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THE RELATIONSHIP BETWEEN THE ENVIRONMENT AND THE BASAL INSENSIBLE LOSS OF WEIGHT [1]

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In 1926, Benedict and Root (1) expressed the belief that a quantitative relationship existed between the heat production in the basal state and the insensible loss of weight. General confirmation was later obtained by Levine and his colleagues (2), and by this laboratory (3).

The insensible loss is caused by the outward passage of water vapor and carbon dioxide, both of which reduce the individual's weight, but it is simultaneously augmented by the absorption of oxygen. The only component of the insensible loss of weight that carries away heat is the water vapor. The use of the insensible loss of weight as a measure of the dissipation of heat is not strictly quantitative, since this loss varies not only with the weight of the water vapor, but is also influenced by the character of the materials being metabolized. This relationship is conveniently expressed as an equation in which the weight of each substance is employed:

$$H_2O + CO_2 - O_2 = \text{Insensible loss of weight.}$$

The insensible loss of weight may be obtained by means of an appropriate balance (1). If the heat production of the individual is determined by indirect calorimetry, the weights of carbon dioxide and oxygen are at hand, and these values may be used to clear the equation. Since water is now the only unknown quantity, one may, by rearranging the equation and substituting the known values, arrive at the weight of water vaporized. Thus:

$$H_2O = \text{Insensible loss} - (CO_2 - O_2).$$

[1] The expenses of this investigation were defrayed in part by a fund for the study of nutrition, created by Mr. W. K. Kellogg, of the Kellogg Corn Flake Company, Battle Creek, Michigan.

[2] National Research Council Fellow in Medicine.

It has been generally understood for a long time that heat is dissipated from the body by radiation, conduction, convection, and the vaporization of water. The latter is of special interest to us since it alone can be measured by change in weight. Since in an organism in the basal state the heat dissipation and heat production are equal, and since the latter may be accurately determined, we have a means of arriving at the heat dissipated. Since, in the second place, the outward passage of water vapor is accompanied by a loss of weight on the part of the organism, an accurate knowledge of the weight of the water vaporized in a unit of time immediately states the rate of loss of heat by this process, for it is true that at body temperature 0.58 Calories are removed with each gram of water vapor.

Accordingly, the determination of heat production by indirect calorimetry and of the insensible loss by means of a balance, under basal conditions, permits one to arrive at, (1) the amount of heat removed from the organism by the evaporation of water, and (2) the ratio between it and the total dissipation of heat.

Our problem consisted of recording the influence of the temperature, humidity, and movement of the air on the heat removed by the vaporization of water, and on the ratio between this value and the total heat dissipated. Since the surface temperature of an individual is not constant, but is influenced by the state of the environment, it was also necessary to record the skin temperature in order to deal with its relation to these same two values. We also wanted to know what changes, if any, are brought about by an elevation of the heat production. Finally, it is also necessary, in order to get a comprehensive understanding of the mechanism, to know the effect of clothing on the subject.

The room in which the experiments were carried out was sufficiently insulated so that the temperature and humidity could be kept at any desired level. The movement of air was obtained by an electric fan. A highly trained, presumably normal male individual was used as the subject. He was 34 years of age, 168 cm. in height, and weighed 61 kilograms. The insensible loss of weight was determined by means of a balance accurate to one tenth of a gram. The subject lay on a support made of wide steel ribbons, and his head rested on a small rubber-covered pillow. The heat production was obtained by indirect calorimetry with the use of a Tissot spirometer and the Henderson-Haldane apparatus for gas analysis. The skin temperature was determined by means of a thermocouple of the usual type. The surface temperature of a number of points on the head, trunk, legs, feet, arms, and hands was obtained, and the average temperature for each of the above areas was multiplied by the fraction of the total area which it represented. The sum of the figures thus secured represents the average surface temperature of the entire body. The desired temperature and humidity of the room was obtained in the early morning and held at that level through the period required for the observations on that day. Only one set of observations was made each day, but further observations were made at the same temperature on other days.

Series 1. Nude Subject

Group A. Basal state. Effect of atmospheric temperature. The temperature was varied from 18° to 40° C., while the relative humidity was kept constant at 20 (±2) per cent. The results are shown graphically in Figure 1. For the sake of clarity, the rate of increase of atmospheric temperature (C) is plotted as a diagonal.

The heat production (B) followed the expected course. Between 25° C. and 37° C., the heat production was practically constant. It rose very slightly thereafter with increasing atmospheric temperature. As the temperature fell below 25° C., there was a sharp increase in heat production. At 18° C., it had increased over the basal more than 50 per cent, but was not accompanied by visible shivering.

From 18° to 30° C., the skin temperature increased at about one half the rate of increase of environmental temperature. Thereafter the rate of increase of surface temperature gradually fell off and approached a constant value of about 36° C. Between the environmental temperatures of 30° and 40° C., the skin temperature increased only 1.5° C.

A comparison between the amount of heat removed by the vaporization of water and the total heat dissipated (produced) can best be made by separating their courses into three periods. Through the range of room temperature between 18° and 25° C., the heat dissipated by the vaporization of water increased slowly at a constant rate even though the total loss of heat decreased rapidly. From 25° to 30° C., the removal of heat by vaporization continued to increase at the former rate even though the heat dissipation throughout this range had a fixed value. From 30° to 40° C., the removal of heat by the vaporization of water increased at a dramatic rate while the total heat dissipation remained practically constant.

Finally, the heat lost by vaporization of water expressed in per cent

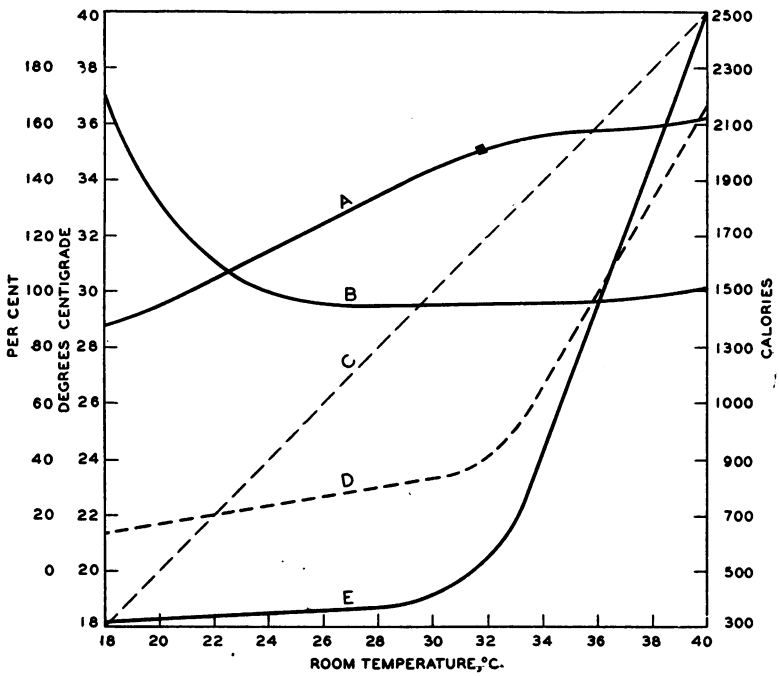

FIG. 1. NUDE SUBJECT. THE EFFECT OF ROOM TEMPERATURE ON SKIN TEMPERATURE, BASAL HEAT PRODUCTION AND THE DISSIPATION OF HEAT BY THE VAPORIZATION OF WATER AT A RELATIVE HUMIDITY OF 20 PER CENT.

A. Skin temperature in degrees centigrade. B. Basal heat production in Calories per 24 hours. C. Rate of increase in room temperature. D. Heat lost by the vaporization of water in per cent of the total heat dissipated. E. Heat dissipated by the vaporization of water in Calories per 24 hours.

of total heat dissipated, is represented by line (D) in the figure. It will be seen that this percentile value was different at every atmospheric temperature. It increased from 15 per cent to 30 per cent of the total outgoing heat, between the atmospheric temperatures of 18° and 30° C.

From 32° to 40° C., it rose rapidly from 35 per cent to 175 per cent. It reached 100 per cent of the dissipated heat when the skin and atmospheric temperatures were the same (i.e. 36° C.).

The events upon which the removal of heat depend may advantageously be thought of as occurring in two fields, separated from each other by an imaginary line cutting through the environmental temperature of 30° C. In the cooler field the ratio between the total dissipation of heat and that portion removed by vaporization is determined by well established physical principles, and no biological factors need be employed. The increase of skin temperature, at a rate one half that of the environmental temperature, gives rise to a constantly decreasing temperature gradient between the subject and his environment; and, consequently, the heat lost by radiation, conduction, and convection was also decreased at a constant rate. On the other hand, the rising skin temperature increased the rate of vaporization of water into an atmosphere whose relative humidity was constant. The actual increase in the vaporization of water in this field was 11 grams per 24 hours per degree change in environmental temperature.

In the warmer field, even at the left hand edge, the difference between skin and room temperatures was already so small that little heat was lost by radiation, conduction, and convection. At 36° C., these temperatures were equal, and beyond that the higher environmental temperature caused a transfer of heat from the environment to the organism. To compensate for the progressive failure of radiation, conduction, and convection to remove the heat from the organism at the proper rate, the vaporization of water increased very rapidly. The physical conditions alone would not account for the observed increase in vaporization of water. (In fact, the almost constant skin temperature accounts for practically no increase in vaporization), and consequently, the observed increase is due to the active delivery of water to the skin by the sweat glands. Thus the dissipation of heat is almost entirely brought about by a physiological adaptation of the subject to his environment. The actual increase in the vaporization of water was 465 grams per 24 hours per degree change in environmental temperature, as contrasted with 11 grams in the other field. At an environmental temperature of 40° C., when the heat production was 1500 Calories, the heat lost by the vaporization of water was 2500 Calories.

The extra 1000 Calories represented the absorption of heat by the individual from the hot air of the room.

Group B. Basal state. Effect of humidity. The effects of relative humidity ranging from 20 per cent to 80 per cent were recorded. The room temperature was maintained at 28° C. These effects are represented in Figure 2. The skin temperature throughout this group

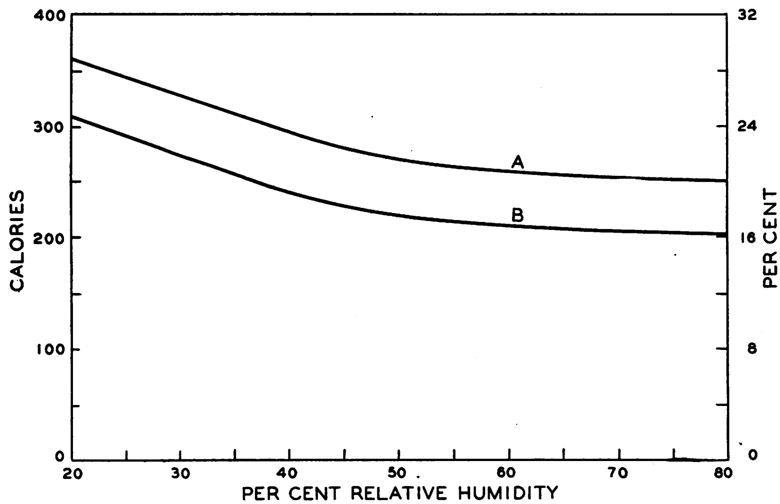

FIG. 2. NUDE SUBJECT. THE EFFECT OF RELATIVE HUMIDITY ON THE DISSIPATION OF HEAT BY THE VAPORIZATION OF WATER AT AN ENVIRONMENTAL TEMPERATURE OF 28° C.

A. Heat lost by the vaporization of water in per cent of the total heat dissipated. B. Heat dissipated by the vaporization of water in Calories per 24 hours.

remained constant at 33.5° C. (±0.2°). The heat production was uninfluenced by the humidity. It is quite clear that an increasing relative humidity of the atmosphere caused a decreasing vaporization of water from the surface of the skin, other things being equal. Since the skin temperature and heat production did not change, the organism was in no way responsible for this phenomenon.

Group C. Basal state. Effect of wind. When a powerful air current was directed against the nude subject, the amount of water vaporized in a unit of time was definitely less than when the air was still and other conditions were unchanged. This decrease can be attributed to the more rapid removal of heat and the consequent lowering of the skin temperature.

Group D. Effect of increased heat production. In order to observe the response of the mechanism for dissipating heat when the heat production was above the basal level, the subject was fed about 600 grams of beef each morning, about one hour before the studies began. The data were obtained during the second and third hour after ingestion of meat because this is the time when the metabolism is most likely to be maintained at the high level characteristic of the response to protein. The conditions to which the subject was exposed were otherwise the same as in "Group A" of this series. It will be seen from Figure 3 that the heat production was increased about 40 per cent over the basal, and showed the same tendency to increase still further in response to cold as was observed in the basal state. In spite of the increase of the heat production the percentile ratio between this value

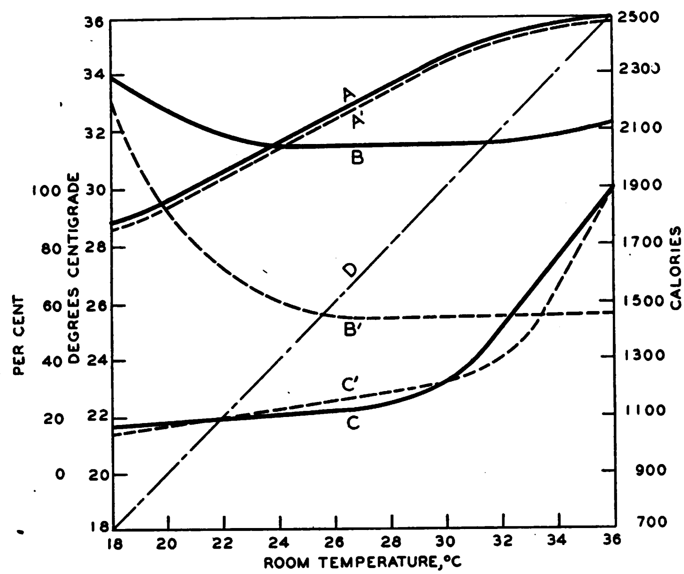

FIG. 3. NUDE SUBJECT. THE EFFECT OF AN INCREASED HEAT PRODUCTION ON THE SKIN TEMPERATURE, AND THE DISSIPATION OF HEAT BY THE VAPORIZATION OF WATER AT A RELATIVE HUMIDITY OF 20 PER CENT.

A. Skin temperature in degrees centigrade. B. The heat production in Calories per 24 hours. C. Heat lost by the vaporization of water in per cent of the total heat dissipated. D. Rate of increase in room temperature. A′, B′ and C′ represent the values found in the basal state. (See Fig. 1.)

and the amount of heat dissipated by the vaporization of water followed the same general plan as it did in the basal state, but differed from the latter in two definite respects: (1) The active participation of the sweating mechanism began at a temperature about 4° lower; (2) during the range of temperature below the sweating level, the amount of heat dissipated by the vaporization of water showed a greater tendency to approach constancy than in the basal state. After meat, as in the basal state, all of the heat was carried away by vaporization when the atmospheric temperature was 36° C., since the skin temperature in both cases had also attained this level at that temperature.

Discussion

The study of the effects of the atmosphere on the nude subject in the basal state has clearly shown that increasing temperature of the air is accompanied by an increasing loss of heat by vaporization of water, and that this increase is first slow and then abruptly becomes rapid. The second fact is the almost uniform decrease in the amount of heat removed by the vaporization of water as the relative humidity increases.

When the heat production is markedly increased above the basal level, the mechanism for the removal of heat conducts itself, broadly, in the same way as when the heat production is at the basal level. However, the activity of the sweat glands is brought into play at a lower temperature. Consequently, the purely physical mechanism fails sooner when extra heat is produced.

If it were intended to measure, in the nude basal subject, the total dissipation of heat, or its counterpart, the heat production, by means of the weight of the vaporized water, it would be essential to construct a prediction table of the per cent of the total heat lost by vaporization of water at every atmospheric temperature and for every relative humidity in still air. Furthermore, it would be desirable to restrict the temperature to the five degree range between 26° and 31° C., since below 26° C. there is a rising heat production, and above 31° C. the increase in heat removed by vaporized water is so rapid that reliable values could scarcely be expected. No one has yet constructed such a table.

Series II. Clothed Subject. Basal State

Group A. Heavy "Canton" flannel pajamas with feet, and without mattress or blankets. The effects of environmental temperature on the subject thus clad were recorded in the same way as in Series I-A. The results are represented in Figure 4. The effect of clothing can be ob-

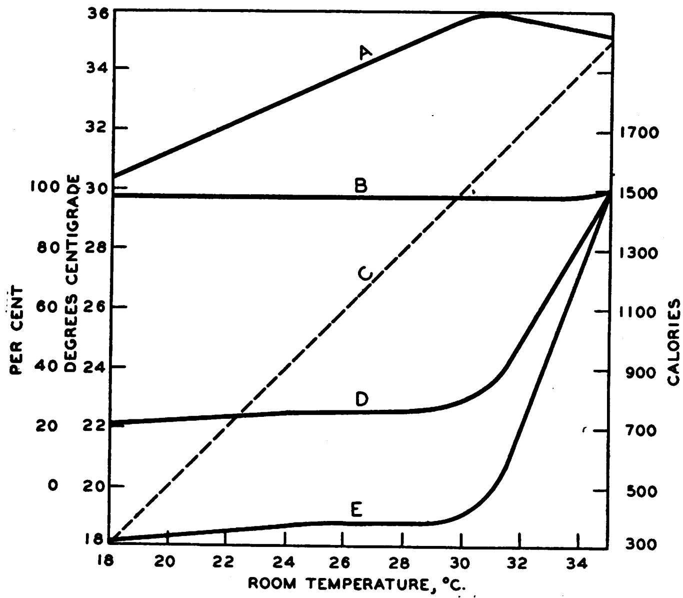

FIG. 4. CLOTHED SUBJECT. THE EFFECT OF ENVIRONMENTAL TEMPERATURE ON THE SKIN TEMPERATURE, BASAL HEAT PRODUCTION, AND THE DISSIPATION OF HEAT BY THE VAPORIZATION OF WATER.

A. Skin temperature in degrees centigrade. B. Basal heat production. C. Rate of increase in room temperature. D. Heat lost by the vaporization of water in per cent of the total heat dissipated. E. Heat dissipated by the vaporization of water in Calories per 24 hours.

tained by comparing Figures 1 and 4, since all other conditions were the same. When the air was cold the protection afforded by clothes permitted a skin temperature high enough so that the organism did not produce extra heat. The significant difference between the nude and clothed states is the tendency for the amount of heat removed by the vaporization of water to approach constancy between the atmospheric temperatures of 18° and 30° C. when the subject is clothed. In fact, the heat removed by vaporization is constant for the 7 degree range between 23° and 30° C., from the subject thus clad.

Group B. Varied kinds of clothing. Since the setting up of a barrier between the subject and the environment produced the above described effect, it became desirable to know whether the further addition of mattress and bedding would widen the temperature range through which a constant amount of the heat would be removed by the vaporization of water.

Throughout this series the subject lay on a mattress which was at times enclosed in a rubber sheet. The subject himself sometimes wore light pajamas, and at other times he wore heavy ones. We tried the effect of covering the mattress with a cotton sheet or with a blanket. The subject was uncovered, or was covered with a sheet, or one or two blankets. With none of these combinations did we obtain satisfactory results.

It seemed possible that the irregular results were caused by the loss or gain of weight of the bedding during the period of observation. In order to overcome this source of error, the following procedure was employed: The subject lay quietly for a half hour, or longer, in the bed. He was then cautiously removed and sat upon an adjoining chair, appropriately covered, while the observer determined the weight of the bed. The subject was then returned to the latter and the insensible loss of weight of the system, of which he was a part, was obtained in two or three successive intervals, which together amounted to about one half hour. After again removing him from the balance, the weight of the bed was obtained a second time. The bed was found to lose or gain from one to ten grams per hour in an irregular manner. The insensible loss of the subject was then obtained by correcting the total insensible loss for this value. This method for correcting for change in the weight of the bed was employed in all subsequent observations.

Group C. Effect of humidity. Since both temperature and humidity affect the rate of insensible loss of the nude subject, it was necessary to study the effect of one of these under the new conditions, while the other remained constant. We chose to vary humidity, while a constant environmental temperature was maintained. The bedding consisted of a mattress covered with a rubber sheet and a blanket, and an additional blanket was over the subject. He wore light pajamas throughout.

It was found that, at an environmental temperature of 25° C., a variation of relative humidity from 20 per cent to 60 per cent did not change the amount of heat removed by the vaporization of water. The observations also showed that the heat removed by water vapor tended to be constant from day to day for this individual when the environmental temperature and the bedding were constant.

Series III. Various Subjects

It remained to be determined whether a series of individuals under the same conditions, would lose a constant proportion of the dissipated heat by vaporization of water. The bedding consisted of a mattress covered with a rubber sheet and a blanket, and an additional blanket was over the subjects. They wore light pajamas. The room temperature was kept at 25° C. Table I sets forth the data thus obtained.

TABLE I

Heat dissipation by the vaporization of water for a group of subjects under constant environmental conditions

Subject	Heat lost by vaporization of H_2O in per cent of total
	per cent
L.B. Diabetic—Age 9. Height 125 cm. Weight 25.65 kgm. Sex—F.	24.6
G.B. Nephritic—Age 10. Height 147 cm. Weight 26.9 kgm. Sex—M.	24.0
C.J.P. Nephritic—Age 16. Height 167 cm. Weight 58 kgm. Sex—M.	28.8
M.K. Normal—Age 23. Height 165 cm. Weight 70.94 kgm. Sex—F.	27.3
	32.0
H.M.K. Obese—Age 29. Height 180 cm. Weight 99 kgm. Sex—M.	22.0
	25.2
	28.2
F.H.W. Normal—Age 28. Height 180 cm. Weight 61 kgm. Sex—M.	19.3
	21.9
	21.9
F.D.J. Diabetic—Age 30. Height 174 cm. Weight 56 kgm. Sex—M.	21.7
L.H.N. Normal—Age 47. Height 168 cm. Weight 54 kgm. Sex—M.	30.5
	34.0
Average	27.2

It will be seen that the heat dissipated by vaporization, under these constant conditions, varied from 19 per cent to 34 per cent of the total heat dissipated. The average value was 27.2 per cent, and the variation from it ranged between −30 per cent and +25 per cent. When the data published by Benedict and Root (1) (Figure 3, page 26) was examined, a similar variation from the average became evident. For example, when the basal metabolism was at the rate of 1500 Calories per 24 hours, the insensible loss of weight in different subjects varied from 24 to 40 grams per hour—a variation of ± 25 per cent from the average.

Since the external factors were constant throughout this series, the variation in the per cent of heat removed by vaporization of water observed to occur from individual to individual, as well as in the same individual on different days, indicates that this irregularity arises from conditions existing within the organism. The record of the amount of heat removed by vaporization of water was always restricted to brief intervals of time. If the organism is so constituted that any undulations in the relationship between vaporization of water and total heat dissipation occur, our brief records would probably fall on different phases of the curve. If this reasoning be sound, it is evident that the determination of insensible water for intervals of a few minutes cannot be expected to give accurate information about the total heat production.

In a subsequent paper, the numerical value of the insensible water over periods of 24 hours duration, or longer, will be considered, and the constancy of this insensible water over these longer periods, in its relation to total transformation of energy, will be emphasized.

SUMMARY

(1) In order to study the relation between the amount of heat removed by the vaporization of water and the total dissipation of heat, under various conditions, the gaseous exchange, the insensible loss of weight, and the skin temperature were obtained.

By means of the equation:

$$H_2O + CO_2 - O_2 = \text{Insensible loss of weight}$$

the insensible loss of water was calculated, and its heat value, in Calories, determined by multiplying it by 0.58.

(2) It was found, that in the case of the nude subject, the heat lost by the vaporization of water increased with environmental temperature and decreased with increasing humidity.

(3) With a clothed subject, changing humidity did not affect the amount of heat vaporized, but this value was still influenced by temperature.

(4) Observations made on a group of subjects under the same conditions in regard to bedding, temperature, and humidity, did not show constant percentile loss of heat by the vaporization of water for either individuals or the group as a whole.

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