Control of Blood Flow to the Extremities at Low Ambient Temperatures

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THIS STUDY was undertaken to explore the extent of autonomic control of blood flow to the hands and feet. That is, to examine the question—is blood flow to the hands and feet at low ambient temperatures still regulated by the thermal state of the body as a whole, or is blood flow to the hands and feet determined by the known direct constricting effect of cold upon their blood vessels? Since the experiments of Sir Thomas Lewis in 1931 (1) there has been a growing understanding that vasodilatation may be produced in the extremities by heating other body areas. An intact sympathetic outflow to the extremity has been shown to be necessary for this reaction (1, 2). Pickering (3) suggested that the vasodilatation is the response to the circulation of warmed blood through the central nervous system, since it does not occur when the part heated is small or its circulation occluded. These observations have been confirmed repeatedly (4, 5). Recently, Miller has been able to prevent freezing of the rabbit's ear for two hours at −55°F. by warming the animal's body (6). The experiments reported herein reveal that a similar protection is available to the extremities of man. Inversely, Ferris and his co-workers (7) in particular have demonstrated that when the body is cooled, heating only the hand will not increase its blood flow over that of a non-heated hand.

The experiments were planned to investigate these specific points: *a*) The effect upon hand and foot temperatures of variation of heat supplied to the rest of the body. *b*) The effect of warming the body upon the temperature of extremities which had become cold. *c*) The differences in the temperature responses between the hands and feet. *d*) The effect upon hand temperature of a sudden increase in the cold stimulus applied to the hand when the body is warm.

METHODS

The main series of experiments was conducted at controlled ambient temperatures of about 0, −20 and −30° F. in a cold room. Four young adult males served as subjects. They sat quietly throughout the experiments. The duration

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of the experiments was two hours or longer, unless there was rapid cooling of the extremities. The method of circulating air beneath clothing described in the preceding paper (8) made it possible to supply the body with as much or as little heat as was desired. It also permitted measurement of the rate at which heat was being supplied to the body, $\Delta H_v'/t$; and of the rate at which heat should be supplied or removed to maintain thermal equilibrium of the man: the 'steady state heat surplus' or $Q\sigma'/t$. A comparison of the two gave a quantitative evaluation of the thermal state of the body, within about 10 Cal/hr. Methods for the determination of these and other variables are outlined in the preceding paper and detailed in (9). The hands and feet received no artificial heat, being separated from the ventilating circuit by air-tight wristlets and anklets. These parts were heated only from their blood supply. Therefore, changes in their temperature indicated alterations in their blood flow. The thermal stress upon the body and the thermal stress upon the hands and feet could be varied independently; the former by variation of the hot air supply, and the latter by variation of the ambient temperature and insulation.

Average hand and average foot temperatures were measured by thermocouples connected in parallel. Those for the hand were located upon the ball of the first, third, and fifth fingers, and the palm and dorsum of the hand. Those for the foot were placed upon the ball of the great toe, the heel, the dorsum of the foot at the base of the first and fifth toes, and the dorsum of the foot just below the lateral and medial malleoli. Heavy footgear (insulation equivalent to 2.6 clo) and intermediate weight gloves (1.0 equivalent clo) were worn. In some experiments one glove was replaced with a rayon insert (0.25 clo) and in others, one hand was bared.

To extend the studies upon the fourth point, above, a supplementary series of experiments was performed in which the bare hand was put into a cold box. Each experiment consisted of two periods. In the first, the subject lay quietly in the nude at an ambient temperature of 65 to 74° F. for approximately 45 minutes, or until toe temperature approached within about 5° F. of the ambient temperature. With the body so cooled, one hand was inserted in the cold box and average hand and finger tip temperatures recorded. In the second period, the body was overheated by the use of an electrically heated blanket. When the subject was sweating, and the temperature of the toe of the uncovered foot had risen from about room temperature to above 89° F., the hand was again placed in the box and its temperature response followed.

RESULTS

Effect upon Hand and Foot Temperatures of Variation of Heat Supplied to the Rest of the Body. In 16 experiments over the temperature range from 0 to −30° F., it was found, without exception, that when the heat supplied was equal to or greater than the amount necessary for thermal equilibrium, the average temperature of the hands and feet was maintained above minimum comfort level (70° F.). But, whenever the heat loss exceeded the heat supply by more than about 15 per cent both the hands and feet became cold, an indication of vasoconstriction. These experiments are summarized in table 1. Experiments listed as A and B were performed consecutively upon the same subject. In this table, T_0 is operative temperature. The values for $\Delta H_v'/t$ and $Q\sigma'/t$ are corrected to a standard surface area, and, for reasons mentioned in the previous paper, are for the body excluding the head. It is to be noted that the difference $Q\sigma'/t - \Delta H_v'/t$ is positive when there is an excess of heat supplied to the clothing, that is, when the body does not need to conserve heat; and negative when there is a net heat loss. The column headed '% Diff.' is calculated from $\dfrac{Q\sigma'/t - \Delta H_v'/t}{Q\sigma'/t} \times 100$.

The temperatures of the hands and feet in two experiments upon the same subject at 0° F. are shown in figure 1, which illustrates the main features of the data of table 1. In *experiment 7-15*, there was a net heat loss from the body of 72 Cal/hr. (41% of $Q\sigma'/t$). The hands and feet cooled rapidly; within 90 minutes hand temperature was 60° F. and the hands were painfully cold. Foot temperature dropped to approximately 75° F. In *experiment 8-7A*, the heat supply equalled the heat loss. Average hand and foot temperatures were maintained above 90° F.

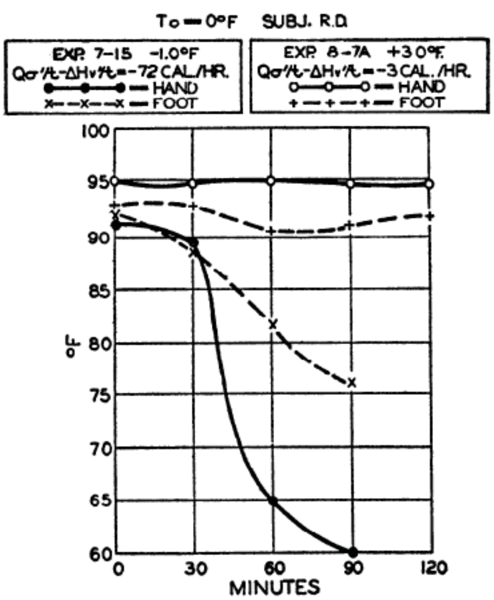

Fig. 1. Hand and foot temperatures under conditions of thermal equilibrium and of high heat loss rate from the body. (Glove of 1.0 equivalent clo, and 2.6 equivalent clo boot.)

Effect of Warming the Body upon Cold Extremities. In four out of five experiments, extremities which had become cold could be rewarmed by heating just the body. One of the four is illustrated by figure 2, the graph of an experiment at 0° F., in which no heat was supplied for 45 minutes. Average hand temperature fell to 61° F. (finger tip temperature of 53° F.) and average foot temperature from 93 to 86° F. Heating was then begun, which reduced the net heat loss rate to 15 Cal/hr. Average hand temperature began to rise almost immediately and reached 90° F. within 55 minutes. Average foot temperature, however, continued to fall to 75° F. After

85 minutes, and concomitant with a reduction in the net heat loss rate to 6 Cal/hr., the average foot temperature began to rise and was 89° F. when the experiment was terminated. In one experiment at −30° F. ambient, the hand did not rewarm in spite of a heat excess of 39 Cal/hr. supplied to the body.

Differences between Temperature Response of Hands and Feet. When the heat supplied to the system exceeded heat loss, both the hands and feet were kept within the comfort range, that is above 70° F. In general, however, the average temperature of the feet was lower than that of the hands despite the greater insulation of the footgear. The difference varied from about 5° F. (*exper. 8-7A*, fig. 1; *expers. 9-9* and *9-10*, table 1) to 10 or 20° F. (*expers. 8-5A*,

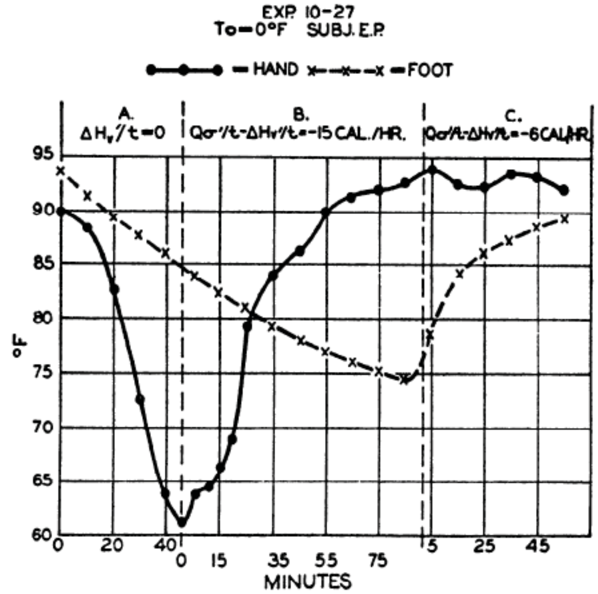

Fig. 2. Effect of rewarming the cooled body on hand and foot temperatures.

8-27, and *9-17*, table 1). When the net heat loss from the system was large, both the hands and feet cooled; but the rate of cooling of the hands was greater than that of the feet (*exper. 7-15*, figs. 1, 2). Since, in this circumstance, the blood vessels of both the hands and feet are constricted, the slower fall of foot temperature is the result of the heavier insulation of the footgear, and the smaller surface area per mass of the foot.

During the latter part of an experiment (*8-5*) at 0° F. there was a small net heat loss which resulted in a fall of average foot temperature but not of average hand temperature. In period A (see table 1), a slight excess of heat was furnished; average hand temperature was maintained at about 90° F. and average foot temperature at about 82° F. In periods B and C, the heat supply was reduced so that deficits were 17 and 21 Cal/hr., respectively (less than 10% of $Q\sigma'/t$). Average hand temperature continued above 90° F., but average foot temperature fell to 65° F. in about $3\frac{1}{2}$ hours.

When the body was heated after the extremities had been allowed to become cold, foot temperature continued to drop until the hands had completely rewarmed. Figure 2 shows an 85-minute lag between the initial rise in hand and foot temperatures. Only a very small part of this lag can be attributed to the

TABLE 1. SUMMARY OF EXPERIMENTS SHOWING EFFECT OF VARIATION OF HEAT SUPPLIED TO BODY

EXPER.	T_o (°F.)	$Q\sigma'/t - \Delta H_r'/t$ (CAL/HR.)	% DIFF.	TEMPERATURE RESPONSES OF HANDS AND FEET
7-15	−1	−72	−41	Hand temperature fell to 60°F. in 90 min. Foot temperature fell to 75°F. in 90 min.
8-7A	+3	−3	−1	Hand and foot temperature kept above 90°F.
8-7B	+2	−30	−15	Hand temperature maintained above 85°F. Gradual fall of foot temperature to 75°F. in 2 hrs.
7-29A	+1	−26	−13	Hand temperature fell to 60°F. in 60 min. Slow fall of foot temperature to 79°F.
7-29B	+1	−41	−20	Electrical heating of hands necessary. Gradual fall of foot temperature to 60°F. in $2\frac{1}{2}$ hrs.
8-5A	+2	+20	+10	Hand temperature kept at 90°F., foot temperature, above 80°F.
10-21	+4	+10	+6	Hand and foot temperature kept above 85°F.
7-31	+4	+25	+11	Hand and foot temperature kept at approx. 87°F.
8-14	−17	+42	+16	Hand and foot temperature kept at approx. 85°F.
8-25	−19	+28	+11	Hand temperature kept at about 80°F., foot temperature, at about 82°F.
8-27A	−20	−52	−20	Hand temperature fell to 64°F. in 25 min.; foot temperature, to 78°F.
8-27B	−21	+10	+5	Hand temperature rose to 90°F., foot temperature kept at about 70°F.
9-9	−31	+33	+12	Hand temperature kept above 90°F., foot temperature, above 85°F.
9-10	−31	+19	+7	Hand and foot temperature kept between 84–90°F.
9-17	−31	+32	+12	Hand temperature kept above 90°F., foot temperature, about 70°F.
11-4	−31	+13	+5	Hand and foot temperature kept above 85°F.

greater heat capacity of the footgear: about one Calorie is required to rewarm the boot.

Effect of a Sudden Increase in Cold Stimulus Applied to the Hand. The effect of a sudden increase in the cold stimulus applied to the hand when the body was warm was observed in 10 experiments by removing one glove within a cold room, and in 9 more by inserting a bare hand into a cold box while the body was heated. The former are summarized in table 2. In most of these, the assembly received slightly more heat (10 to 38 Cal/hr.) than was calculated as being lost. In several, a thin rayon insert was substituted for the glove,

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