REGULATION OF HEAT LOSS FROM THE HUMAN BODY

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The loss of heat from the body has an important rôle in the regulation of temperature but there have been surprisingly few careful measurements. Bazett and McGlone[1] and Burton[2] have made most important contributions to this subject. Winslow, Herrington and Gagge[3] who have used the Hardy radiometer, but with experimental conditions quite different from ours, have in the last few weeks published curves which are very similar to some shown in our report. The large respiration calorimeter of the Russell Sage Institute of Pathology and the radiometric apparatus recently devised by Hardy[4] make it possible to measure simultaneously all the external factors of heat production and heat loss. The technique of human calorimetry has been fully described by Lusk.[5] Precise determination of the oxygen consumption, the CO_2 production and the urinary nitrogen furnish the data necessary for calculation of the heat produced within the body. The water vaporized from the skin and lungs is collected and weighed, and the purely thermal loss (convection, conduction and radiation) is measured by a flow-calorimeter. The rectal temperature and the surface temperature are measured as well as the temperature of the surrounding air and walls. Measurement is also made of the relative humidity of the calorimeter. The air in the calorimeter is practically still except for the natural convection currents arising from the warm surface of the naked man.

Experimental.—Two normal men were chosen as subjects. Their physical data are given in table 1.

TABLE 1

SUBJECT	AGE	HEIGHT, CM.	WEIGHT, KG.	TOTAL SURFACE AREA SQ. M.	B. M. R. (CAL. PER SQ. M. PER HR.)
D B	54	179	77.5	1.95	34.9
H	33	168	67.0	1.77	34.8

They were studied nude in environments ranging from 23°C. to 35°C. under basal and other experimental conditions. Observations were made during the winter, spring and early summer months in 1935 and 1936. No seasonal changes were observed.

The day before an experiment the calorimeter thermostat is adjusted to the desired temperature. The room is provided with both heating and cooling units so that any temperature can be obtained. By 9 A. M. on the day of an experiment all necessary preparations have been completed and the calorimeter, with the cooling water circulating through the coils, has established thermal equilibrium in all parts. The subject arrives about this time and sits in ordinary clothing for an hour in the prevailing atmosphere. As he undresses the skin temperature under the clothing is measured. Immediately after voiding he is weighed, the rectal thermometer inserted and he is then sealed in the calorimeter before 10:30 A. M. The air circulation through the calorimeter is started and the preliminary period begun. During the next half hour the subject measures his skin temperature and the radiation temperature of the calorimeter walls, top and bottom. He then

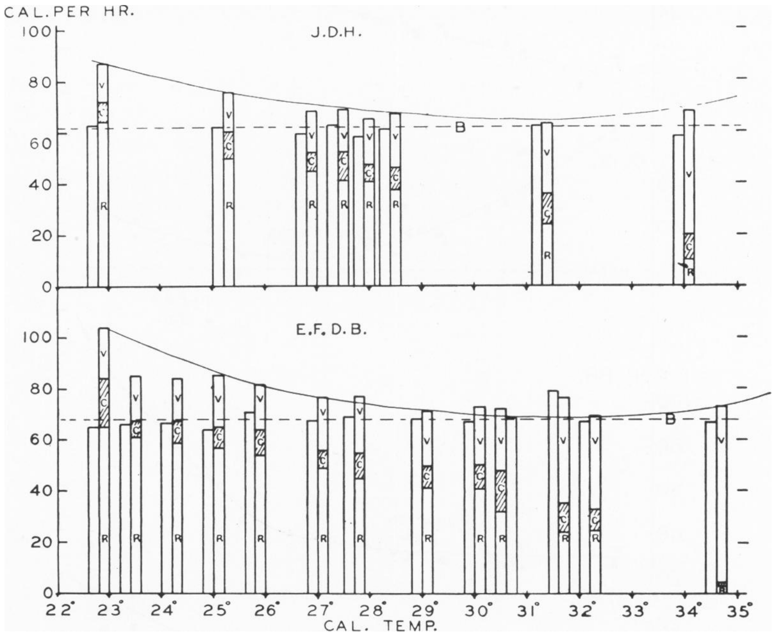

FIGURE 1

Basal experiments on two nude subjects at different calorimeter temperatures. Heat production shown in clear columns; heat loss divided into radiation, R, convection, C, and vaporization, V. Dotted line B, average basal metabolism.

remains motionless for about ten minutes and the first experimental period is started at about 11:15. During this hour the subject remains as quiet as possible. Immediately after the start of the second period the skin and wall temperatures are again measured. The second and third periods are used for studying the effects of chills, exercise or forced air currents from a fan. The surface temperature may be measured several times during these intervals. The rectal temperature is read every four minutes with a resistance thermometer so that a complete record of body temperature is obtained. The basal or control period lasts an hour unless some reaction such as an approaching chill cuts it short.

Results.—It was possible to obtain basal hours throughout the whole experimental range of temperatures. Periods after exercise or fan were considered basal if the heat production fell within 5 per cent of the average value for control periods, regardless of the amount of heat given off by the body. The values for the heat production, shown to the left by the clear

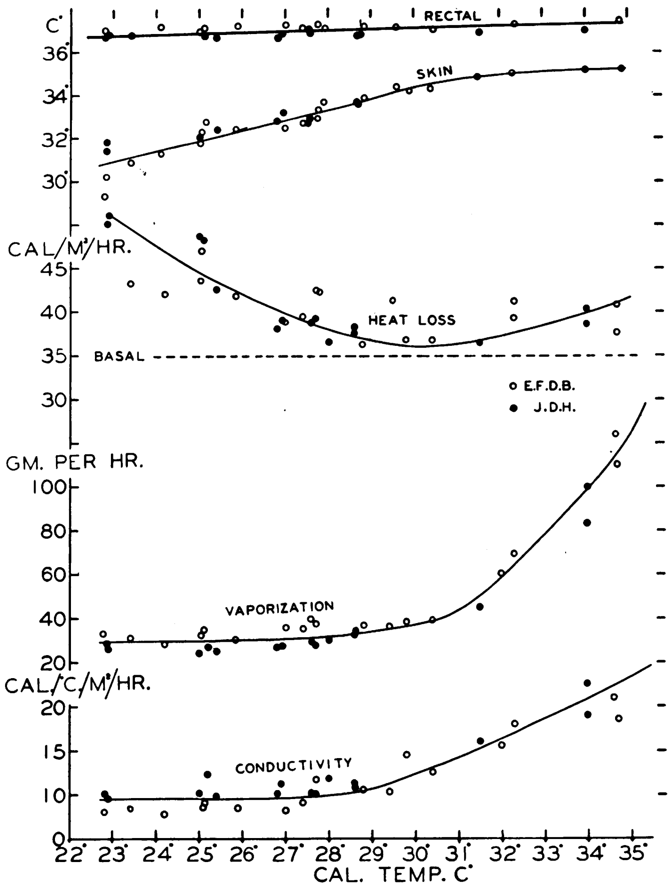

FIGURE 2

Changes in factors involved in heat loss regulation with increasing calorimeter temperatures.

columns, and the heat lost, divided into vaporization convection and radiation, are plotted for both subjects in figure 1.

Although both subjects were on the point of shivering at the end of the basal periods in many of the experiments in which the temperature was lower than 27°C., no increase in oxygen consumption was observed until the subject felt the usual waves of muscular contraction passing up from the lower extremities. It was possible for the subjects to warn the observers of an approaching chill so that the basal period could be terminated and the chill studied in a separate period.

The effect of environment on the heat loss is evident. In the zone from 30°C. to 32°C. the body eliminated a minimal amount of heat, equal to the heat produced. This temperature range might therefore be termed the "neutral zone." The heat loss increased both in colder and warmer environments. On the cold side it increased in proportion to the fall in room

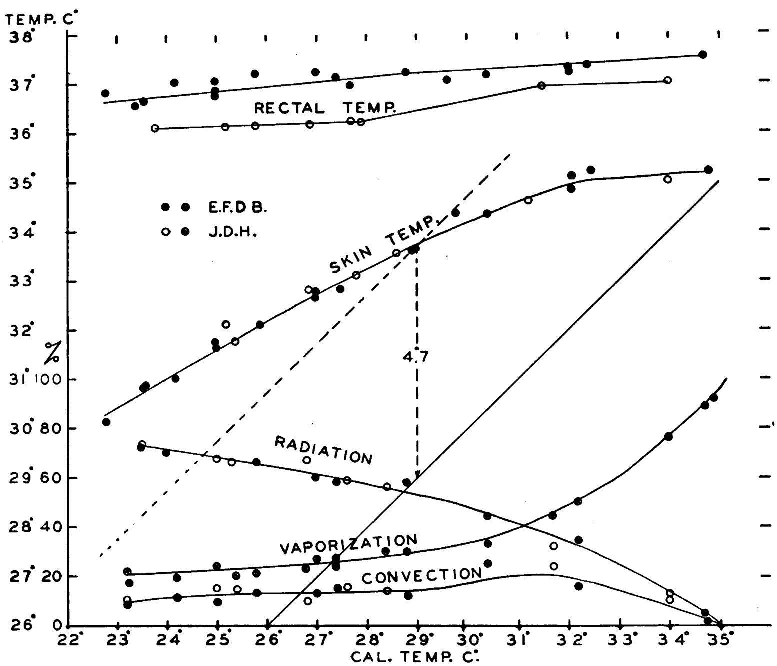

FIGURE 3

Relation of rectal temperature, skin temperature and per cent of heat loss due to radiation, vaporization and convection, to environmental temperature

temperature at the rate of approximately 3 calories per degree. This increased loss is due entirely to increased convection and radiation. Radiation, which depends only upon the difference between the skin and wall temperature, falls from 67 calories per hour and 64 calories per hour at 23°C. to zero at 35°C. Convection varies considerably from one experiment to another, and shows a definite trend only when the skin and air temperatures become nearly the same. It approaches zero at 34.7°C.

Vaporization loss is uniform up to 30°C. In environments warmer than 30°C. vaporization changes rapidly and at 34.7°C. nearly all of the body heat is dissipated by this means. The regulation of body heat loss from 30°C. and higher temperatures is brought about by a combination of increased blood flow to the skin and by vaporization. In figure 2 are plotted the rectal and skin temperatures, heat loss, vaporization and tissue thermal conductance curves. The regulation of heat loss from the body depends upon these four factors and the surface area. The cold temperature and neutral range will be discussed separately in a subsequent paper.

In the warm air temperature zone the rectal temperature rises from an average level of 37.10 to 37.30. The surface temperature curve breaks and instead of rising 0.5°C. for every degree rise in room temperature, increases only 0.7°C. for the five degree rise from 30°C. to 35°C. It is interesting to note that although the skin temperature rises only a small amount the increase in thermal conductance of the tissues is about 75 per cent and this is due entirely to the flow of blood to the periphery. In this case increased blood flow is not accompanied by a rise in skin temperature, and as will be shown later in exercise the blood vessels of the skin may become greatly dilated while the surface temperature falls several degrees on account of the increased vaporization. The sweating of the body increases with the increased blood flow adjusting itself exactly to take care of the heat loss. The vaporization loss almost triples in the range from 30°C. to 35°C. During these warmer experiments the body is moist but no large amount of excess moisture or dripping of sweat is present. The sensitivity of the heat loss regulation in this zone is greater than in any other temperature range and seems to show an anxiety on the part of nature to prevent overheating of the body in hot weather. The parallelism between the increased blood flow and the sweating curve suggests that they are closely related phenomena. At lower temperatures when the blood flow becomes constant the vaporization curve also becomes constant.

Figure 3 shows the percentages of heat lost by radiation, conduction and convection. Radiation has a maximum value of 70 per cent in this study and decreases almost uniformly with warmer environments until it becomes zero at 35°C. Vaporization increases in importance from about 17 per cent at 23°C. to 100 per cent at 35°C. A definite bend upward in this curve occurs at about 30°C., the point of beginning sensible perspiration. Convection, the percentage value of which does not seem to change much between 23°C. and 29°C., increases from 10 per cent at 23°C. to about 15 per cent at 24°C. Between 29°C. and 32°C. convection rises to about 22 per cent, this increase probably being due to increasing velocity of the air through the calorimeter necessary to remove the water vapor. Between 32° and 35° convection decreases at a uniform rate to zero.

Vasomotor regulation of body heat loss is seen, in figure 3, to be effective down to about 28.5°C., the low temperature portion of the neutral zone. At this point the difference in skin and environmental temperature is about

5°C. If the temperature of the body is to be preserved, without increase in metabolism, this gradient should not be exceeded when the room temperature is lowered. That is, the skin temperature should fall at the same rate as the environmental temperature from this point on. This course is marked with the dashed line in figure 3. As a matter of fact the skin temperature falls at only half the rate of the environmental temperature, so that the heat lost from the body as the environment becomes cooler, must be progressively greater than that produced. This excess heat loss causes a fall in body temperature and in due time the man breaks into a chill. Figure 4 shows a series of chills brought on by exposure and also experiments with voluntary exercise. These observations were made in environments ranging from 23°C. to 30°C.

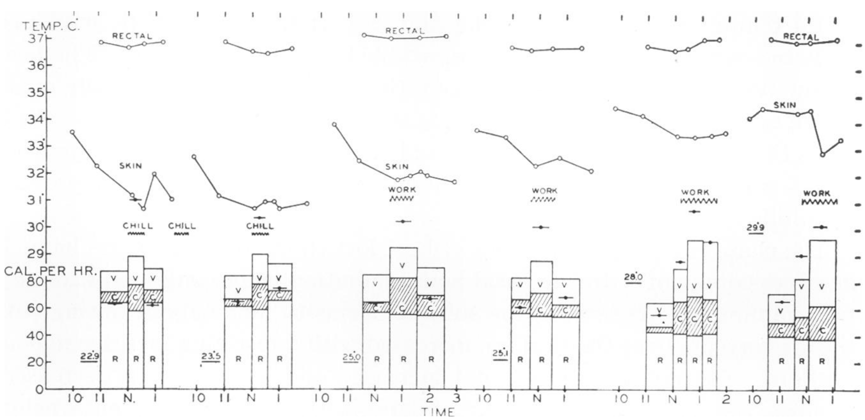

FIGURE 4

Heat production and elimination during chills and voluntary exercise. Calorimeter temperature 22.9°C. to 29.9°C. Short lines with dots represent heat production.

In the chill experiments the subject lay motionless during the preliminary period of about an hour and for another fifty to sixty minutes as a basal control period. By exerting sufficient mental effort the onset of the chill could be delayed some ten minutes and warning given to the observers in time to close the basal period. So long as the subject was not conscious of muscular tremors the oxygen consumption was not increased, and the metabolism was at the basal level, although the body was being rapidly cooled. The metabolism in the control periods of two chill experiments shown in figure 4 was 63 Calories for subject H and 65 Calories for subject D B, and the average basal levels were 62 Calories and 68 Calories, respectively. The subjects were uncomfortably cold during these periods and evidence of the "chemical regulation" of Rubner might have been expected. The fact that the metabolism remained basal practically up to the onset of the chill shows a complete absence of such a phenomenon in these two subjects. These observations are in accord with the studies of Speck[6], Loewy[7], Johansson[8] and Benedict[9] and Swift[10], although Rubner[11], Hill[12], Martin[13] and others have found evidence of Rubner's chemical regulation.

The onset of chill was usually abrupt and after having consciously suppressed activity for a time, the subjects shook with such violence as to rock the entire calorimeter. The chill itself was usually pleasant, accompanied by a feeling of increased warmth, and it lasted generally between fifteen and twenty-five minutes. The experimental period was cut short as soon after cessation of the shivering as possible in order to find the rate of heat production. This was 100 to 150 per cent above basal while the heat eliminated increased only 10 or 15 per cent. Thus there was a considerable storage of heat in the body and the average skin temperature rose 0.5°C. to 1.5°C. The rectal temperature stopped falling and sometimes rose. With increased body temperature the men felt comfortable for perhaps an hour. The heat production fell immediately to about the basal level and the body again began to cool. As soon as the cooling was sufficient another chill resulted. Thus the only method of regulation of body temperature in these environments was repeated chills, unless voluntary exercise was used to prevent the chills.

The changes in the proportions of heat lost through the various channels deserves comment. In the basal hours radiation is maximum and convection minimum. As soon as the subject begins to move about during chill the air currents over the skin are increased with a resulting increase in convection. The radiation loss is not increased and is more often decreased, because the skin becomes cooler. Vaporization in environments below 25°C. is not appreciably affected. The increased heat loss during chill is therefore entirely due to the change in convection.

The experiments with voluntary exercise differ in no respect from those with chills. The metabolism does not happen to rise quite so high but other changes, rectal and skin temperature, convection, radiation and vaporization, all show the same tendencies as in chills. In the one experiment performed at 28°C. we find a different set of circumstances because here the subject was on the edge of vasomotor regulation. In this experiment exercise brought about a 0.4°C. rise in rectal temperature and a constant level of skin temperature. Vaporization more than doubled and convection increased about seven times; radiation remained practically unchanged. It will be noticed that the heat eliminated rose immediately upon beginning exercise to values almost double the basal heat elimination. This is in contrast to the situation during chills when the elimination changes but little. The efficiency of vasomotor regulation in preventing overheating of the body is thus contrasted to the absence of such regulation at lower temperatures.

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THE PHYSICAL LAWS OF HEAT LOSS FROM THE HUMAN BODY

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In a previous publication[1] the automatic regulation of heat loss was shown to be effective in environmental temperatures above 28°C. That is, vasomotor changes combined with activity of the sweat glands were capable of adjusting the loss of heat from the body to the heat production. In environments colder than 28°C. the body lost heat until some mechanism set off a chill and thereby increased the metabolism. With a more or less steady series of chills the temperature of the body could be maintained within the range of environments studied, down to 23°C. It was pointed out further that the thermal conductance of the body tissues remained constant below 28°C. and that no evidence of generalized vasomotor response could be found. This implies that the body reacted to temperature change in this region in much the same way as any warm inanimate object. It therefore seemed advisable to make direct comparisons between the heat loss from the human body and from a properly chosen physical object, especially as some evidence in the past would indicate that the physical laws of heat loss could not be applied directly to the human body.

Experimental.—An elliptical, galvanized-iron cylinder, 50 cm. long and 18 and 30 cm. in minor and major axes, was selected as having somewhat the shape of the trunk of a man and at the same time having an area which was easily calculated and completely effective in heat loss. The outer sur-