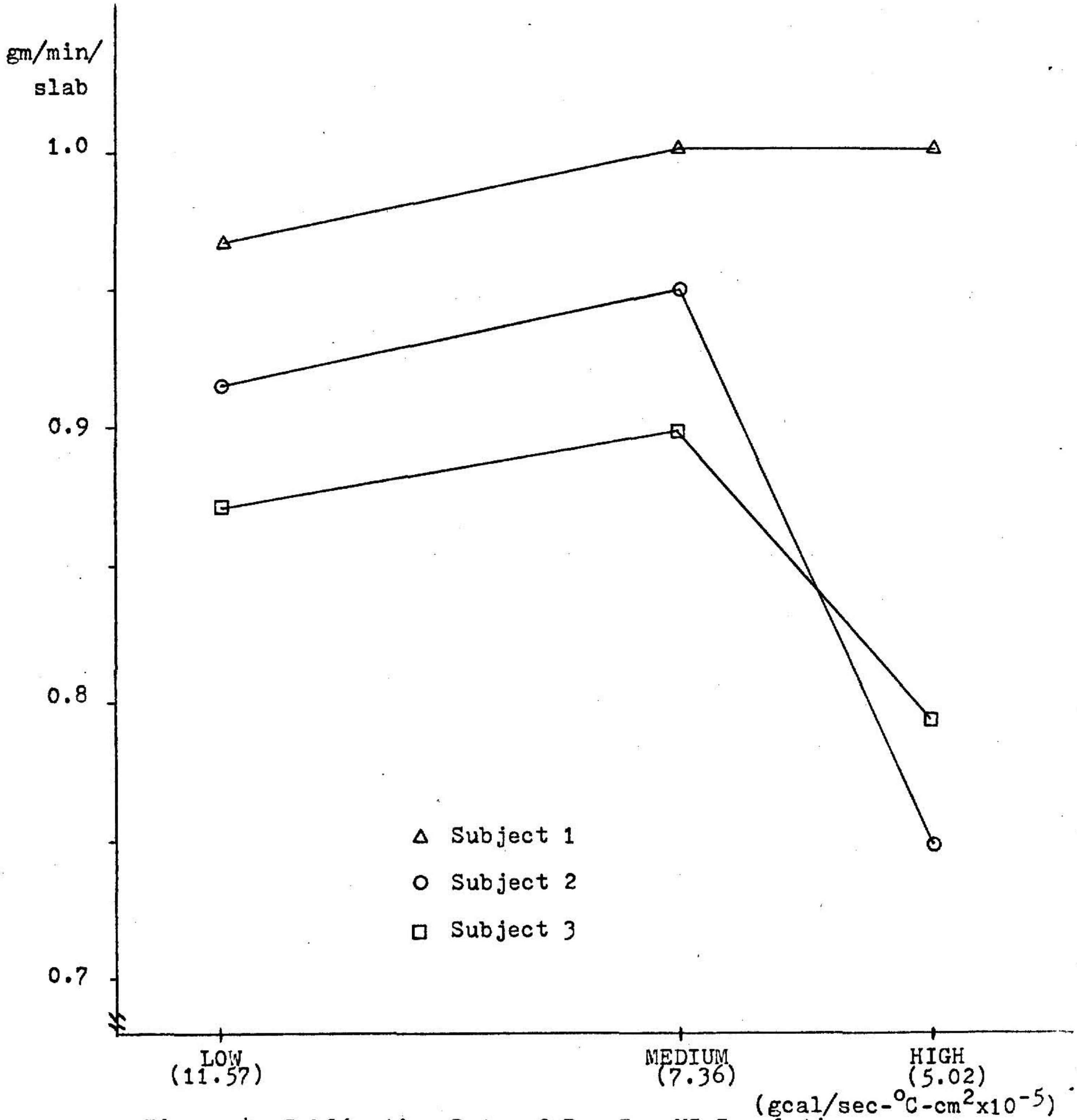

Figure 4 Sublimation Rate of Dry Ice VS Insulation

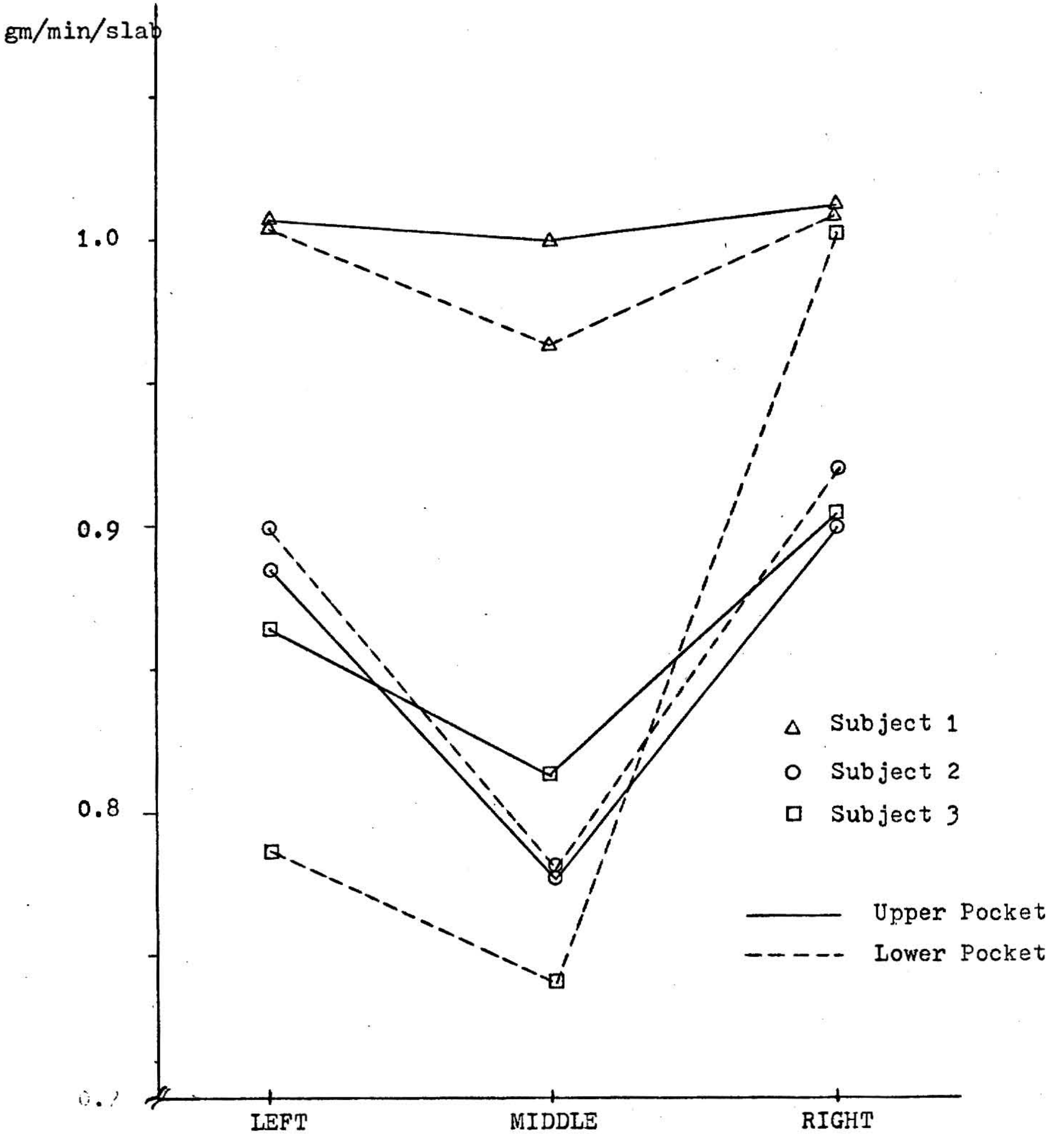

Figure 5 Sublimation Rate of Dry Ice in The Back Pockets

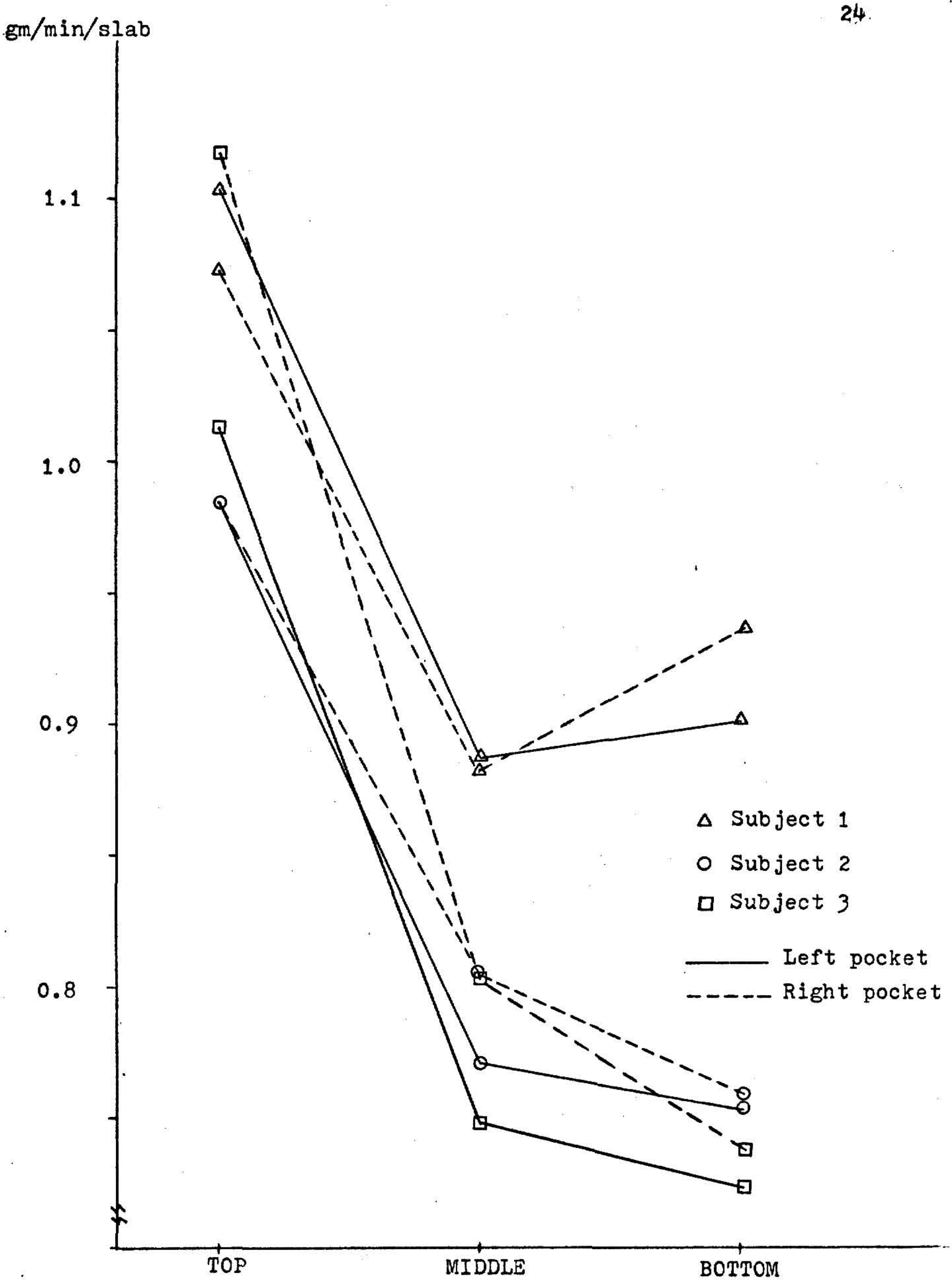

Figure 6 Sublimation Rate of Dry Ice in The Front Pockets

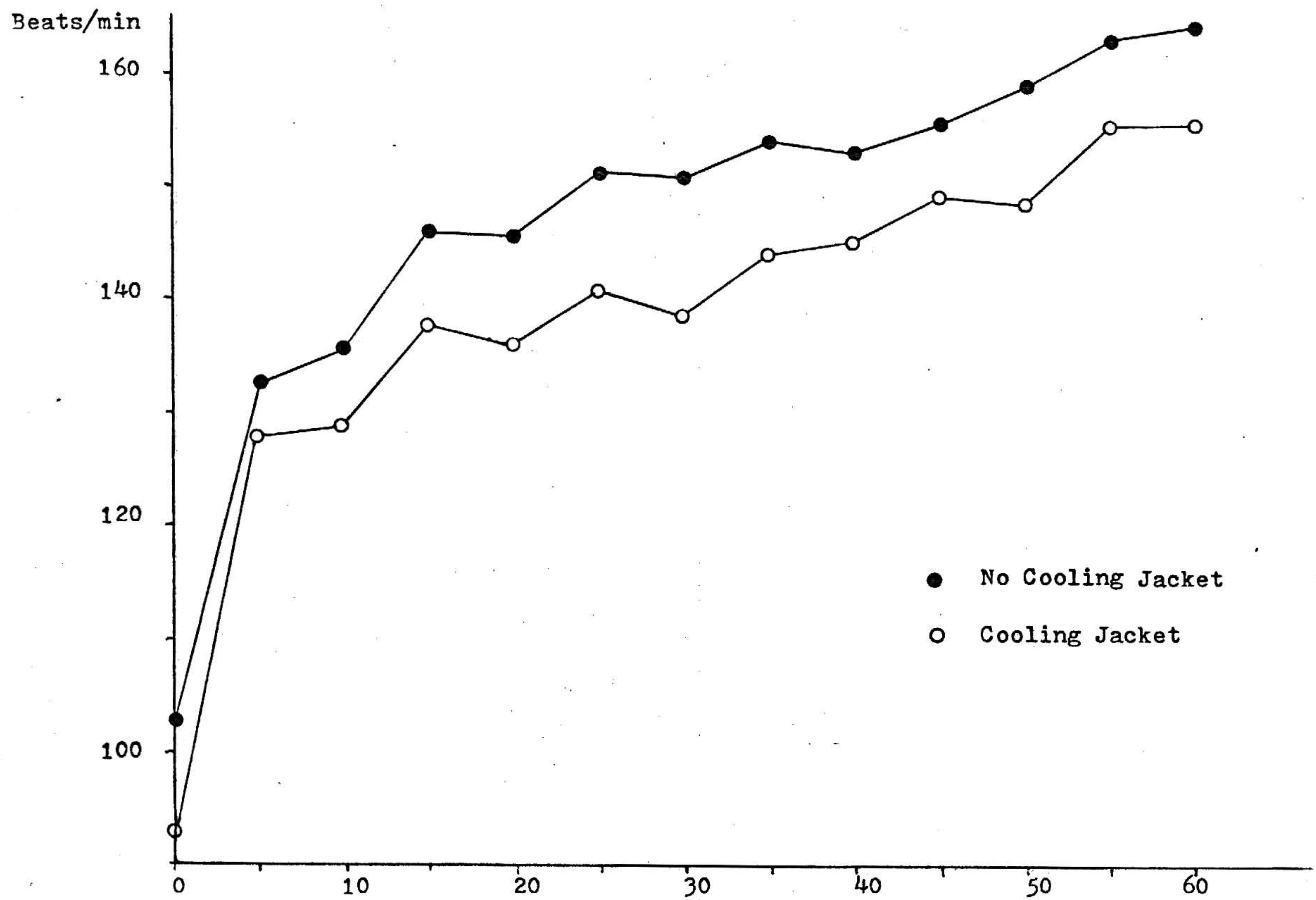

Figure 7 Mean Heart Rate VS Time

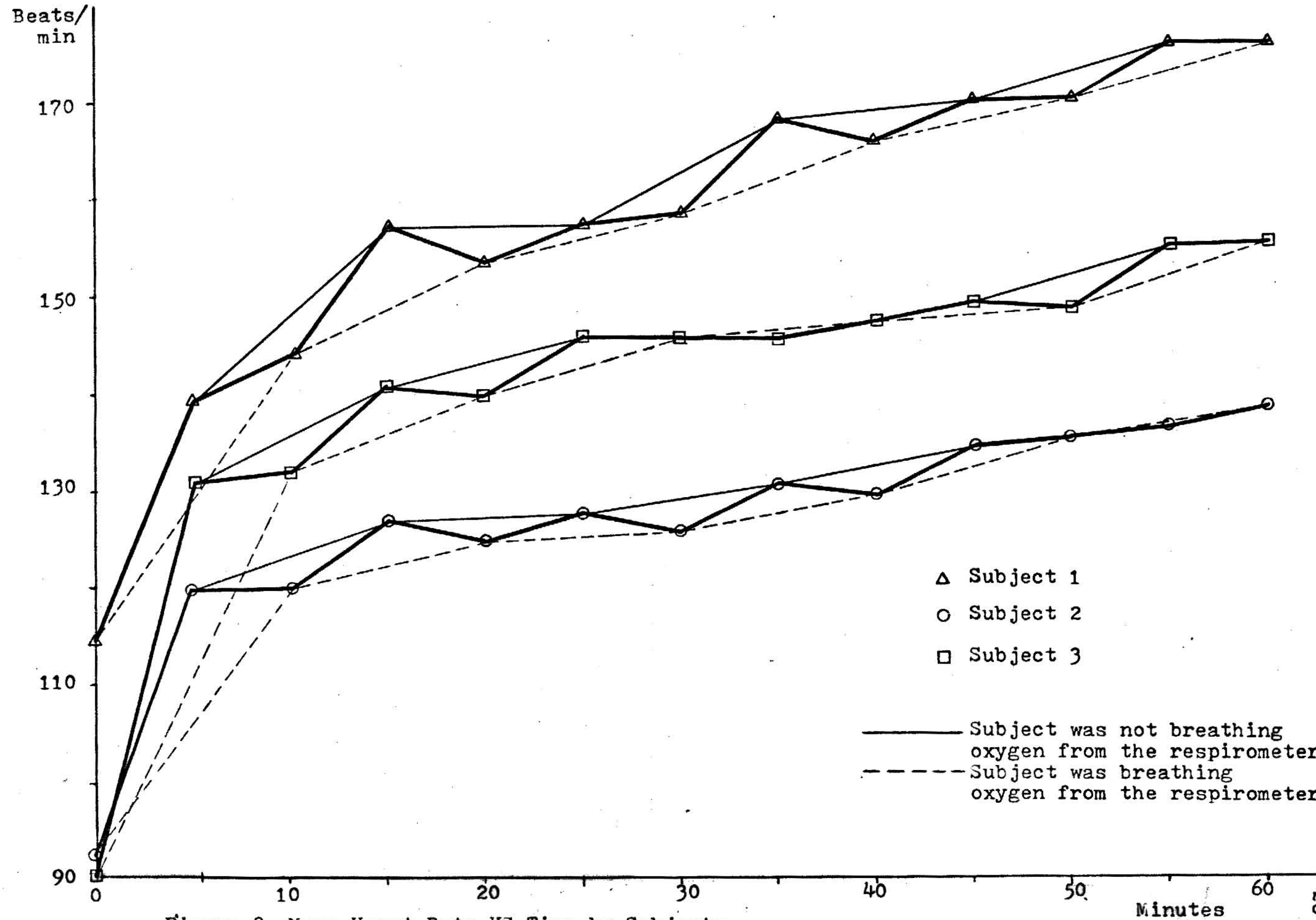

Figure 8 Mean Heart Rate VS Time by Subjects

also a significant effect among subjects, Subject 1 always had a higher heart rate than Subject 2 and 3.

Rectal temperature

The mean rectal temperature at the end of 60 minutes exposure was 38.04°C when subjects wore the cooling jacket which was significantly ($p < .01$) less than the 38.21°C for the no-cooling condition. Figure 9 shows the mean rectal temperature for the no-cooling and the cooling condition during the 60 minute exposure. There was a significant effect of the level of insulation. The mean rectal temperature of 37.72°C for low insulation (11.57 $gcal/sec\text{-}^{\circ}C\text{-}cm^2 x10^{-5}$) which was also higher than the 37.48°C for high insulation (5.02 $gcal/sec\text{-}^{\circ}C\text{-}cm^2 x10^{-5}$). Figure 10 shows the effect of insulation on the mean rectal temperature.

Oxygen consumption rate

Oxygen consumption rate was measured for two minutes at the beginning of the experiment and every ten minutes during the 60 minutes exposure. The mean oxygen consumption rate was 2.64 liters/min when subjects wore the cooling jacket; that was significantly ($p < .01$) higher than the 2.08 liters/min for the no-cooling condition. Figure 11 shows the mean oxygen consumption rate of three subjects for no-cooling and cooling condition with three levels of insulation over the 60 minutes exposure. There was a significant difference among the subjects,

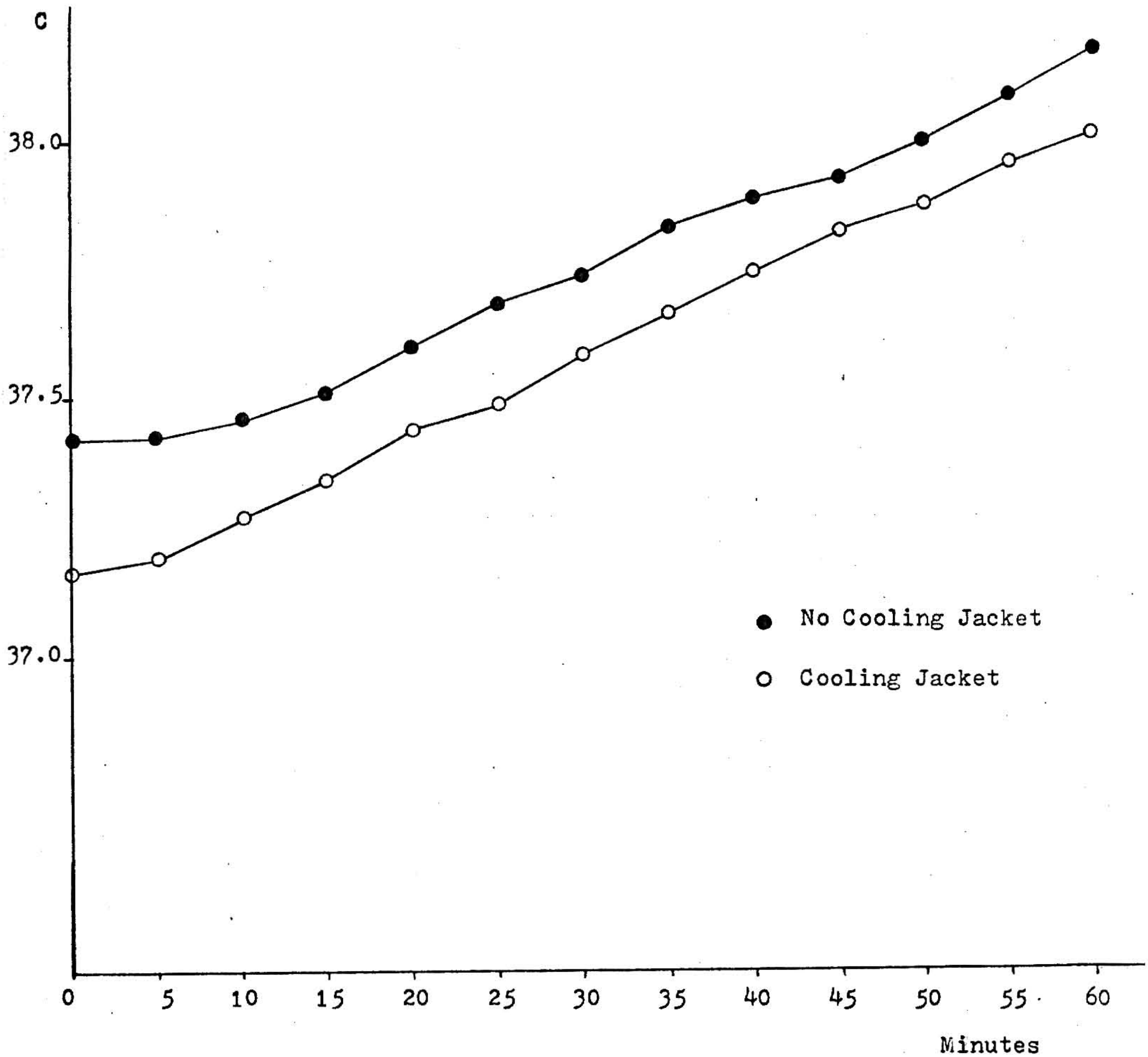

Figure 9 Mean Rectal Temperature VS Time for No Cooling and Cooling Jacket

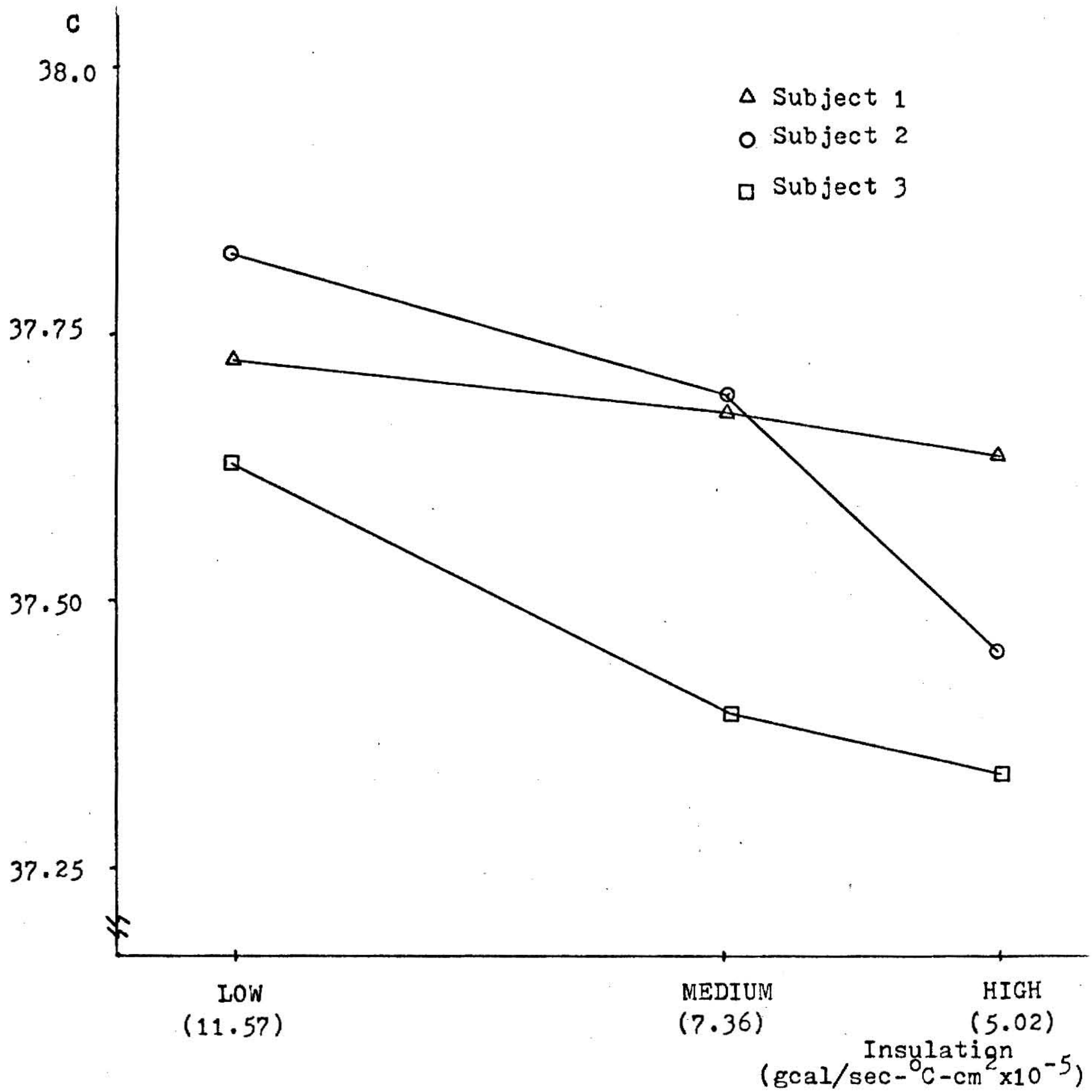

Figure 10 Rectal Temperature VS Insulation

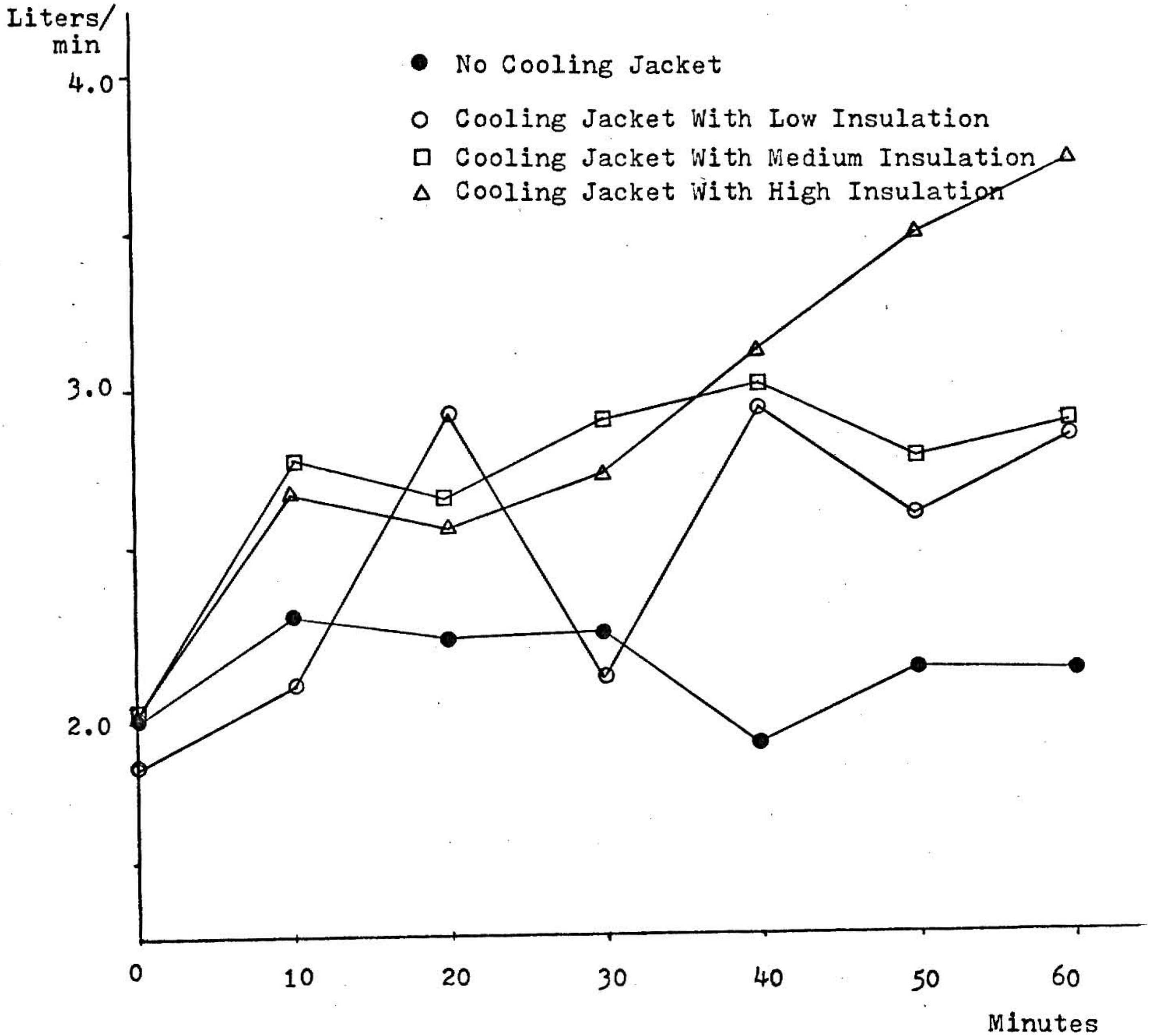

Figure 11 Mean Oxygen Consumption Rate VS Time

since the oxygen consumption rate of subject 1 was always higher than the other two. There was also a significant difference ($p < .01$) between low and high insulation. No statistically significant differences were found for either low and medium or medium and high insulation.

EMG

An attempt was made to measure shivering when the subjects wore a cooling jacket by measuring the integrated EMG of the muscle activity under the dry ice pocket. But, due to lack of experience of the experimenter and improper measurement procedure, no information about shivering was obtained from this experiment. The subjects did not notice any shivering.

Discussion

The horizontal pocket orientation gave a few advantages over the vertical pocket orientation. They were:

1. Slabs of dry ice in horizontal pocket sublimed more uniformly than the slabs in the vertical pocket. This implies that:
   1.1 The subject was more comfortable by getting a better uniform cooling from the horizontal pocket.
   1.2 Dry ice in horizontal pocket lasts longer due to more efficient use of the dry ice.
2. Sublimation rate of dry ice in horizontal pocket (mean was 0.933 gm/min) was 4.6% higher than the dry ice in the vertical pocket (mean was 0.892 gm/min).

To predict the sublimation rate of each compartment in the front pockets, the following formula was modified from the Duncan's experiment:

$$S = K_1K_2K_3K_4K_5K_6K_7(31.4 + .132(IW))$$

S = sublimation rate/slab, grams/hr

IW = initial weight of the slab, grams, $150 < IW < 400$

K_1 = thickness factor

= 1.0 for 16 mm thick slab

= 0.93 for 22 mm thick slab

= 1.39 for 5 mm thick slab

K_2 = pocket location factor

= 1.0 for top pocket compartment

= .69 for middle and lower compartment

K_3 = jacket vs vest factor

= 1.0 for jacket

= 1.04 for vest

K_4 = dry bulb environmental temperature

= 1.0 for 35°C

= 1.07 for 45°C

K_5 = water vapor pressure in environment

= 1.0 for 33 mm Hg.

= 1.04 for 16 mm Hg.

K_6 = environmental time factor

= 1.085 for time from 0 to 60 minutes

= 1.0 for time from 0 to 120 minutes

= 0.83 for time from 0 to 240 minutes

K_7 = insulation factor

= 0.94 for low insulation (11.57 gcal/sec-°C-cm^{2}x10^{-5})

= 0.87 for medium insulation (7.36 gcal/sec-°C-cm^{2}x10^{-5})

= 0.83 for high insulation (5.02 gcal/sec-°C-cm^{2}x10^{-5})

In the analysis of variance of mean dry ice sublimation rate twelve compartments (Table 4), we found that:

1. There was no significant difference between the Front-Top slabs and the Back-Right slabs.
2. The mean sublimation rate in Back-Left was .925/1.046=89% of the mean sublimation rate in the Front-Top slabs.
3. The mean sublimation rate in the Back-Middle slabs was .848/1.046=81% of the mean sublimation rate in the Front-Top slabs.

Therefore, the formular predicting the sublimation rate of the slabs in the vertical pocket was modified to predict the sublimation rate of the slabs in the horizontal pocket as follows:

K_2 = pocket location factor

= 1.0 for vertical top slab and right horizontal compartment

= .89 for horizontal left slab

= .81 for horizontal middle slab

= .69 for vertical middle and lower slab

The absolute error of prediction was 7.2%

There was a significant increase in oxygen consumption rate when subject wore a cooling jacket; the same result as in Duncan's experiment. Guyton (1961) described the characteristics of shivering as:

' Shivering is the results from excitation of the posterior hypothalamus by cold. Impulses are transmitted thriugh bilateral tracts that pass ventrolateral to the nuclei down the brain stem into the lateral columns of the spinal chord, and finally to the anterior motoneurons. These impulses are not rhythmical and do not cause actual muscular shaking. Instead, they simply facilitate the anterior motoneurons. This facilitation at first increases the muscle tone throughout the body, which raise the overall metabolic rate as much as 50 to 100 percent even without any shivering. Then, shivering begins when the degree of facilitation reaches a certain critical level'.

These statements can be depicted as in Figure 12.
Therefore, the increase in oxygen consumption rate may be just the increase in muscle tone due to the cold from the dry ice cooling.

A computer program, under development at Kansas State University, simulates a mathematical model of the thermoregulatory system. A comparison of physiological responses between the mathematical model and the experimental data was made for each individual subject under both cooling and no-cooling conditions.

The data input which varied for each subject was:

1 Age

2 Height

3 Weight

4 Physical fitness

5 Total metabolism

6 Sublimation rate of dry ice

7 Heat production due to non-shivering thermogenesis

The total metabolism in watts was determined by multiplying the mean oxygen consumption rate under a no-cooling condition by 4.825 Kcal/liter O_2 and 1.163 watt/Kcal/hr.

By using a straight line approximation, heat production due to non-shivering thermogenesis was determined from the difference between the oxygen consumption rates under a cooling and no-cooling conditions. Figure 13 gives an example of this method. The work efficiency was assumed to be 0.22, which

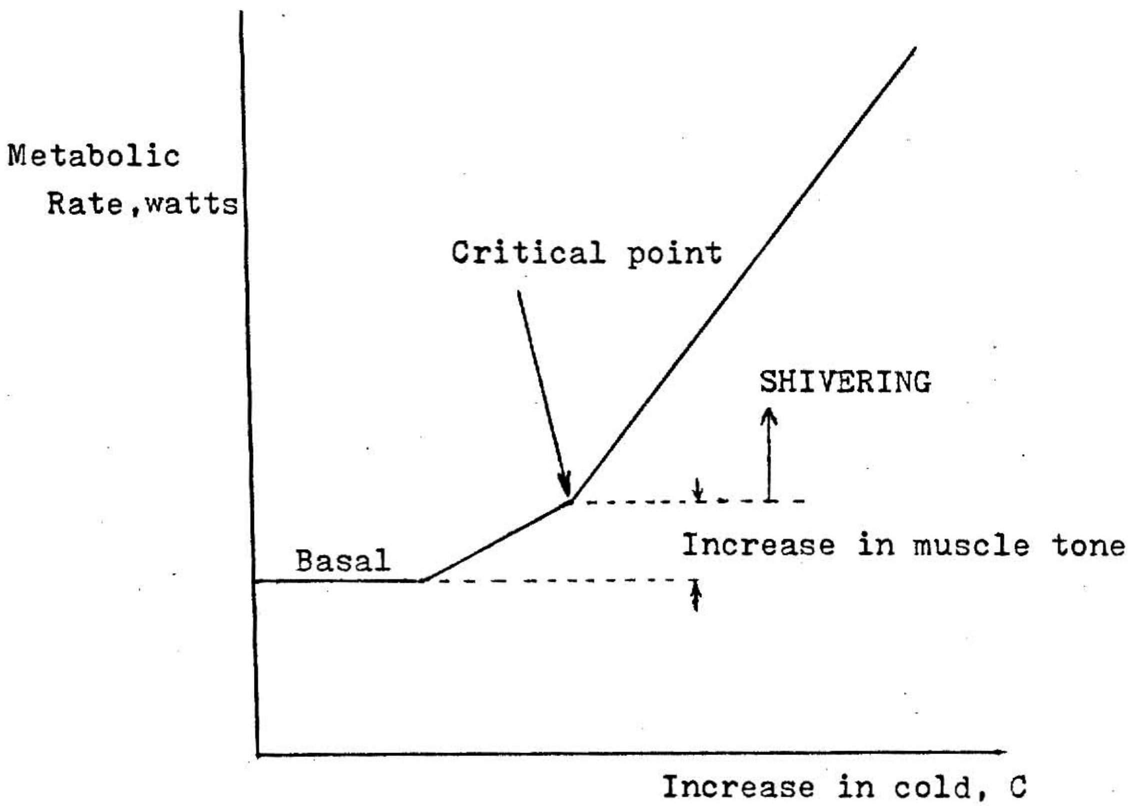

Figure 12. Characteristics of Shivering.

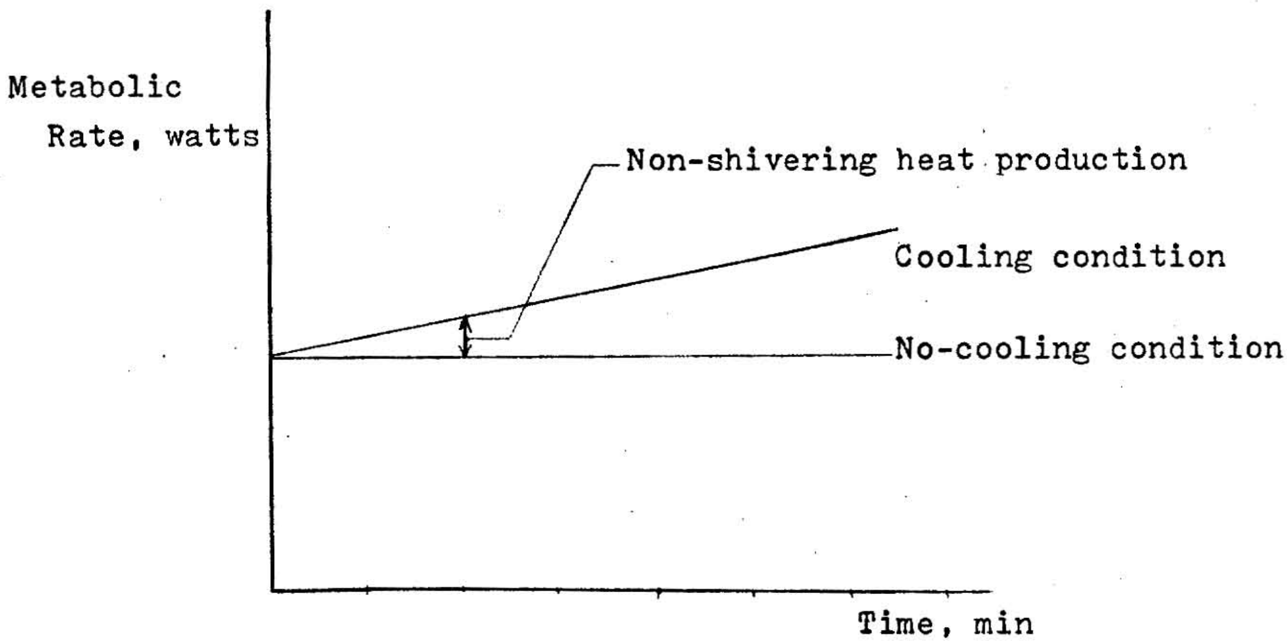

Figure 13. Illustration of Non-shivering Approximation Method.

implies that 78% of the total metabolism goes to heat production and 22% is mechanical output.

The comparison between the experimental and the simulated rectal temperature for each subject is shown in Figure 14, 15 and 16 for the no-cooling condition and in Figure 17, 18 and 19 for the cooling condition. In the simulated data, the rectal temperature increased at a higher rate throughout the exposure.. This may due to the inaccuracy of work efficiency as well as the total metabolism.

The comparison between the experimental and the simulated heart rate are shown in Figure 20, 21 and 22 for no-cooling condition and Figure 23, 24 and 25 for cooling condition. The experimental heart rate was generaly higher in subject 1 and 3, but lower in subject 2. This may due to the difference in fitness of the subjects; see characteristics of the subjects in Table 1.

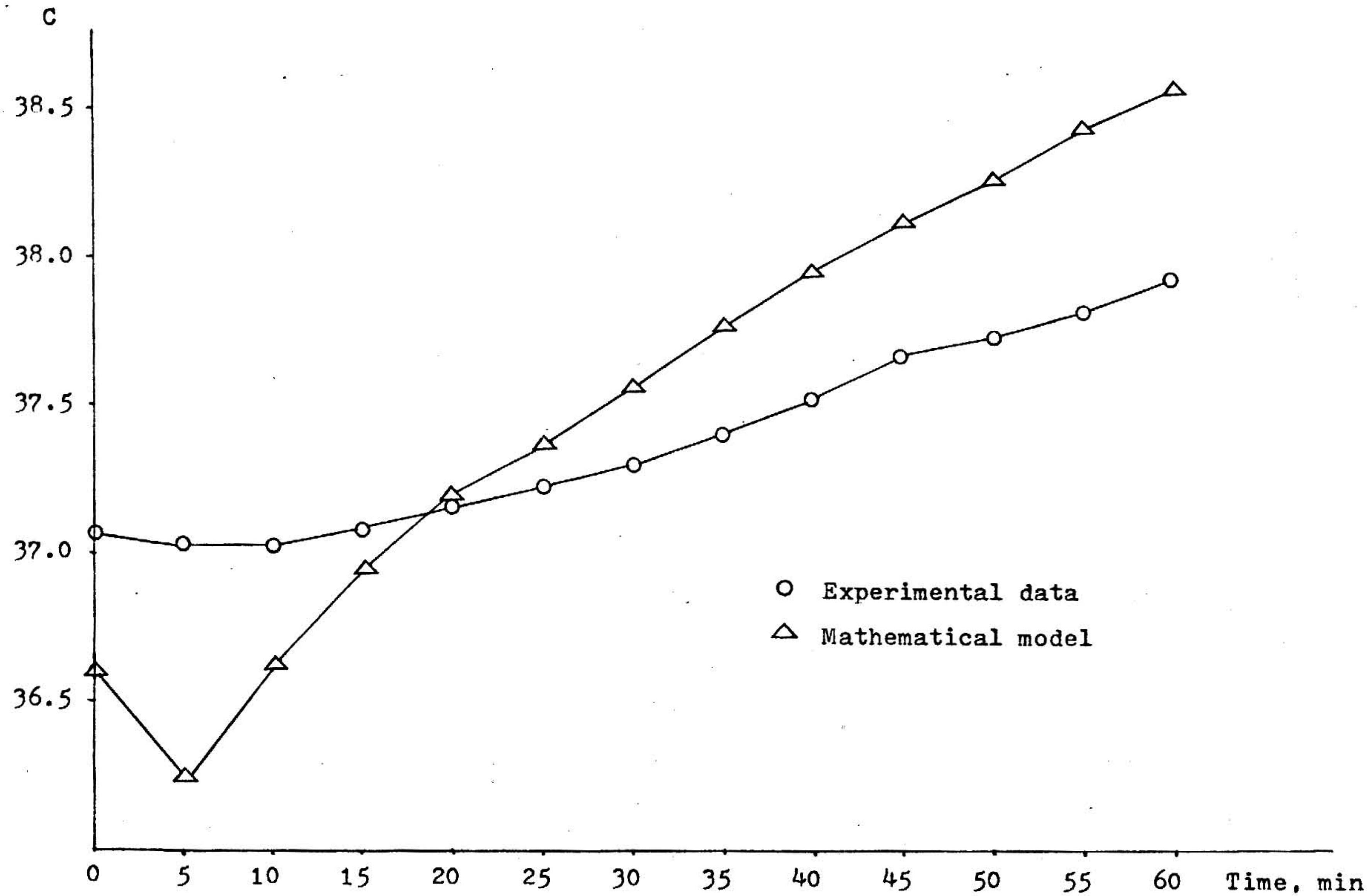

Figure 14. Comparison of Rectal Temperature for Subject 1 for No-cooling Condition.

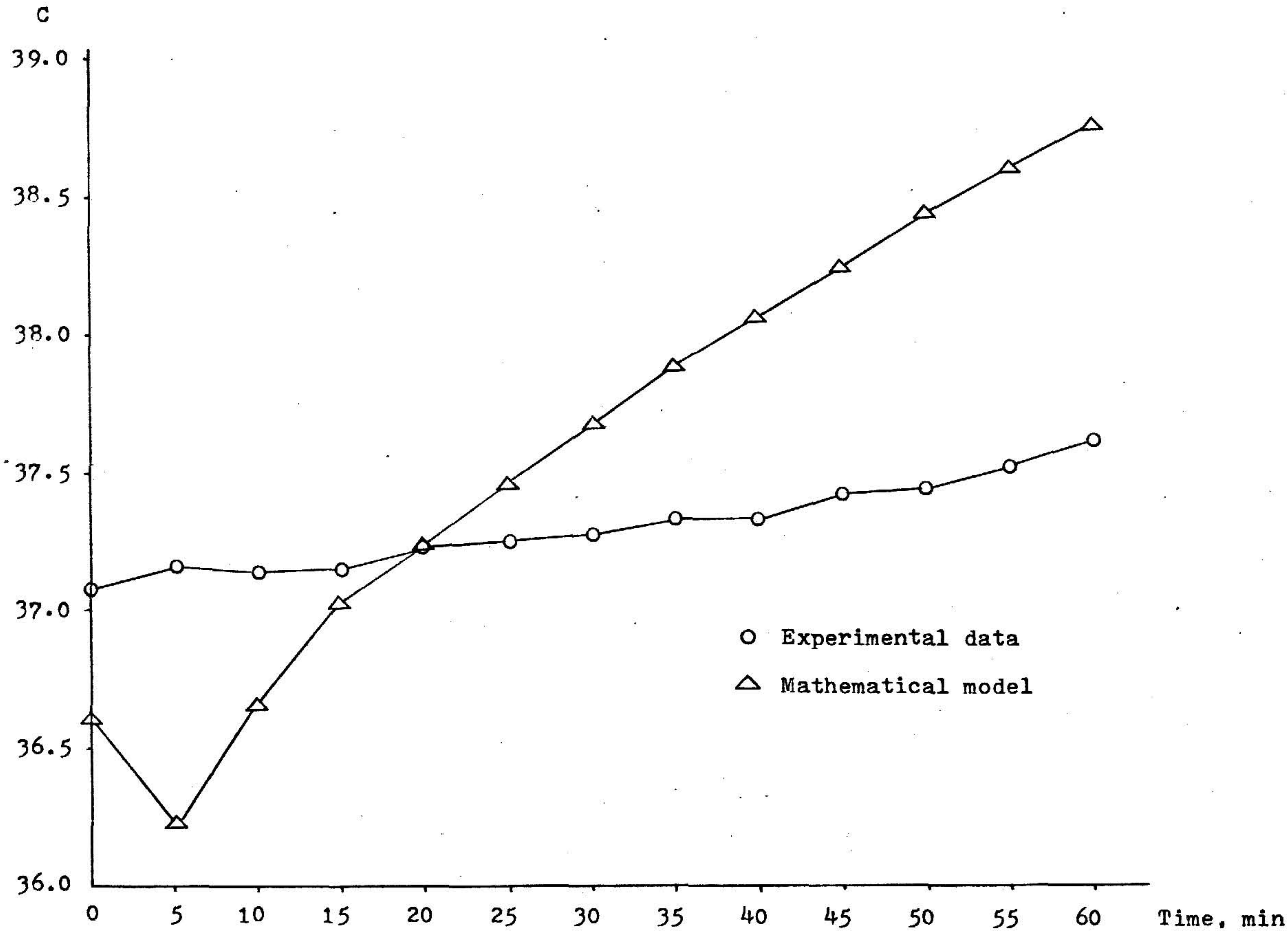

Figure 15. Comparison of Rectal Temperature for Subject 2 for No-cooling Condition.

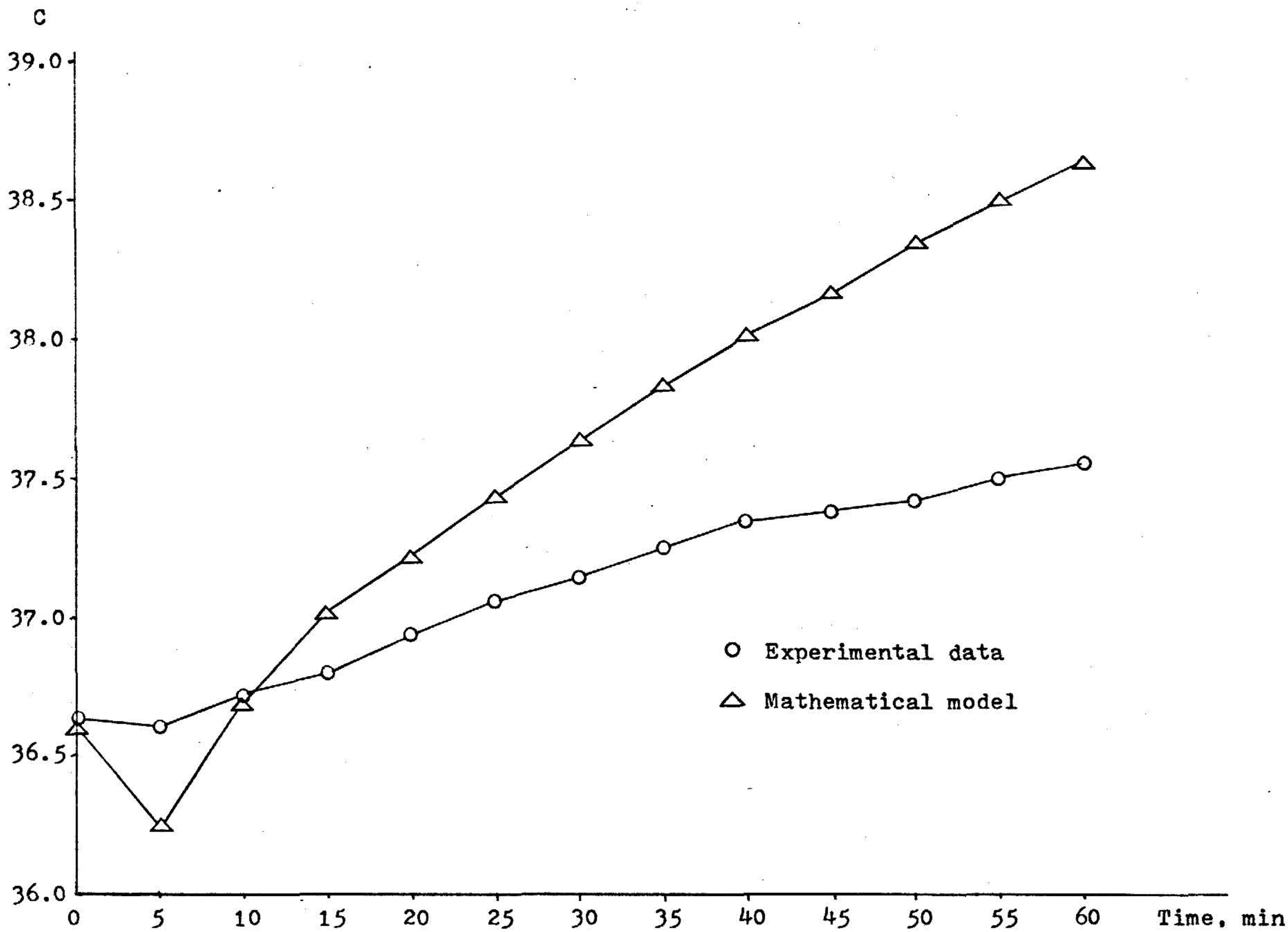

Figure 16. Comparison of Rectal Temperature for Subject 3 for No-cooling Condition.

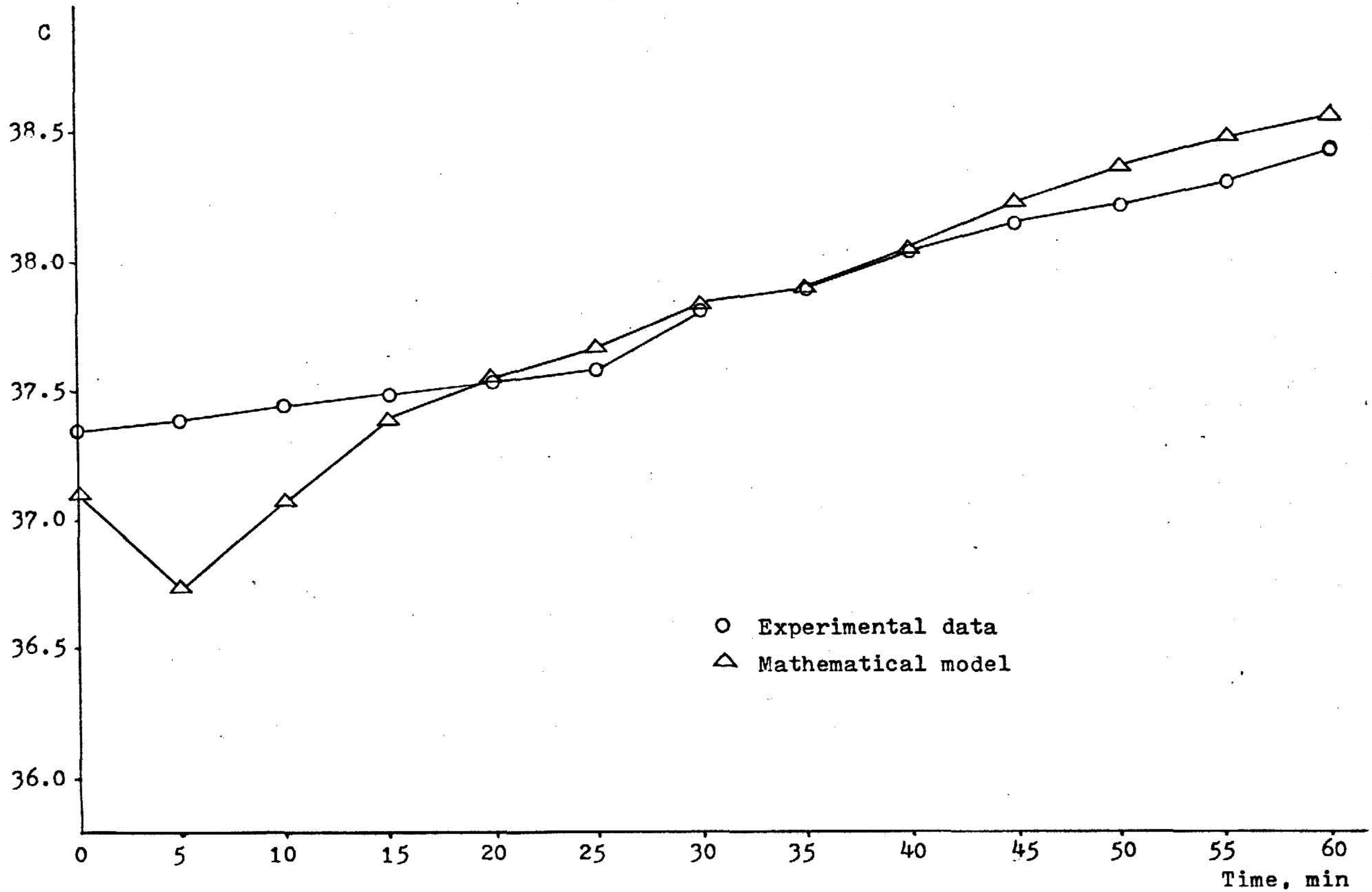

Figure 17. Comparison of Rectal Temperature for Subject 1 for Cooling Condition.

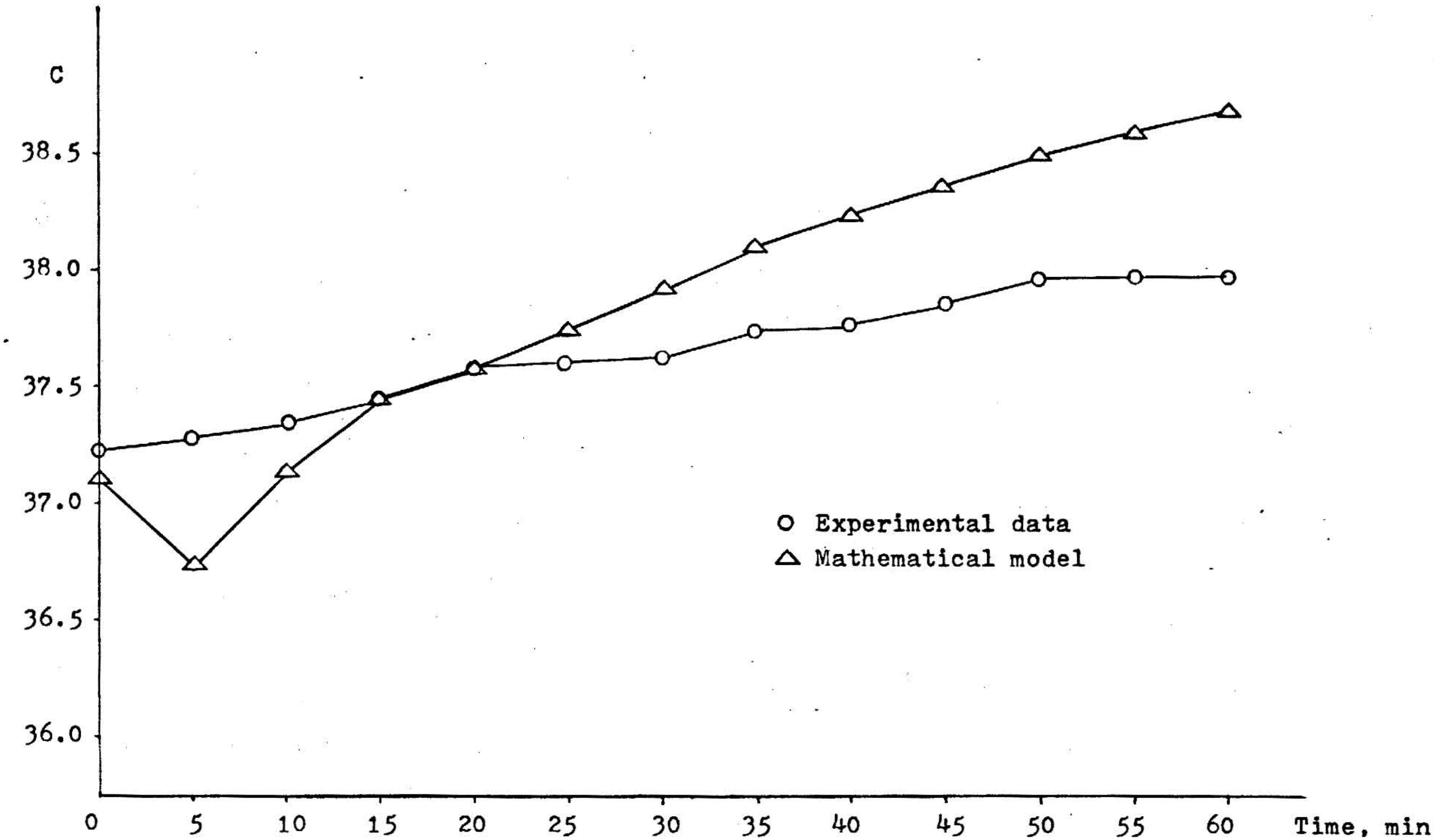

Figure 18. Comparison of Rectal Temperature for Subject 2 for Cooling Condition.

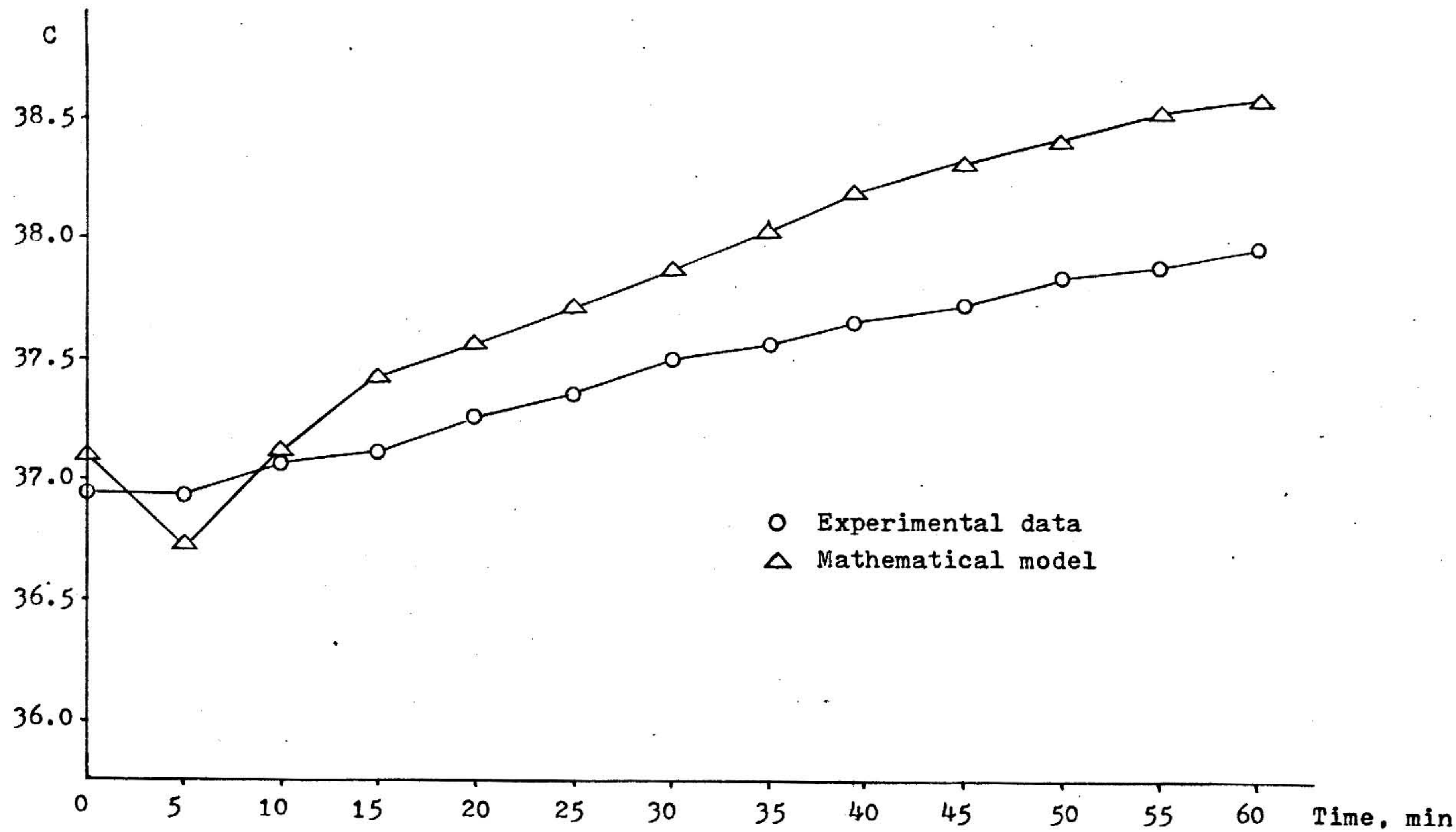

Figure 19. Comparison of Rectal Temperature for Subject 3 for Cooling Condition.

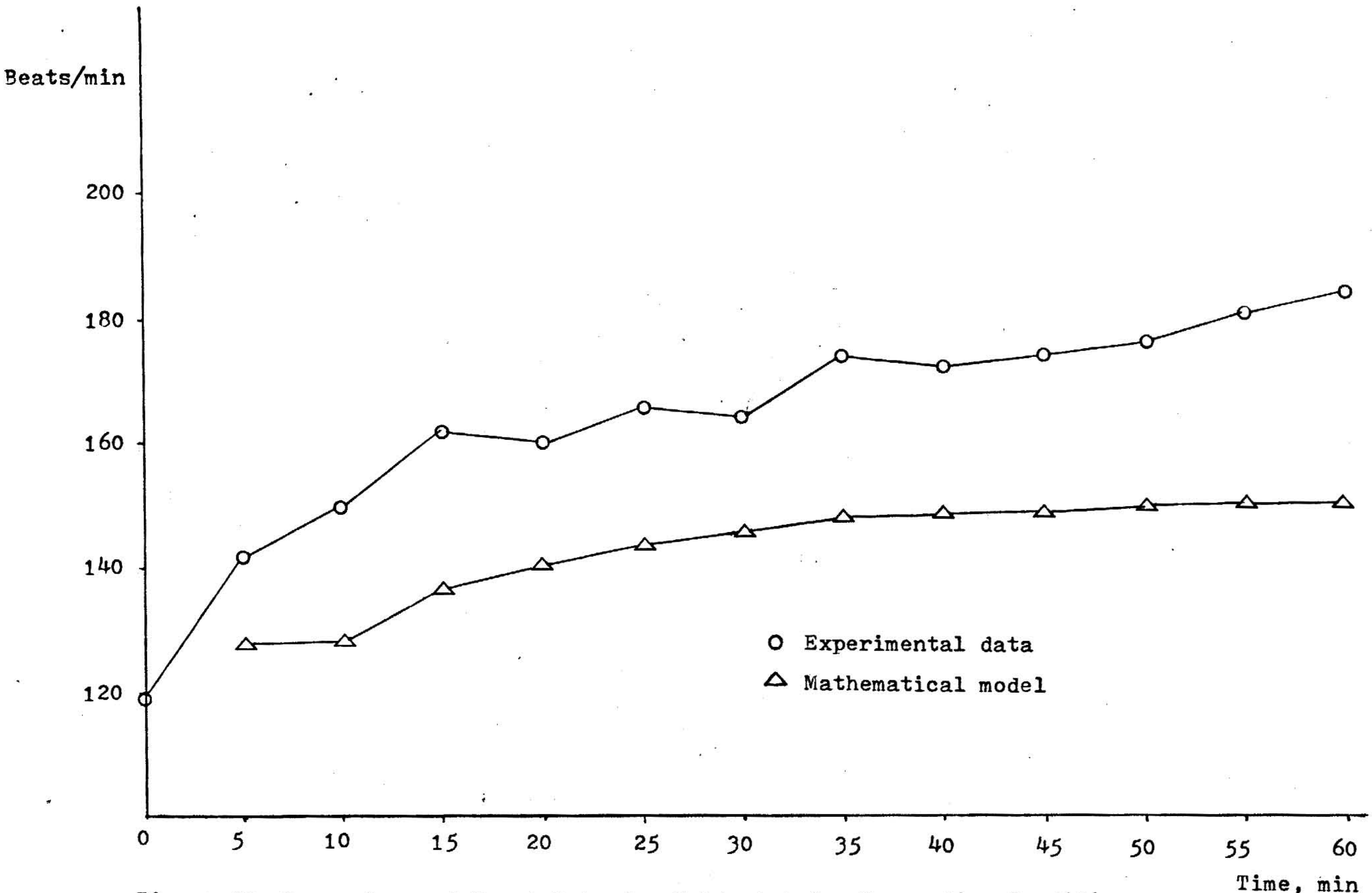

Figure 20. Comparison of Heart Rate for Subject 1 for No-cooling Condition.

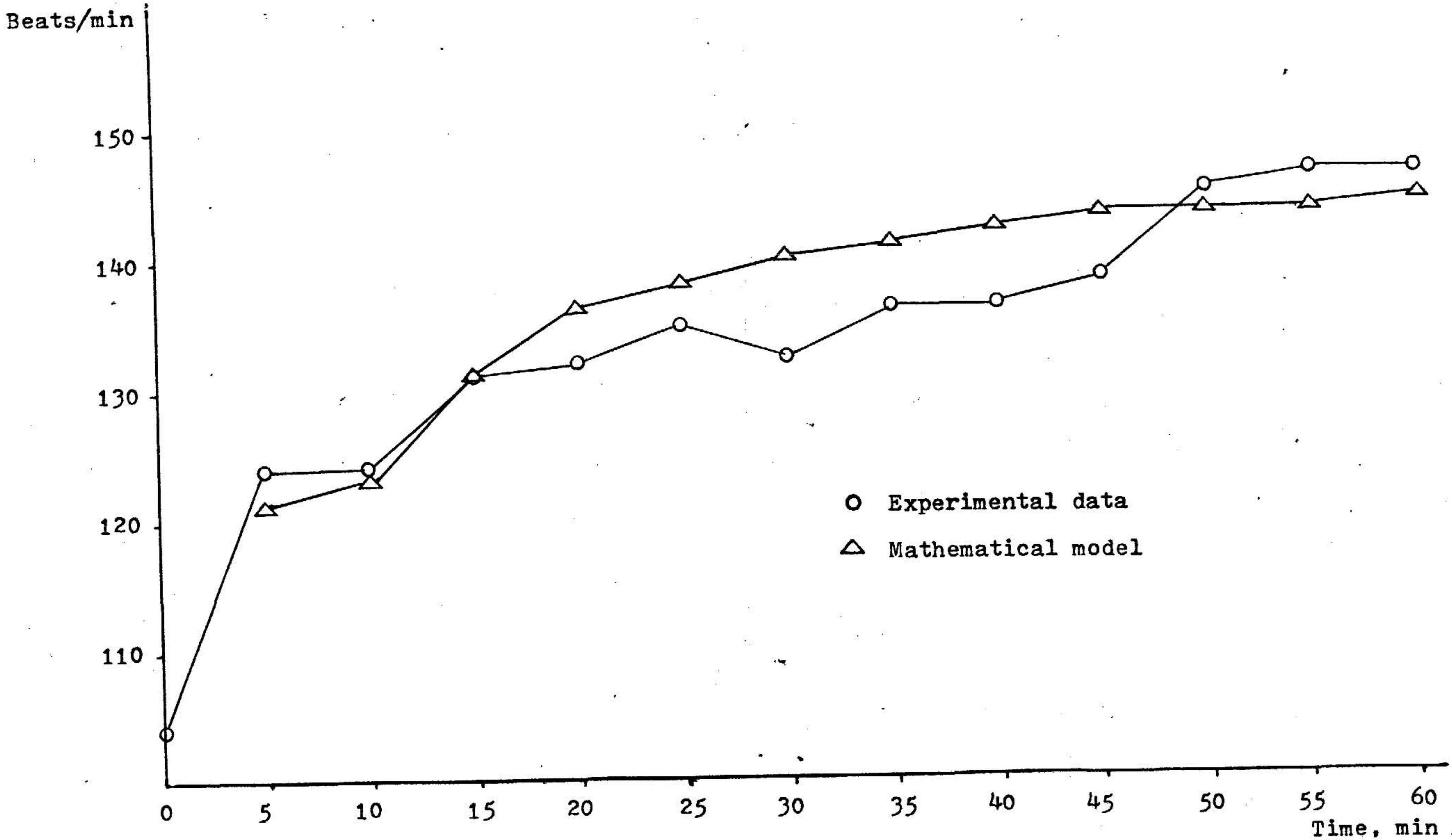

Figure 21. Comparison of Heart Rate for Subject 2 for No-cooling Condition.

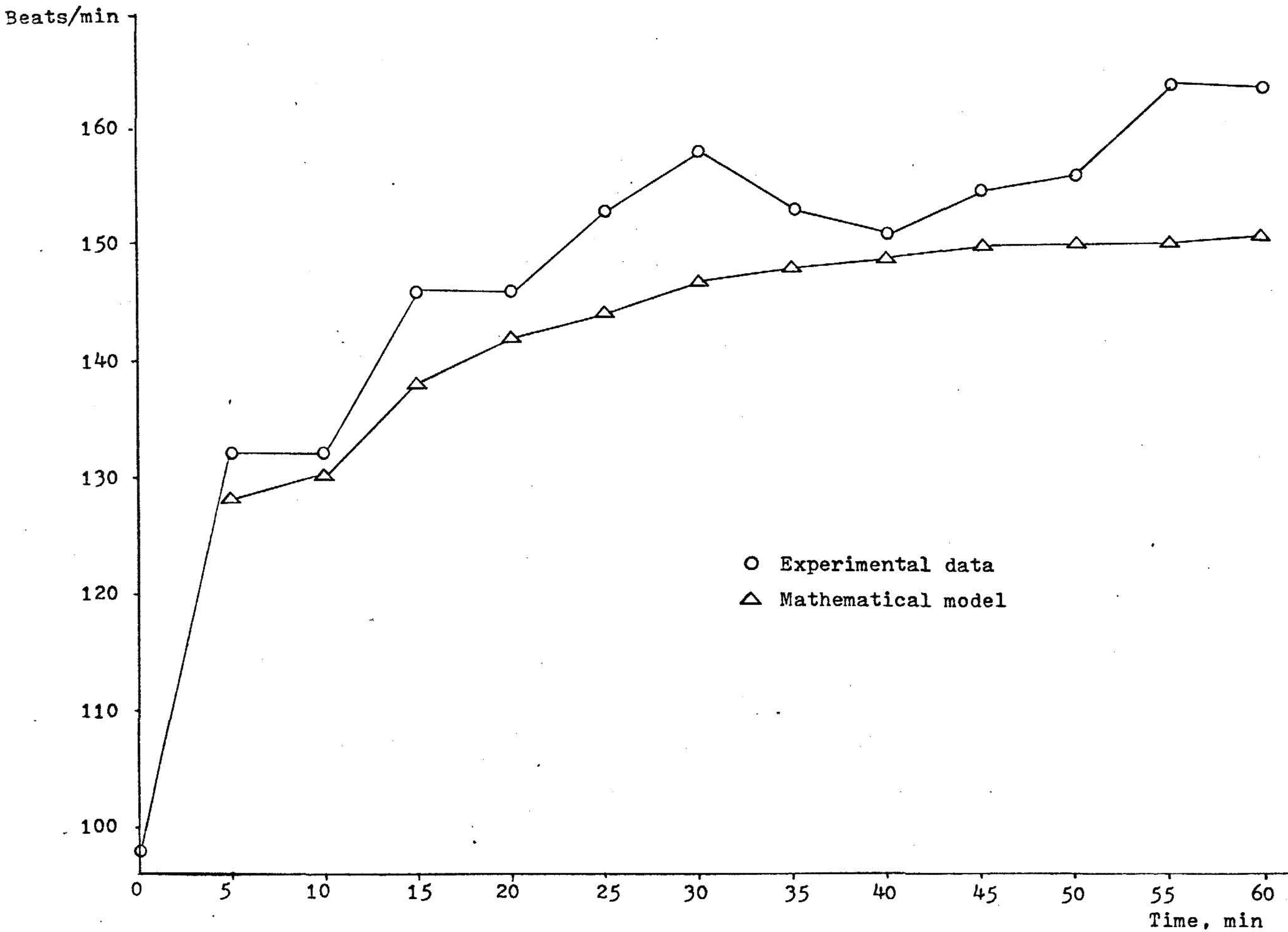

Figure 22. Comparison of Heart Rate for Subject 3 for No-cooling Condition.

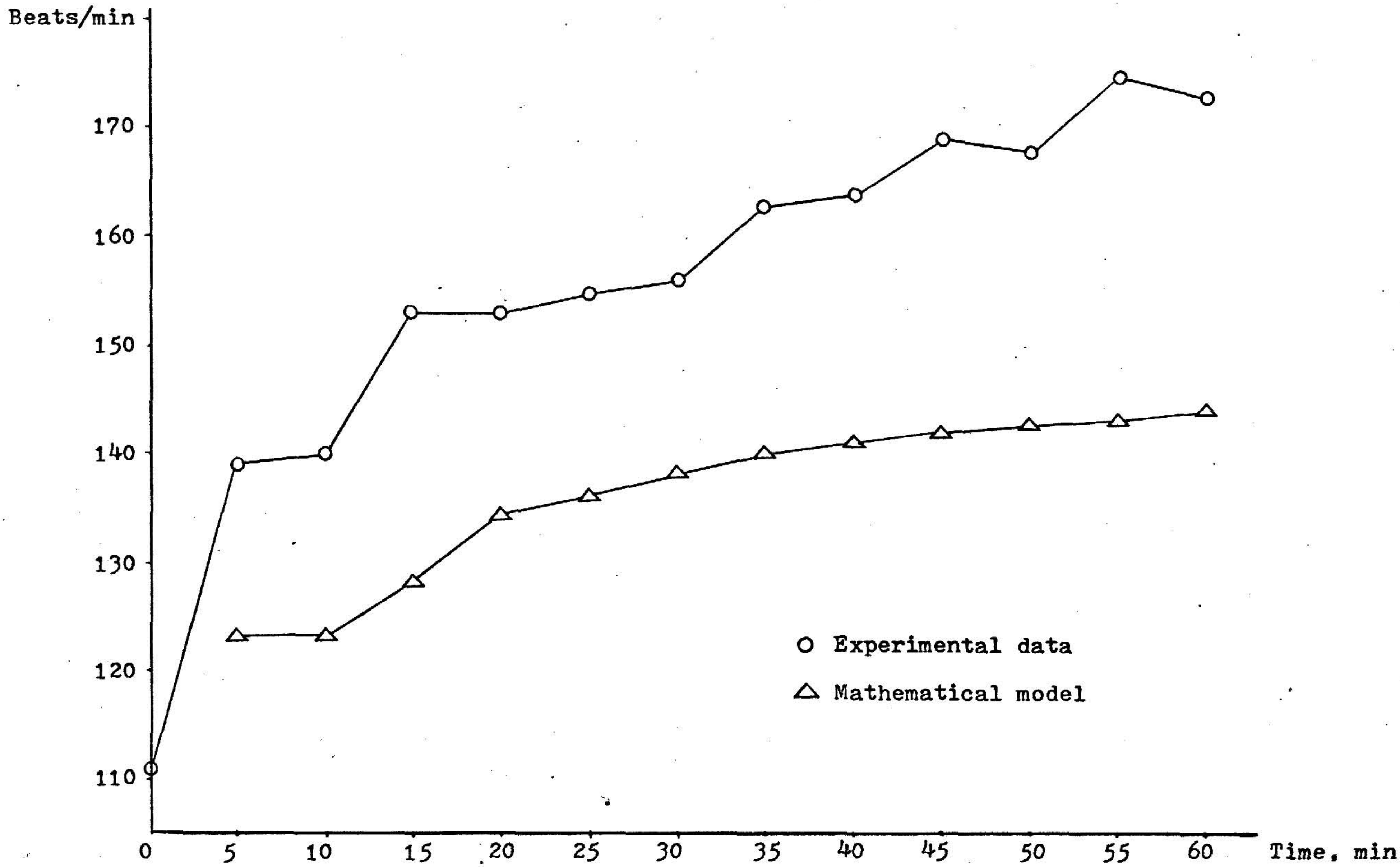

Figure 23. Comparison of Heart Rate for Subject 1 for Cooling Condition.

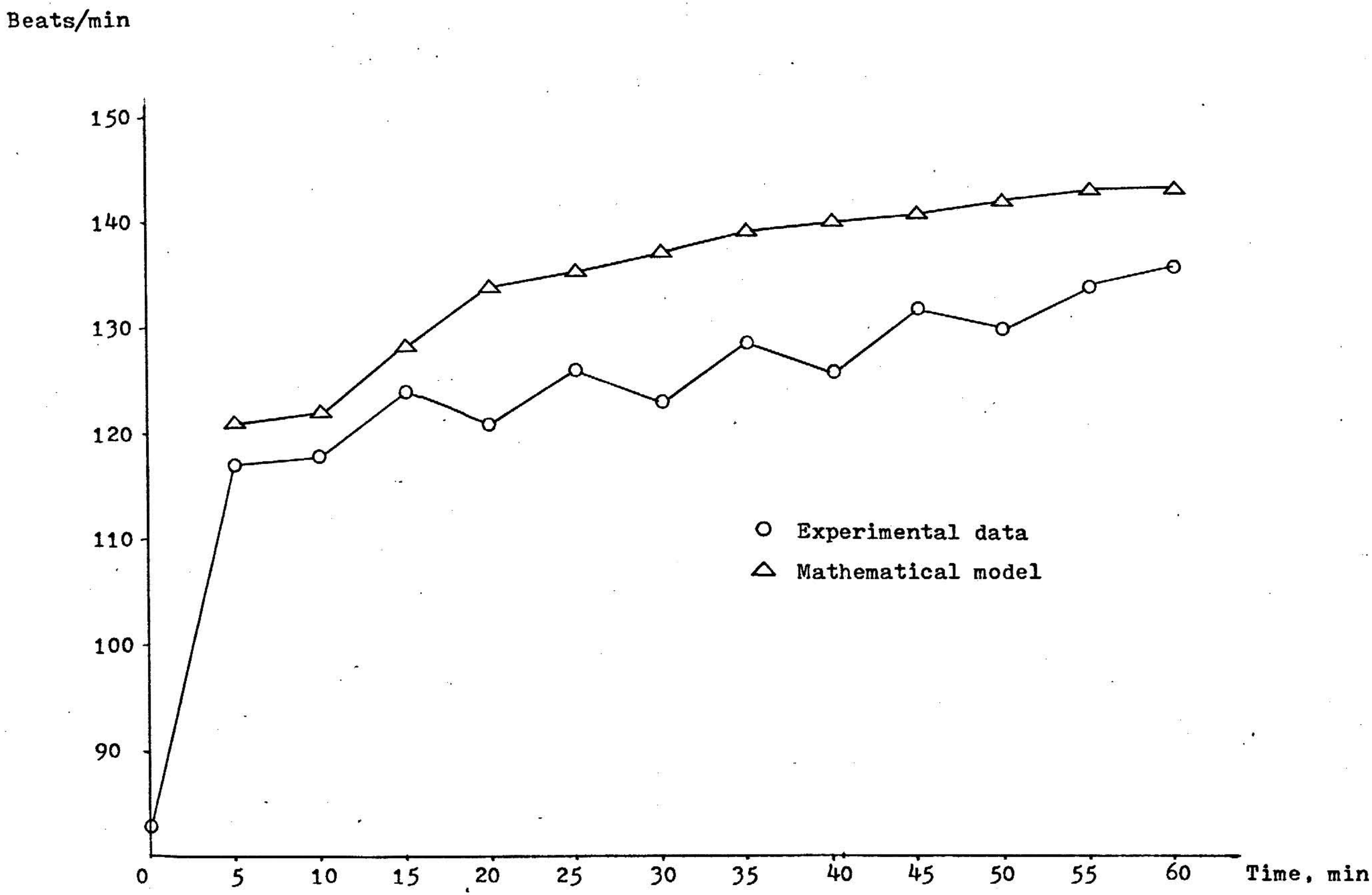

Figure 24. Comparison of Heart Rate for Subject 2 for Cooling Condition.

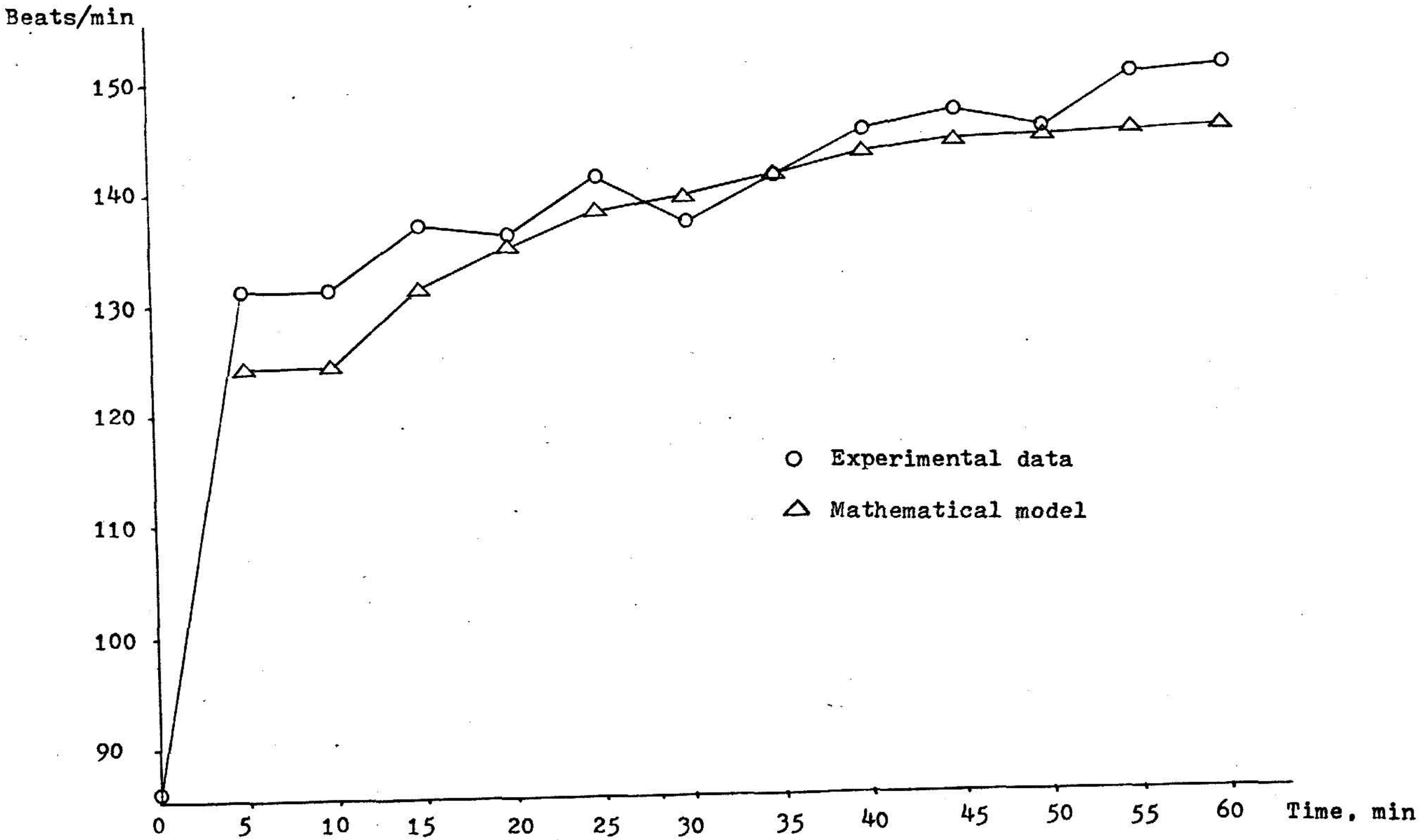

Figure 25. Comparison of Heart Rate for Subject 3 for Cooling Condition.

Conclusion

The dry ice cooling jacket, again, was proved to be an effective means in reducing physiological strain (heart rate and rectal temperature) of a person in high thermal heat stress. A complaint made by subject 1 was that he felt rather uncomfortable around the waist due to overcooling of the jacket. This problem can be solved by:

1. move the horizontal pockets up one or two inches
2. let the cold carbon dioxide gas, which was trapped around the waist, flow down the inside of the pants to cool the lower part of the body. The amount of the cold gas flow down to the lower part of the body can be controlled by the looseness of the garment arounf the waist.

High insulation is desirable to prevent overcooling as well as extending the effective cooling period. A horizontal pocket is recommended in both front and back.

REFERENCES

Aherne, W. and Hull, D., Brown adipose tissue and heat production in the new born infant, Journal of Pathology and Bacteriology, 91;223,1966.

Ashcoff, J. and Wever, R., Kern und schale in warmehuashault des meschen, Die Naturwissenschaften, 45;477-485,1958.

Bigland, B. and Lippold, O.C.J., The relationship between force, velocity and integrated electrical activity in human muscles, Journal of Physiology, 123;214-224,1954.

Byrnes, D., Effect of heat stress on saliva, Master's Thesis, Kansas State University, 1970.

Consolazio, C., Johnson, R., and Pecora, L., Physiological Measurements of Metabolic Functions in Man. New York: McGraw-Hill, 1963.

Depocas, F., Chemical thermogenesis in the functionally eviscerated cold-acclimated rat, Canadian Journal of Biochemistry and Physiology, 36;691,1958.

Duncan, J., A physiological evaluation of two designs of conductive cooling hood, Master's Thesis, Kansas State University, 1969.

Duncan, J., Design of a personal dry ice cooling garment: Its physiology and heat transfer aspect, Ph.D. dissertation, Kansas State University, 1975.

Folk, G., Jr., Textbook of Environmental Physiology, Philadelphia; Lea and Febiger, 1974.

Ganhok, G., Physiological evaluation of an air cooled helmet system, Master's Thesis, Kansas State University, 1970.

Hein, T. and Hull, D., The blood flow and oxygen consumption of brown adipose tissue in the new born rabbit, Journal of Physiology, 186;42-55,1966.

Imai, Y., Horwitz, B. and Smith, R., Calorigenesis of brown adipose tissue in cold exposed rate, Proceedings of Society for Experimental Biology and Medicine, 127; 717,1968.

Jansky, L., Participation of body organs during nonshivering heat production, in Nonshivering Thermogenesis, Prague, Czechoslovakia: Academia,1971.

Jansky, L. and Hart, J., Participation of skeleton muscle and kidney during nonshivering thermogenesis in cold acclimated rats, Canadian Journal of Biochemistry and Physiology, 41;953,1963.

Jansky, L. and Hart, J., Cardiac output and organ blood flow in warm and cold acclimated rats exposed to cold, Canadian Journal of Physiology and Pharmacology, 46; 653.1968.

Konz, S., Hwang, C. L., Perkins, R. and Borell, S., Personal cooling with dry ice, American Industrial Hygiene Association Journal, 35:137-147,1974.

Konz, S., Duncan, J. and Masud, A., Dry ice sublimation in a personal cooling, AIAA 10th Thermophysics conference, Colorado, AIAA paper no.75-716,1975.

Mejesnar, J. and Jansky, L(Ed.), Method for estimating of nonshivering thermogenesis, in Nonshivering Thermogenesis, Prague, Czechoslovakia: Academia,1971.

Mitchell, D., Stydom, N., van Graan, C., and van der Walt, W. Human surface area: Comparison of the Dubois formular with direct photometric measurement. Pflugrs Archives, 325,180-190,1971.

Sharma, S., Physiological evaluation of an air cooled system, Master's Thesis, Kansas State University, 1970.

Smith, R. and Horwitz, B., Brown fat and thermogenesis, Physiological Reviews, 49;2,330-425,1969.

Smith, R., Thermogenic activity of the hibernating in the cold-acclimated rat, The Physiologist, 4;113,1961.

HEAT FLOW AND METABOLIC REACTION DURING DRY ICE COOLING

BY

PAISAN TECHAPATANARAT

B.Eng., Chulalongkorn University, Thailand, 1973.

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements of the degree

MASTER OF SCIENCE

Department of Industrial Engineering

Kansas State University

Manhattan, Kansas

1976

Abstract

A personal dry ice cooling jacket for workers in heat stress environments was developed at Kansas State University. The back pocket orientation of a Model-C cooling jacket was rearranged from a vertical to a horizontal design.

The cooling jacket was evaluated under three levels of insulation in laboratory heat stress environments, where the dry bulb temperature was 35°C, and the relative humidity was 70%. Three male subjects pedalled an ergometer bicycle for 60 minutes. The sublimation rate of dry ice was significantly lower at high insulation than at low and medium insulations. The horizontal pocket gave a more uniform sublimation rate. The mean heart rate throughout the 60 minute exposure was 138 beats/min with the jacket and 148 beats/min without the jacket. Mean rectal temperature of 37.72°C for low insulation was higher than the 37.58°C for medium insulation, which was also higher than the 37.48°C for high insulation. Oxygen consumption with the jacket was 27% higher than without it. This could be explained by an increase in heat production due to an increase in muscle tone during the pre-shivering period when the jacket was wore. Physiological responses of a subject were simulated by a computer model of human thermoregulation.