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THE EFFECT OF BODY HEATING ON THE CIRCULATION IN SKIN AND MUSCLE

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The blood flow in the human forearm increases when the body temperature is raised by heating. The problem is to determine whether the increase is occurring in skin, or in muscle, or in both. Barcroft, Bonnar & Edholm (1947) studied the effect of body heating on the forearm blood flow after the cutaneous circulation had been suppressed by the iontophoresis of adrenaline. They came to the conclusion that the greater part of the increased flow was due to dilatation of the muscle blood vessels. Subsequently, similar experiments, with some modification in technique, showed that the increase in the skin blood flow on body heating was apparently much greater than the earlier work suggested (Cooper, Edholm, Fletcher, Fox & Macpherson, 1954). In fact, the increase in the skin blood flow was so large it seemed possible that with further refinements of technique the whole of the increase might be found to be passing through the skin. The experiments to be described were performed in an attempt to decide this point.

METHODS

Healthy men aged 27–46 acted as subjects; one had taken part in the two previous investigations. Room temperature was 26·5±0·5° C. The subject sat in a bath with the legs and lower part of the trunk immersed in water. The bath water was kept vigorously stirred and its temperature could be regulated as required. An inflated immersion suit covered the trunk, head and upper arms and reduced heat loss from the non-immersed part of the body (Kerslake & Cooper, 1954). Forearm blood flow was measured simultaneously in the two arms, using essentially the same technique as Cooper, Edholm & Mottram (1955), except that ten inflow traces were obtained, with the venous occlusion on for 5 sec, and open to atmosphere for 10 sec. Flow recordings lasted for 2½ min and the interval between recordings was 2½ min. The blood flow for each 5 min period represents the average of the last eight inflow traces made during the first 2½ min of that time.

Adrenaline iontophoresis. The general procedure was similar to that described by Cooper *et al.* (1955). The solution of adrenaline 1:2000 was prepared immediately before use by dissolving 1·50 g adrenaline in 3 l. boiled glass-distilled water acidified with phosphoric acid (H_3PO_4) at a

temperature of 34–36° C. When the adrenaline was in solution the pH was adjusted to 4·5 by the addition of trisodium phosphate buffer. In all experiments the details of the iontophoresis were precisely similar, i.e. the current was increased up to 20 mA during the first 2 min, maintained at 20 mA for 16 min, and lowered to zero mA in 2 min, giving a total of 20 min.

Experimental procedure. The experiments began at about 2 p.m. After the subject had entered the bath, the fitting of the plethysmographs and initial calibration occupied approximately 30 min. Great care was taken to ensure the subject's comfort, and in all experiments the subjects were drowsy and relaxed by the time the first blood-flow measurements were made. Four or more series of blood-flow measurements were carried out at 5 min intervals, and during this period the bath temperature was adjusted so that the subject's body temperature did not alter significantly

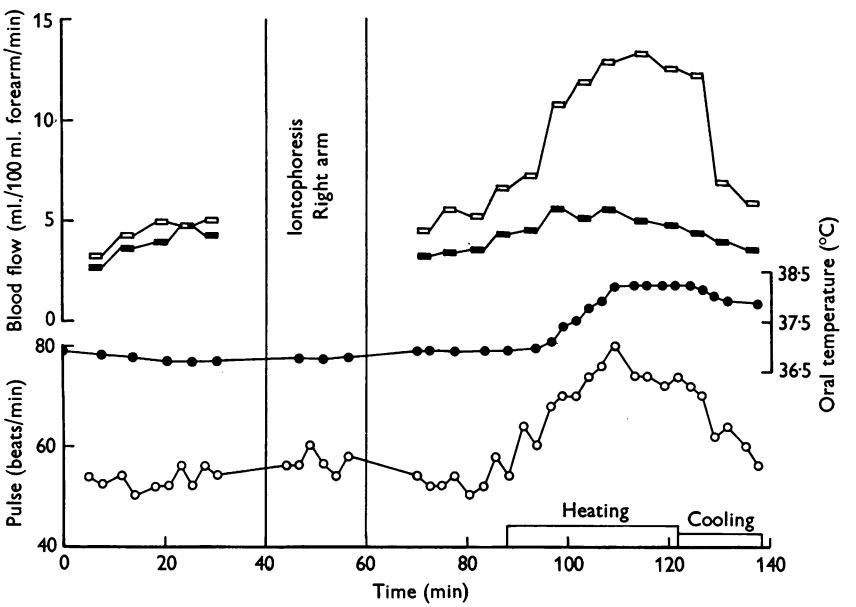

Fig. 1. Blood flows in both forearms (■ right, □ left) before and after adrenaline iontophoresis of the right forearm and showing the effect of body heating; also shown are pulse and oral temperature which remained relatively constant until the period of heating.

after entering the bath. The plethysmograph temperatures were kept constant at 34° C throughout the experiment. One forearm, either the left or the right, was then removed from its plethysmograph, the iontophoresis was performed and the forearm returned to its former position in the plethysmograph. A further four blood-flow determinations were obtained and then the temperature of the bath was raised to 41° C. When the oral temperature had risen to approximately 37·8° C the bath temperature was lowered to 38° C. This prevented any further rise in oral temperature, which remained at about 38° C. Four or more series of blood-flow determinations were made, and then the effect of cooling the bath to 25° C was observed before the experiment was terminated.

RESULTS

The results of one experiment are shown in detail in Fig. 1. Initially the blood flows in both forearms were similar. After adrenaline iontophoresis of the right forearm the blood flow through it decreased. The blood flow in the left

forearm responded to body heating by increasing from just over 5 ml. to about 13 ml./100 ml. forearm/min. On cooling the bath to 25° C the blood flow returned to its preheating level. The blood flow in the right forearm showed little change during heating or cooling.

The response of the forearm blood flow, with and without adrenaline iontophoresis, to body heating in the remaining eight experiments is shown in Fig. 2 (i–iv). One further experiment in this series had to be discarded because there was a marked general absorption of adrenaline. In two of the experiments (Fig. 2, nos. iii*a* and iii*b*) there is clear evidence of some increase in the blood flow in the treated forearm when the subject was heated, in one experiment there is a suggestion of a decrease (Fig. 2, no. ii*b*), and in the remainder there is either no change or a very small increase.

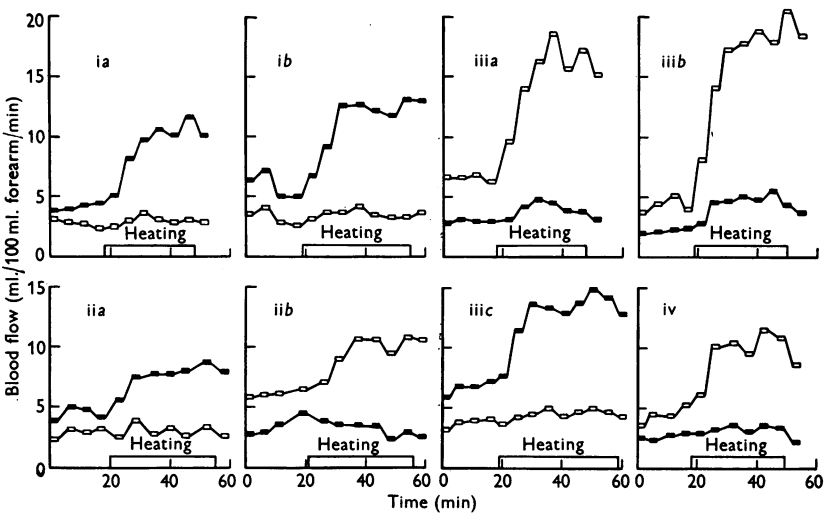

Fig. 2. The blood flow through normal and treated forearms, the latter being shown in the lower trace in every case, in eight experiments on four subjects (i–iv) before and after heating; symbols as Fig. 1.

Control experiments were performed on each subject to show that on heating (without iontophoresis) the vasodilatation was approximately equal in both forearms, and further, that after iontophoresis to one forearm, when the subject was not heated, the blood flow in the treated forearm remained at a consistently low level for periods in excess of an hour (Fig. 3).

Before concluding from these experiments that iontophoresis of adrenaline suppresses the vasodilatation, which normally occurs on heating, by occluding the skin circulation, it was necessary to show that the iontophoresis had not been so drastic that adrenaline had penetrated below the superficial tissues and in some way prevented the muscle vessels from responding. To exclude

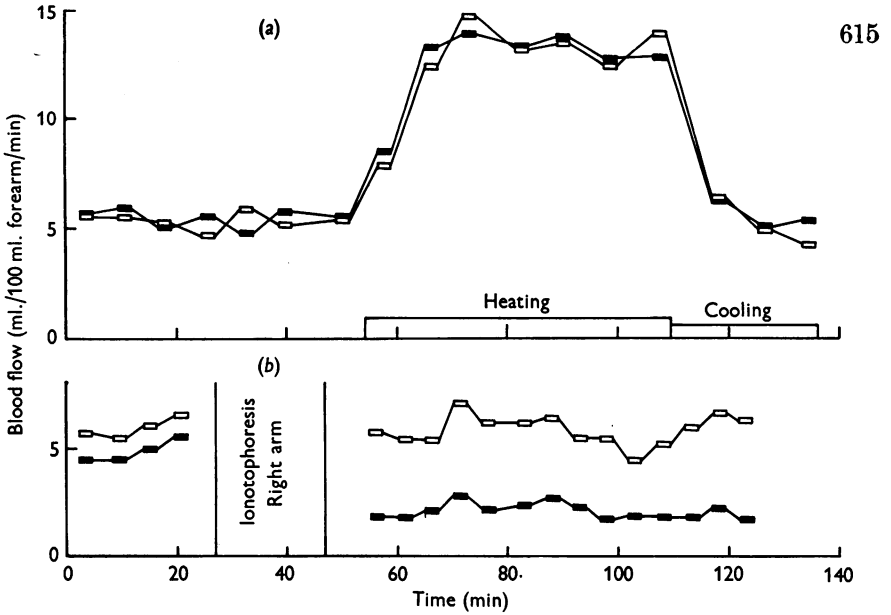

Fig. 3. Representative control experiments: (*a*) blood flows in both forearms with body heating and cooling, without adrenaline iontophoresis; (*b*) blood flows in both forearms before and after adrenaline iontophoresis of the right forearm, without body heating; symbols as Fig. 1.

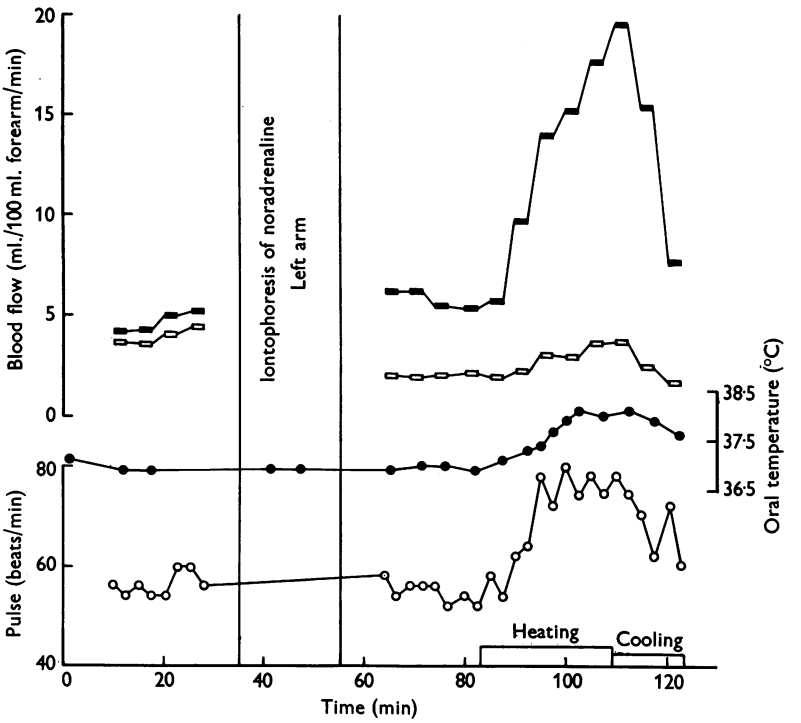

Fig. 4. Results of expt. in which noradrenaline was used in place of adrenaline for the suppression of the cutaneous circulation in the left forearm; symbols as Fig. 1. The results are similar to those shown in Fig. 1.

this possibility the post-exercise hyperaemia following a standardized hand-gripping exercise was measured simultaneously in control and treated forearms, both when the body temperature was normal and when it was raised. The increase in blood flow was the same in the control and treated forearms, so it was concluded that the use of adrenaline to suppress the cutaneous circulation had not appreciably affected the muscle blood vessels.

Two experiments were performed on two subjects using noradrenaline instead of adrenaline. The results of one experiment are shown in Fig. 4, and are similar to those obtained using adrenaline. However, there were subjective indications of absorption, and there did not appear to be any advantage in substituting noradrenaline for adrenaline.

DISCUSSION

Skin and muscle together comprise about 70% of the human forearm and the remaining tissues are all relatively avascular (Cooper *et al.* 1955). If the assumption is made that the blood flow through the forearm tissues other than skin and muscle is comparatively small, the results reported may be used to provide an indication of the partition in blood flow between skin and muscle. The difference between the forearm blood flows before and after iontophoresis represents the skin blood flow, and the post-iontophoresis values the muscle blood flow. When body temperature is raised the difference between the flows in the treated forearm and the control forearm represents the skin blood flow, and the flow through the treated limb represents the muscle blood flow. The mean values for skin and muscle blood flows taken from the nine iontophoresis experiments, together with additional points obtained from the control experiments, are plotted against total forearm flow in the scatter diagrams (Fig. 5). The mean value for the muscle blood flow at normal body temperature was 2·75 ml./100 ml. forearm/min. If the muscle flow remains unchanged when the body temperature is raised the skin blood flow should bear a one-to-one relationship with the total forearm flow after subtracting the muscle flow. The line which represents this relationship is shown in Fig. 5, and it can be seen how closely the observed values fulfilled this condition.

The values for skin blood flow shown in Fig. 5 range from approximately 1 to 14 ml./100 ml. forearm/min. These values can be expressed in terms of the blood flow per unit volume of skin, using the figures given by Cooper *et al.* (1955) for the calculation. During body heating, approximately 75% of the total flow is passing through the cutaneous vessels, and the flow is up to a maximum of 165 ml./100 ml. skin/min. This is a high figure, especially when it is remembered that no arteriovenous anastomoses have so far been demonstrated in the forearm skin.

In some experiments, however, there was a small increase in the blood flow

in the treated forearm on heating, and this can only be explained either by a vasodilatation in the muscle and deeper tissues, or in areas of skin in which the iontophoresis was incomplete. At the end of each experiment the forearm was carefully inspected for evidence of flushing after a period of arterial occlusion, but this test did not reveal any consistent difference in the appearance or response of the forearm skin between those experiments in which the

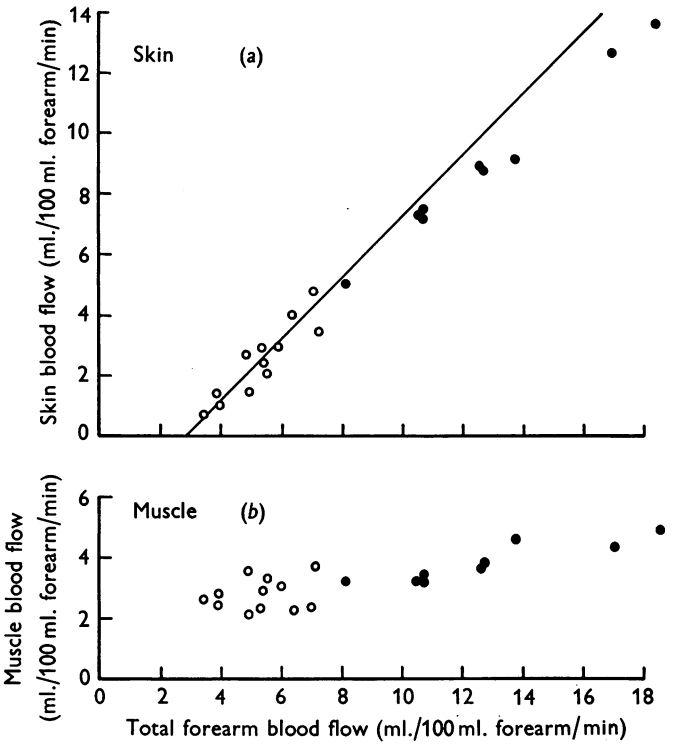

Fig. 5. Relation between total forearm blood flow and (*a*) skin blood flow, (*b*) muscle blood flow; ○, flows before body heating; ●, flows during body heating. The line shown in (*a*) represents the one-to-one relationship for an increase in total forearm blood flow above 2·75 ml./100 ml. forearm/min and is the line on which the points would fall if all the increase were passing through the skin.

increased blood flow was observed and those in which it was absent. Nevertheless, since there were some experiments in which there was no appreciable change in the forearm blood flow and in the remaining experiments the increase was of a variable magnitude, it seems probable that when the vasodilatation was observed it was caused by a failure to obtain a complete closure of the skin vessels. If this view is accepted, the results of our experiments show that the increase in forearm blood flow, which occurs when the temperature of the body is raised by heating, is confined to the skin and superficial tissue.

In some experiments, not included in this series, the duration of the iontophoresis was reduced to 10 min. In spite of an apparently complete cutaneous vasoconstriction, there was a significant increase in flow on body heating. It has, indeed, proved to be difficult to produce a uniform effect by the iontophoresis of adrenaline into the skin. Increasing the duration or intensity of the iontophoresis incurs the risk of adrenaline absorption with increased pulse rate, blood pressure and muscle blood flow, in addition to unpleasant subjective effects.

An explanation which appears to fit the facts is that part of the increased blood flow in the skin is taking place in the deeper layers to which the adrenaline penetrates only with an adequate current intensity; and this may explain the difference between these results and those previously reported. It seems probable that the duration and intensity of the iontophoresis is the critical factor. In the earlier work of Cooper *et al.* (1954) there was some increase in flow during body heating after the skin circulation had apparently been suppressed. In those experiments the current intensity was frequently less than in the experiments reported here. Pallor of the skin is not an adequate guide to the completeness of the suppression of the cutaneous circulation.

The conclusion of this work, that the increase in blood flow on body heating is entirely, or virtually entirely, in the skin vessels, is in substantial agreement with the recent findings of Barcroft, Bock, Hensel & Kitchin (1955), who used a calorimetric sound to measure the muscle blood flow in the calf and forearm. There was no increase in the muscle blood flow on body heating; indeed, there was on occasion an apparent decrease. Further information is given by Roddie, Shepherd & Whelan (1956) using the O_2 saturation of venous blood draining the skin and muscle vessels as an indicator of flow, who have shown that there is no change in muscle flow but a substantial increase in the cutaneous blood flow on body heating.

SUMMARY

1. The blood flow in the human forearm was measured using water-filled plethysmographs under standardized conditions, before and after iontophoresis of adrenaline to occlude the skin circulation and with the body temperature in normal and elevated states.

2. The results indicate that the increase in forearm blood flow which occurs when the body temperature is raised by heating is confined to the skin and superficial tissues.

3. The difference between these results and those previously reported, in which the iontophoresis technique was also used, is attributed to the more intense iontophoresis of adrenaline into the skin. Pallor of the skin is not an adequate guide to the degree of the cutaneous vasoconstriction.

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