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Analysis of Tissue and Arterial Blood Temperatures in the Resting Human Forearm

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QUANTITATIVE ANALYSIS of the relationship between arterial blood and tissue temperatures has not been previously attempted. Bazett and McGlone's measurements of tissue temperature indicate that the deep thermal gradient in the resting normal human forearm does not extend deeper than 2.5 cm.; deeper measurements are not reported (1). According to recent observations in this laboratory, the temperature gradient in intact human biceps muscle extended beyond this depth to approach the geometrical axis of the limb (2), as would be expected if the analytic theory of heat flow by conduction is applicable to a localized arm segment. With the stimulus of this observation, the temperatures of the normal human forearm tissues and brachial arterial blood have been measured to evaluate the applicability of heat flow theory to the forearm in basic terms of local rate of tissue heat production and volume flow of blood.

TECHNIQUE

Temperature measurements were made with standard thermoelectric technique. The galvanometer system (Leeds and Northrop) had a full sensitivity of 0.75 microvolt per mm. deflection on a scale at 1.0 meter distance, critical damping resistance of 49.0 ohms, period of 1.2 seconds and internal resistance of 18.2 ohms. In operation, sensitivity was reduced by a 90.0 ohm copper-wire resistor permanently in parallel across the galvanometer; this resistor also served to provide a slightly underdamped return deflection on exclusion of the thermocouple from the circuit. The reference junction was sealed permanently in a double-layered vacuum flask container in a thermostatically controlled ($\pm 0.1^\circ$) water bath. Indications of a Beckmann thermometer sealed along side the reference junction did not vary by more than 0.005° in a 3- to 4-hour period. Temperature at the reference junction was approximately 34.5° ; consequently measurements at

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the active junction could be made by direct deflection technique without need for a compensating circuit.

The reference thermocouple consisted of 20-gauge (B. and S.) copper and constantan wire, 135 cm. in length. Four different types of active thermocouples were used. All types consisted of 40-gauge (B. and S.) copper and constantan wire, 90.0 cm. in length and covered with a commercial enamel insulation; loop terminals were employed on all models. For the precise exploration of deep tissue temperatures, *Y*-models were made. The junction was 'spot-soldered' with the two wires crossed at an angle of 10 to 20°; length of the junction in no case exceeded 0.20 mm. One copper arm was then clipped cleanly at the junction. The two arms of the *Y* were drawn taut and made to adhere to each other by smooth application of a bakelite resin varnish over a length of 10.0 cm.; the junction was insulated by application of the same varnish but the electrically inactive tail of the *Y* (a continuation of the constantan wire) received no further treatment. The thermocouples were hung under tension and the varnish baked hard. Leakage resistance at the junction insulation measured at least 30 megohms; this was sufficient to provide adequate insulation as shown by simultaneous calibration of several thermocouples in physiological salt solution with the circuit at working sensitivity. Needle thermocouples used in tissue were constructed in polished stainless steel tubing of standard 26 gauge (for further description of needles, see page 95). The rectal thermocouple was constructed in a silver tube 2.5 cm. in length. Measurements of rectal temperature were made at depths of 10.0–12.0 cm. The brachial artery thermocouple is shown in figure 1; readings of the arterial blood temperature were accepted as valid only when removal of the inner needle was followed by free arterial bleeding from the outer needle. Resistance of all thermocouples averaged 100 ohms. Temperature coefficients for the circuit ranged between 0.33° to 0.36° per cm. deflection; relative precision of readings was $\pm 0.01^\circ$.¹ Differences between thermocouples in temperature coefficients were consistent for all calibrations; calibration curves were linear over the experimental range of temperature (fig. 2). The same temperature coefficients were obtained on calibrations at depths of immersion in water ranging from 1.0 to 4.0 cm. In order to establish the validity of the small correction for drift in reference junction temperature, a calibration of this junction over a 1.5° range was performed at a constant temperature of the calibrating water bath. The same figure was obtained as for the active junctions. The terminals of all thermocouples were connected in the circuit inside a specially constructed copper-lined box to prevent against air convection currents and changes in environmental temperature. Connections were not exposed throughout each experiment. A single constantan bar of 0.64 cm. diameter received all the constantan terminals whereas the connections on the copper side were in parallel. Individual thermocouples were inserted into the circuit by heavy, thermoelectrically neutral, single-pole, single-throw copper switches. Consequently the entire circuit was of the 'all copper type'. 'Parasitic' E.M.F.'s between the various channels were rarely large enough to cause differences in galvanometer deflection of 0.25 mm. at working sensitivity.

Skin temperatures were measured both by thermocouple and radiometric technique. The radiometer was the model of Hardy and Soderstrom (3) furnished commercially.² All measurements were made with frequent balancing of the potentiometric system, according to the room temperature-body and Leslie Cube indications. Readings were accurate to $\pm 0.1^\circ$. The internal diameter of the radiometer aperture was 3.65 cm. and the external diameter 4.75 cm.

¹ All temperatures are expressed in degrees centigrade.

² Baird Associates, Cambridge, Massachusetts.

The experimental subjects were all normotensive males in the basal state drawn from the ward population of the Neurological Institute. None of these patients had subjective, clinical or laboratory evidence of disease of the neuromuscular system of the upper extremities. Experiments were begun between 8:00-9:00 A.M. and lasted four to six hours. The experimental period covered May-August 1947. On entering the laboratory from the wards, subjects stripped immediately and lay on an ordinary hospital

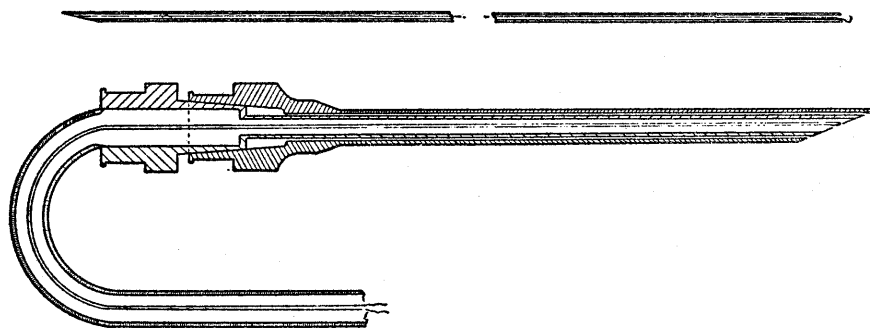


Fig. 1. *Top.* 26-GAUGE STAINLESS STEEL NEEDLE used for introduction of Y-model thermocouple. Needle contains steel wire coated with varnish and baked in place. Loop at end of wire receives lead wire of thermocouple which is knotted in place. This needle is shown in place in the forearm in figure 5a. *Bottom.* Brachial artery thermocouple, built in a 24-gauge hypodermic needle with insulated junction in bevel of needle. Preliminary puncture of artery performed with 19-gauge needle with 10 cc. syringe attached; on appearance of arterial blood, syringe is disconnected and the 24-gauge needle slipped into the 19-gauge needle, the two bevels lying flush. Between readings of arterial blood temperatures, the inner needle is routinely removed long enough to show arterial spurting from the 19-gauge needle. No anesthesia used in punctures.

bed with a small sheet draped over the hips and with two pillows under head and shoulders. Air and wall temperatures in the laboratory were identical. The majority of experiments were conducted at a room temperature of 25.0-27.0°; over the experimental period of four to six hours, temperature usually rose about 1.0°. Relative humidities, measured by wick psychrometer and hair hygrometer, were within the range of 45 to 74 per cent, the average humidity being 62 per cent. No air currents were perceptible to the subjects; linear air velocity as measured with a delicate anemometer was always below 20 feet per second.

All readings were taken on the right arm with the limb in the position of figure 3a. The needle (fig. 1 *top*) and the Y-thermocouples were autoclaved at 120° for 30 minutes prior to use; for protection of the wires during use, they were enclosed in a plastic tubing, resistant to sterilization at autoclave temperatures. During insertion of the needle and wires, arm and forearm were draped in sterile towels. The skin at entrance and exit sites of the needle of figure 1 *top* was rubbed with 70 per cent alcohol on gauze sponges. Control experiments showed that the alcohol lowered local skin temperature by as much as 4.0 to 5.0° with a gradual return to the neighbor-

hood of the original level in 30 to 60 minutes. Consequently at least one hour was allowed to elapse after insertion of the *Y*-model thermocouple and the first readings. Figure 3b gives the point of insertion of the needle, the description of the needle and the description of the technique of passage of the *Y*-thermocouple. Definite symptoms of pain referred in a distinct peripheral nerve distribution during the passage of the needle were not

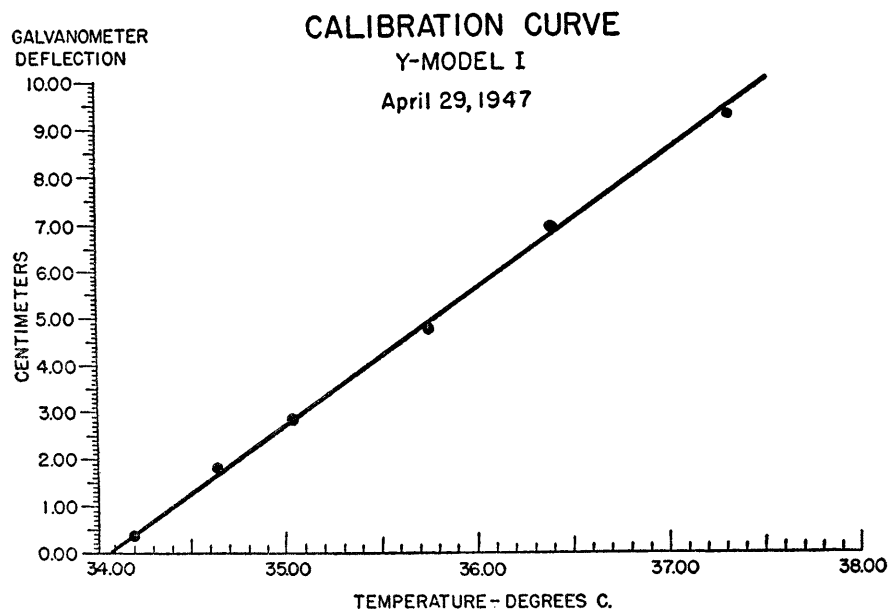


Fig. 2. TYPICAL CALIBRATION CURVE, *Y*-model thermocouple. Temperature coefficient = 0.34° per cm.

encountered. When pain was elicited, it was deep and diffuse at the level of insertion; phlegmatic subjects occasionally reported no unusual pain. It is apparent from figure 3c that the path of the needle provides maximum possible distance from arteries and nerves; this was confirmed by dissection of two forearms. The x-rays of figure 5 show the actual relationship of radius and ulna at the experimental transverse plane (I). Both bones are in the lateral half of the forearm (supero-lateral quadrant) because the forearm is pronated.

After insertion of the *Y*-thermocouple into the forearm, the depth of the junction below the skin was regulated and measured by the wire controller of figure 4. This instrument provided constant tension on the two sides of the thermocouple so that no visible slack appeared in the wires. Without fixation of the thermocouple under tension, the wires curled in the forearm tissues and depth estimations were subject to a variable and unknown error (fig. 5a, b and c). The precision of adjustment of position of the junction received an internal check in technique because the total length

of the axis to be traversed by the junction was already known from measurements on the needle of 1b in the forearm (see legend of fig. 3b). Experiments were considered valid only when the total axis measured on passage of junction between lateral and medial skin surfaces coincided within 2.0 mm. with the axis estimated by needle measurements.

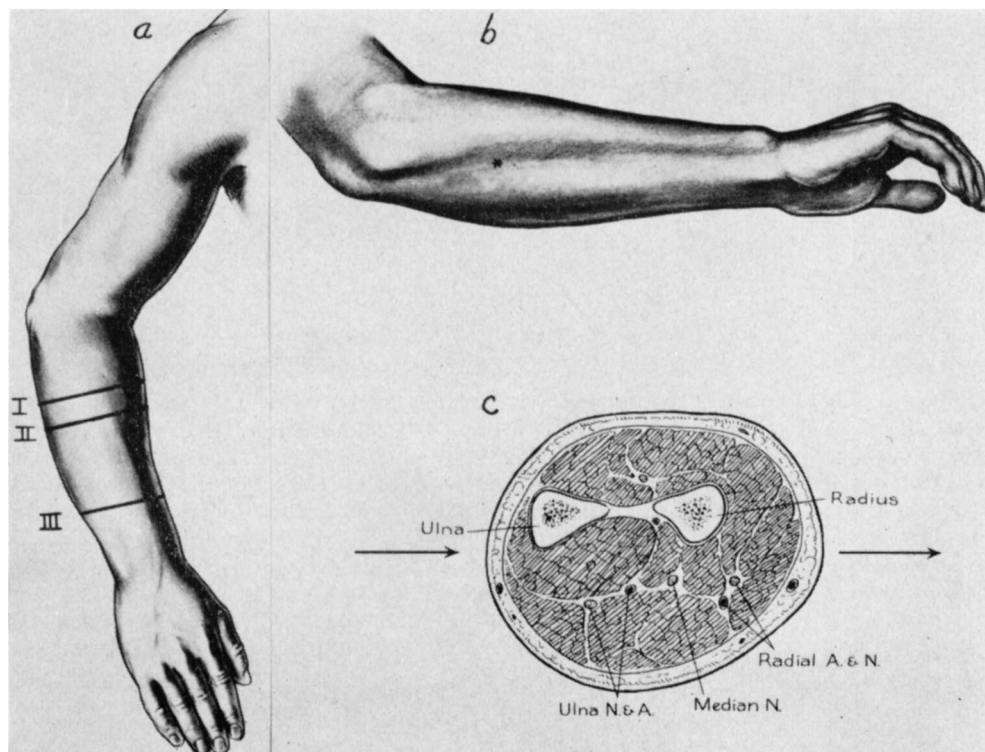


Fig. 3a. EXPERIMENTAL POSITION OF THE RIGHT ARM (superior surface). The pronated forearm was centered between the 2 vertical supports of the wire controller shown in figure 4. The elbow was supported by a soft rubber disc with a central opening just wide enough to receive the medial malleolus of the humerus. The palm of hand was supported on a flat surface of linen towels extended from the head of the metacarpals to the finger tips. Forearm and distal half of upper arm were completely in the air. Inferior aspect of the forearm 5.0 cm. above base of the wire controller (fig. 4). Horizontal *line I* indicates the plane of passage of the needle; *line II* indicates the level of figure 3c.; *line III* indicates the distal plane around the circumference of which temperature was measured in 4 subjects (see section III).

Fig. 3b. EXPERIMENTAL VIEW RIGHT FOREARM (lateral surface). Asterisk indicates point of insertion of the needle of figure 1 (*top*). This plane was always 8.0 cm. distal to tip of ulna olecranon and midway between superior and inferior surfaces of the forearm. The needle was directed perpendicularly to lateral aspect of the forearm. After penetration of the medial side of the arm, the protruding lengths of needle were measured with millimeter-graduated flexible rule. The sum of these two lengths subtracted from total needle length gave the length of the experimental transverse axis. The thermocouple was drawn into the arm by pulling the needle completely through; the needle was then discarded by clipping lead wire. At end of experiment, the thermocouple was removed by traction on 'active' wire so that the path was reversed.

Fig. 3c. CROSS-SECTIONAL ANATOMY of pronated forearm at level II. Broken arrow indicates path of Y-model thermocouple. (Adapted from Morris's Textbook of Human Anatomy, 9th ed., p. 451, 1933.)

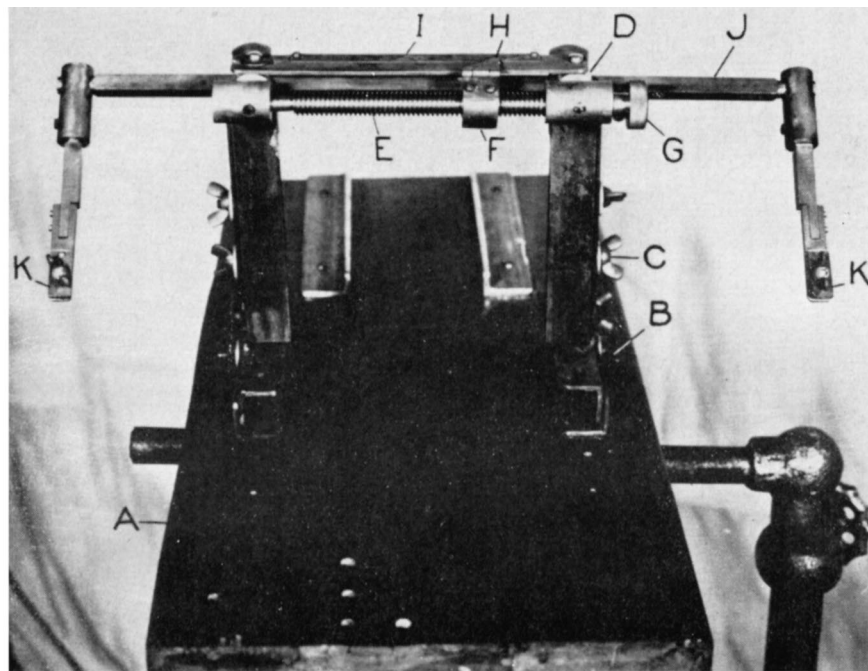


Fig. 4. PHOTOGRAPH OF WIRE-CONTROLLER. The forearm was placed midway between upright supports; elbow at near end of base, hand at far end, experimenter to right. Base, *A*; adjustment along long axis, *B*; adjustment along vertical axis, *C*; universal joint for independent adjustment of right or left side, *D*; worm, *E*; nut, *F*, with slip coupling (not shown); knurled knob for manual control, *G*; position indicator, *H*; millimeter-lined metal scale, *I*; horizontal cross-bar governing movement of wire, *J*; felt-lined clamps for wire, *K*. In operation, the thermocouple wire is stretched taut in the 2 clamps *K* and parallel to the horizontal cross-bar *J*. Manual control of knob *G* causes equal displacements of bar *J* and wire read directly on scale *I*.



In some subjects, occlusion of the circulation was performed above and below the proximal forearm (plane I, fig. 3a). Occluding pressures of 200–240 mm. Hg were obtained from a reservoir. For interruption of the arterial inflow to the forearm, a 13.0 cm. width blood pressure cuff was used on the midportion of the upper arm. For interruption of the venous return from the distal forearm and hand, a 5.5 cm. width cuff was wrapped about the forearm so that the proximal border of the cuff lay 5.0–7.0 cm. below the level of plane I. Pressures in the reservoir and in the cuffs were read from mercury manometers. In these experiments temperatures were read with the radiometer at the experimental plane *I*, at the midpoint of the lateral surface *L*, superior surface *S*, medial surface *M* and dorsum of hand *H*. Readings were taken successively at each skin area; interval between readings at the same area averaged 60 to 80 seconds.

RESULTS

I. Comparison of temperature-measurement techniques

A. SKIN TEMPERATURE DETERMINATIONS WITH RADIOMETER AND THERMOCOUPLES. The absolute precision of skin temperature measurement by thermocouples has been questioned by Hardy (4) but supported by Mendelson (5) using a technique of partially imbedding in the skin thermal elements of low mass and heat capacity. Palmes and Park recently reported that temperatures taken simultaneously on the same skin area with a thermocouple assembly and radiometer showed only very small differences (6). The technique described by Mendelson (5) was used to measure skin temperature with thermocouples on the superior surface of the forearm. Four *Y*-model thermocouples were lined perpendicularly to the long axis of the forearm with the tail and active wire weighted by clamps of 0.58 grams. This amount of weighting was sufficient to cause a faint furrow in the skin, seen on removal. The thermocouples were moved from point to point within a circle of diameter equal to that of the radiometer aperture, measurements being made at each point; between each series of thermocouple readings, a reading was taken from the total area with the radiometer.

Mean thermocouple readings in 6 subjects (table 1) were higher in two subjects (0.1° , 0.2°), lower in three (0.1° , 0.1° – 0.2° , 0.2°) and coincided with the radiometric reading in one subject. Even taking into account the

Fig. 5. X-RAY PHOTOGRAPHS OF FOREARM to illustrate technique of introduction of *Y*-model thermocouple. *A*. Needle of fig. 1 (*top*) in place after passage through forearm at experimental plane I. *B*. Lead wire of thermocouple (*Y*-model) has been drawn into place in forearm. No tension on wire. Note slack in wire, introducing unknown and variable error in depth estimations. *C*. Lead wire drawn taut in clamps of the wire controller (fig. 4, *K*). Note that the needle of 5a and the wire in 5c follow identical paths.

fact that relative precision of the radiometric determination was only $\pm 0.1^\circ$, these findings do not support Hardy's conclusion that an absolute accuracy of 1.0°C . is the best that can be expected by thermocouple technique (4).

Typical spatial variations of temperature are seen in figures 6a and 6b. The maximum differences observed between adjacent points separated only 5-7 mm. are 0.31° (fig. 6a) and 0.23° (fig. 6b); mean of this maximum difference for the 6 subjects was 0.38° . Maximum difference between any two points lying within the radiometer aperture was 0.67° for the subject of figure 6a and 0.47° for the subject of figure 6b, with a mean of 0.73° for

TABLE 1. COMPARISON OF TEMPERATURE, SUPERIOR SURFACE PROXIMAL FOREARM WITH THERMOCOUPLES AND HARDY RADIOMETER

THERMOCOUPLE READING (mean of 16 points) $^\circ\text{C}$.	RADIOMETER READING $^\circ\text{C}$.	ROOM TEMPERATURE $^\circ\text{C}$.
34.24	34.0	25.8
30.93	31.2	26.0
32.75	32.9	26.5
33.48	33.6	26.5
34.98	35.0	26.7
34.63	34.5-34.6	26.6

the 6 individuals. These differences could not be correlated with observable variations in vascular patterns; the superior surface of the forearm usually showed no discernible veins. Mendelson likewise reported that skin temperatures in the arm differed by as much as 0.5° at points less than 1.0 cm. apart (5).

B. COMPARISON OF DEEP TISSUE TEMPERATURES WITH NEEDLE AND Y-MODEL THERMOCOUPLES. The high thermal conductivity of the steel needle thermocouples theoretically should cause a flow of heat from tissue to needle and outward flow along the needle shaft. The same factors should also operate with the Y-model thermocouple, but the disturbance of tissue

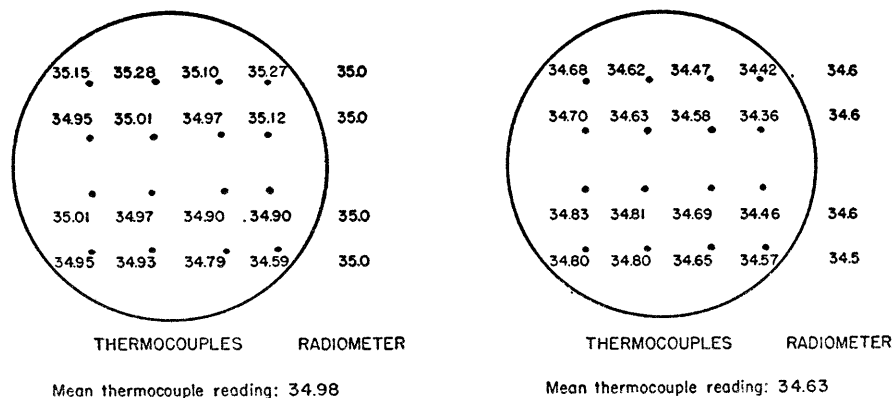


Fig. 6. COMPARISON OF SKIN TEMPERATURES measured with Hardy radiometer and with thermocouples. Measurements made on superior surface, proximal forearm.

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temperature should be less because of the much smaller dimensions of these thermocouples. Although theoretical calculations of approximate nature could be made of the heat conducted along needle and *Y*-models for a given temperature gradient, the actual lowering of tissue temperature thereby produced would depend on the character of the tissue temperature gradients and the theoretical analysis would become quite insecure. Moreover, in such a calculation the effect of other factors attendant on thermocouple technique is ignored. Bazett and McGlone devised an empirical correction formula based on various approaches to the problem (1). Their data indicate that the lowering of tissue temperature is least for their smallest dimen-

TABLE 2. COMPARISON OF TISSUE TEMPERATURE READINGS WITH NEEDLE AND *Y*-MODEL THERMOCOUPLES¹

DEPTH OF INSERTION cm.	NEEDLE THERMOCOUPLE READINGS °C.	<i>Y</i> -MODEL READINGS °C.
3.5	(a) 36.87	36.88
	(b) 36.85	36.91
	(c) 36.91	36.90
4.0	(a) 36.65	36.70
	(b) 36.65	36.69
	(c) 36.67	36.70

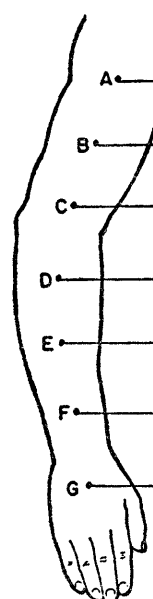
¹ Three needle thermocouples (*a*, *b*, and *c*) tested against same *Y*-model thermocouple in 2 subjects.

sion needles; the needles used in this study had an external diameter of 0.46 mm. with wall thickness of approximately 0.10 mm. and weight of 0.8 mgm. per mm., being comparable to the needles for which Bazett and McGlone found smallest error. In this study, needle thermocouples were used only (in conjunction with brachial arterial determinations) to find the maximum temperature of the forearm, and for this purpose were always inserted radially to the gradients to a depth of 3.0–4.0 centimeters. If tissue temperature lowering by the needle is significant at this depth of insertion, then the temperature indicated at the same point by the *Y*-model should be higher than for the needle. Direct determinations of temperature at the same point were therefore carried out in two subjects with the two thermocouple types. The *Y*-model was introduced as described and measurements taken until a steady state was obtained. The point of the needle thermocouple was then inserted into the arm 3.0 to 4.0 mm. away from the point of entrance of the wire. By means of a specially constructed angular controller, the needle was advanced till its thermojunction lay a calculated 2.0 mm. from the *Y*-model thermojunction.

In five instances, the needles gave lower indications (-0.01° to -0.06°); in one instance, the needle gave a higher indication ($+0.01$, table 2). These

differences either fall within the limits of precision of the technique or barely exceed those limits. During the insertion of the various needles, the galvanometer deflection caused by the *Y*-model was continuously observed. No change in deflection was noted as the needles reached their final position in tissue; this ruled out the possibility that the needles really did lower tissue temperature significantly, with an effect extending to the junction of the *Y*-model. In order to determine the absence of contact between needle point and *Y*-model thermojunction, the needle was advanced

TABLE 3. TEMPERATURE DISTRIBUTION, LONG AXIS OF ARM, SUPERIOR SURFACE. RADIOMETER READINGS. VALUES IN °C.



Subject (°)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)	(18)	(19)	(20)	(21)	(22)
A	32.2	32.1	33.9	32.4	33.4	33.6	35.4	35.2	34.0	34.2	33.2	34.4	34.4
B	31.6	31.1	34.0	31.9	33.3	33.7	35.2	33.3	33.8	34.0	33.1	34.4	34.4
C	31.4	32.3	33.8	31.5	33.3	33.8	35.0	33.3	33.4	33.4	32.4	34.5	34.0
D	31.5	32.3	33.8	31.5	33.2	34.5	34.7	33.2	33.5	33.8	31.9	34.9	34.1
E	31.7	31.8	33.8	31.3	33.1	34.2	34.7	33.2	33.6	33.6	31.7	34.7	33.8
F	32.4	32.8	32.7	31.0	33.3	34.6	34.7	33.5	33.8	33.9	31.7	34.8	34.1
G	33.5	34.6	31.7	29.9	33.5	35.0	35.2	33.8	34.5	34.5	31.9	35.0	34.8
Room Temperature	25.0°	25.0°	25.5°	25.5°	25.5°	25.5°	26.0°	26.0°	26.0°	26.0°	26.0°	26.5°	27.0°

forward and backward 2.0 mm., and the readings repeated; the same values were obtained within the limits of precision of measurement. Such small displacements of the needle caused insignificant change in the temperature indication because the measurements were being made on the flattest portion of the temperature-depth curves (fig. 15). Heat loss along the two thermocouples must then have differed insignificantly at depths of 3.5 to 4.0 cm. because the same temperature indications were obtained. The heat loss along the thermocouple is theoretically proportional to the temperature gradient; at these depths the gradient in the neighborhood of the junction is quite small and this must be a major factor in the virtual equality of the indicated temperatures. It is possible, however, that the heat loss was less for the *Y*-model and that more intense inflammation about the needle raised the temperature locally.

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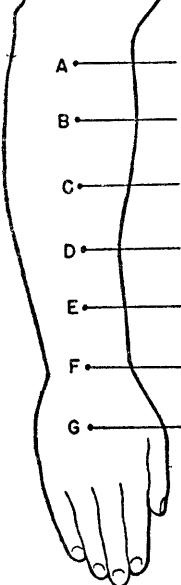
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II. Skin temperature distribution along the long axis of the upper extremity

The analysis of the depth-temperature curves found at plane I of the forearm (fig. 15) would be considerably simplified if the temperature gradient along the long axis of the forearm were negligible. Consequently, skin temperature determinations were made on the superior surface of the arm, with radiometric technique at the points indicated in tables 3 and 4 and with typical curves plotted from these data in figures 7 and 8.

TABLE 4. TEMPERATURE DISTRIBUTION, LONG AXIS OF FOREARM, SUPERIOR SURFACE. RADIOMETER READINGS. VALUES IN °C.



	Subjects (23)	(24)	(25)	(26)	(27)	(28)	(29)	(30)	(31)	(32)	(33)	(34)	(35)	(36)
A	31.9	31.9	33.0	33.2	31.5	32.3	34.0	33.6	33.8	32.5	34.6	33.5	34.8	34.9
B	31.8	31.7	33.2	33.3	31.6	32.0	33.8	33.7	33.8	32.6	34.3	33.5	34.5	34.4
C	31.8	31.5	33.2	33.4	31.5	31.9	33.8	33.8	34.0	32.6	(34.5)	33.5	34.5	34.4
D	31.8	31.8	33.0	33.1	31.3	32.5	33.9	33.9	34.4	32.6	34.7	33.4	34.5	34.5
E	31.9	(32.3)	32.9	33.2	30.0	33.9	33.8	33.9	34.6	32.3	34.5	33.3	34.0	34.6
F	32.3	32.9	33.4	33.6	29.1	(34.1)	33.9	33.8	34.9	33.8	(34.6)	33.9	34.0	35.3
G	34.4	33.6	35.0	33.8	29.4	34.3	35.0	34.8	35.3	34.3	34.7	34.5	34.3	36.0
Room Temperature	25.0°	25.0°	25.5°	25.5°	26.0°	26.0°	26.0°	26.0°	26.0°	26.5°	26.5°	27.0°	27.0°	27.5°

The longitudinal temperature gradient along the proximal one third of the forearm (centered between positions *D-E*, table 3 and fig. 7; centered about *B*, table 4 and fig. 8) was flatter than along the more distal portion of the extremity. Mean temperature difference (independently of algebraic sign) between successive positions of the forearm was as follows (calculated from table 4): *A-B*, 0.2°; *B-C*, 0.1°; *C-D*, 0.2°; *D-E*, 0.4°; *E-F*, 0.4°; *F-G*, 0.8°. Since distance between adjacent points averaged 5.0 cm., the mean gradient between *A* and *B* was 0.04° per cm. and between *B* and *C* was 0.02° per centimeter. These gradients were negligible in comparison with the radial gradients at plane I. The break in the mean temperature curve occurred near the junction of proximal and distal portions of the forearm, with a steeper slope between wrist and hand. The uniformity of temperature along the longitudinal axis in the proximal one third of the forearm is, in all probability, partly a function of the more uniform contour of this arm segment in contrast to the distal narrowing and flattening of the limb.

Three types of temperature distribution along the long axis were found for the entire arm (fig. 7): a higher temperature in distal forearm or hand than in proximal arm occurred in 8 subjects; a lower temperature in 4 subjects; and negligible ($\pm 0.1^\circ$) differences in 2 subjects. Likewise for the forearm (fig. 8): a higher distal temperature in 11, a lower in 2, and uniform temperature in 1 subject.

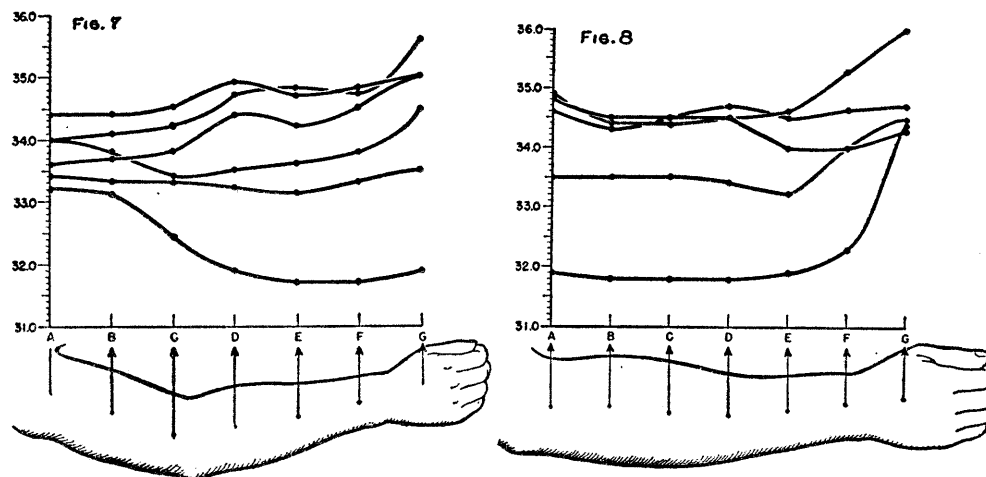


Fig. 7. TEMPERATURE DISTRIBUTION, long axis, superior surface of arm. Measurements with radiometer. Note 3 major types of distributions, described in text. Note the relative absence of gradient in the proximal half of forearm.

Fig. 8. TEMPERATURE DISTRIBUTION, long axis, superior surface of forearm. Measurements with radiometer. Note 3 major types of distribution, described in text. Note the relative absence of gradient in the proximal half of forearm.

Statements occur in the literature to the effect that the hand surface is relatively cool or that there is a tendency for skin temperature to be higher near the trunk (5, 6). The above data indicate, however, that the distal forearm and hand tend to be warmer than the proximal arm at room temperatures of 25.0 to 27.5° . This fact is supported by figures given by Stewart and Haskell, the measurements being taken at a room temperature of 27.0° and humidity of 50 per cent (8). The dynamics involved are partly revealed in the data of Roth *et al.* to the effect that maximal finger skin temperatures of 33 to 35.0° are reached at room temperatures of 25.0 – 26.0° (9).

The thermal distribution along all four surfaces of the forearm was studied to see if the gradient present on the superior aspect were present on the other three surfaces. In figure 9 the superior surface shows the typical distal rise of temperature in all three subjects. The same effect is seen in the medial and lateral surfaces in one subject and in all other three surfaces in the other two subjects.

III. Skin temperature distribution around the circumference of the forearm

Further simplification of the analysis of the deep tissue temperature curves would be possible if the cutaneous circumference of the forearm at plane I were at uniform temperature. Radiometric measurements were therefore made of temperature at successive points 1.0 to 2.0 cm. apart around the entire circumference of the forearm at plane I and in a few instances at plane III.

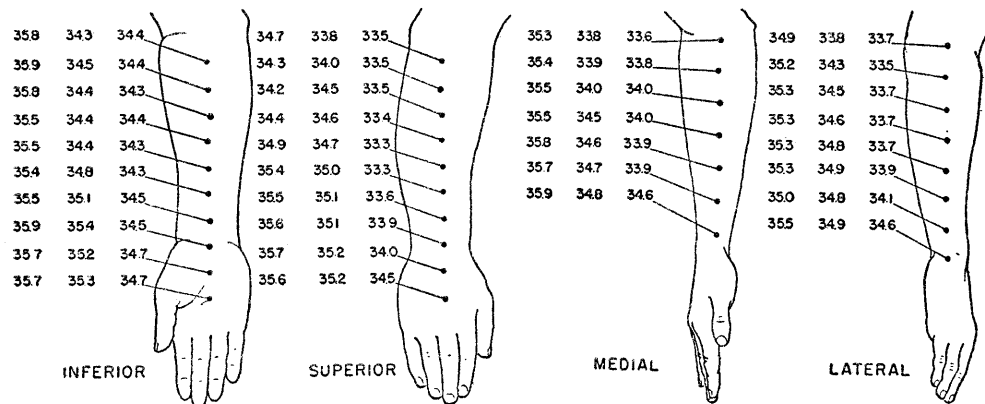


Fig. 9. TEMPERATURE DISTRIBUTION along all 4 surfaces of forearm. Measurements with radiometer. All values are given in °C.

Isothermal conditions were never found around the circumference of planes I or III (table 5, fig. 10). The distribution of temperature followed an irregular and unpredictable pattern from subject to subject. Maximum difference around the forearm circumference ranged from 0.7 to 2.6°. Average maximum difference for the group of 17 subjects was 1.2°. Highest temperature occurred over the medial half in 12 subjects, lateral half in 3 subjects and over both halves in 2 subjects. The most common distribution was a minimum in the supero-lateral quadrant and a maximum in the supero-medial or infero-medial quadrants (7 subjects; see *subject 35*, fig. 10).

Readings from the supero-lateral quadrant were taken from skin over the subcutaneous surface of the ulna. Possibly the predominant occurrence of minimum temperatures in this quadrant is due to the presence of superficial bone and to the fact that the medial half of the forearm contained all soft tissue. For this reason, the circumferential distribution of temperature was explored at both levels I and III in 4 subjects, because at level III the radius occupies the medial compartment of the arm, and bone and soft tissue are more symmetrically placed than at level I. Practically the same distributions were found at both levels in 3 out of 4 subjects (table 5, fig. 10), thereby excluding asymmetry of bone and soft tissue as a sufficient

TABLE 5. TEMPERATURE DISTRIBUTION, CIRCUMFERENCE OF FOREARM AT PLANE I. RADIOMETER READINGS IN °C.¹

Subject		Plane I												Plane III							
		32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	33	36	37	39
31.4	31.0	32.4	32.0*	31.6	33.6	33.6	31.6	33.2	34.3	30.9	34.3	33.5*	33.3	33.4	33.7	33.8	35.0	32.1*	34.4	32.7	34.4
31.1	31.8	33.0	32.2	31.6	33.6	33.6	31.5	33.0*	34.0	31.3	34.2	33.5*	33.1*	32.8	33.5	34.3	34.9	32.3	34.4	32.6	34.0
31.0*	31.6*	33.3	32.2	31.5*	33.6	33.6	31.4	33.0*	33.5	31.4	34.1	33.6	33.4	32.8	33.6	34.5	34.5	32.3	34.4	32.5*	33.6
31.0*	31.6*	33.4*	32.3	31.6	33.8	33.8	31.5	33.0*	33.2	31.5*	34.4	33.6	33.7	32.8	33.8	34.8*	34.3*	32.4	34.4	32.5*	33.5
31.2	32.1	33.1	32.2	31.7	34.0	34.0	31.5	33.5	33.0	31.3	34.0	33.5*	33.8	32.8	33.4	34.7	34.4	32.4	34.5	32.7	33.4*
31.2	32.3	33.0	32.3	31.7	34.3	34.3	31.7	33.2	32.9	31.1	33.8*	33.6	33.5	32.7*	33.1*	34.5	35.2	32.4	34.5	32.8	33.5
31.5	32.4	32.6	32.4	31.9	34.3	34.3	31.8	33.1	32.9	30.8*	34.1	34.2*	33.3	33.0	33.2	34.3	35.6*	32.6	34.5	32.9	33.4*
31.8	32.6*	32.6	32.5	31.9	34.2	34.2	32.0	33.6	32.8	30.7	34.0	34.2*	33.5	33.6	33.5	34.2	35.3	32.8	34.5	33.2	33.4*
32.4	32.5	32.8	32.7	32.0	34.2	34.2	32.3	33.9*	32.8	30.9	34.3	34.0	34.1	33.8*	34.1	34.2	35.3	32.9	34.5	33.6	33.8
33.0	32.4	32.8	32.7	32.2	34.3	34.3	32.5	33.6	32.8	20.9	34.5*	34.0	34.2*	33.8*	34.4*	34.4	35.0	32.9	34.5	33.8*	34.3
33.6*	32.5	32.7	32.7	32.3	34.5	34.5	32.9	33.4	32.7*	30.8*	34.5*	33.5*	34.0	33.7	34.3	34.4	34.9	32.9	34.5	33.8*	34.5
33.6*	32.5	32.5	32.6	32.5	34.6*	34.6*	33.1*	33.2	32.9	30.8*	34.5*	33.5*	33.9	33.7	33.9	34.0	34.9	32.9	34.5	33.6	34.6*
33.5	32.1	32.3*	32.8*	32.6*	34.6*	34.6*	33.1*	33.2	33.5	30.9	34.5*	33.8	33.6	33.5	33.8	33.8	33.6*	33.0*	34.6*	33.6	34.2
			32.8*	32.6*	34.6*	34.6*	32.9	33.2	34.0		34.4		33.3	33.5		33.6*		33.0*	34.6*	33.5	34.2
			32.7	32.5	34.5	34.5	32.6	34.5*	34.5*							33.8			34.6*	33.3	34.5
				32.5	34.3	34.3	32.6	34.5*	34.5*										34.5	33.1	34.3
				32.3	33.9	33.9	32.6	34.5*	34.5*										34.3*	32.9	
				32.0	33.6	33.6	32.7	34.5*	34.5*											32.8	
				31.6	33.5	33.5	32.7	34.3	34.3											32.8	
					33.4*	33.4*	32.5		34.1											32.8	

Room temperature																					
25.0°	25.0°	25.5°	25.5°	25.5°	25.5°	25.5°	25.5°	25.5°	26.0°	26.0°	26.0°	26.5°	26.5°	26.5°	26.5°	26.5°	27.0°	25.0°	25.5°	25.5°	26.0°

Room temperature

25.0°	25.0°	25.0°	25.5°	25.5°	25.5°	25.5°	25.5°	25.5°	26.0°	26.0°	26.0°	26.5°	26.5°	26.5°	26.5°	27.5°	27.0°	25.0°	25.5°	25.5°	26.0°
-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------	-------

Maximum temperature difference

2.6°	1.0°	1.1°	0.8°	0.9°	1.2°	1.2°	1.7°	0.9°	1.8°	0.8°	0.7°	0.7°	1.1°	1.1°	1.3°	1.2°	1.3°	0.9°	0.3°	1.3°	0.9°
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¹ The initial reading in each column is over the midpoint of the lateral aspect of the forearm; the order of succeeding readings is superior—medial—inferior at 1.0-2.0 cm. placements of the radiometer. The last reading in each column therefore represents a skin area immediately inferior to that of the first reading.

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factor. During the measurements the medial surface of the forearm faced the trunk of the subject, the distance between the two surfaces being about 30 cm. Because of the relatively high skin temperature of the trunk, heat loss by radiation from the medial side of the forearm might well have been lower than from the lateral side which radiated out to the walls of the laboratory and intermittently to the body of the investigator. This factor could not be sufficient in itself to account for the characteristic higher temperature on the medial side, because of the cases in which this temperature distribution was not found, but it is probably contributory. All forearms had a more or less prominent basilic vein on the lateral aspect which coursed inferior to the posterior border of the ulna before dipping downward and around to the infero-medial aspect of the arm; the superior surface of the forearm usually contained no large veins; the medial and inferior aspects of the forearm always bore a variable number of conspicuous venous channels.

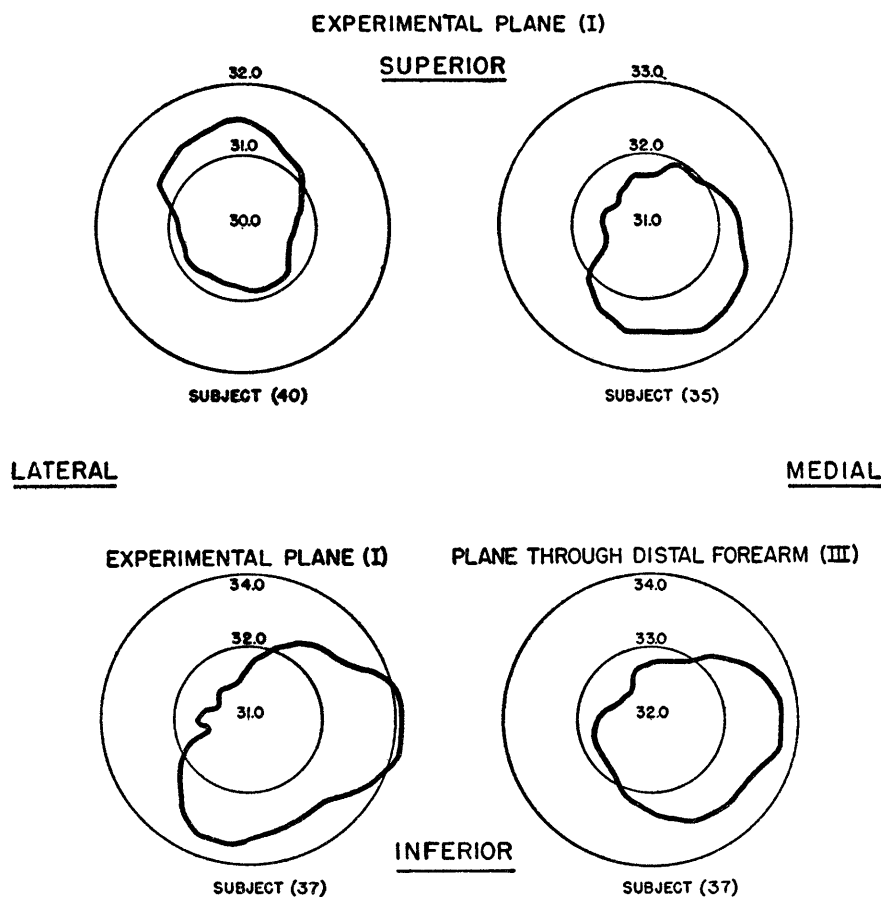


Fig. 10. TEMPERATURE DISTRIBUTION around circumference of forearm at planes I and III. *Subject 35* illustrates the most common type of distribution: minimum in supero-lateral quadrant and maximum in infero-medial (or supero-medial) quadrant. *Subject 40* shows the second most common type of distribution. *Subject 37* shows that the form of the distributions at planes I and III is similar.

The most frequent occurrence of maximum temperatures on the medial side of the forearm may be causally related in part to the greater venous density in this area as compared with the relative paucity of veins in the superolateral quadrant.

Foged found with mercury thermometers in a large series of normal subjects at a room temperature of $24.0-25.0^{\circ}$ that the maximum mean difference between two positions on different surfaces of the forearm was 1.1°

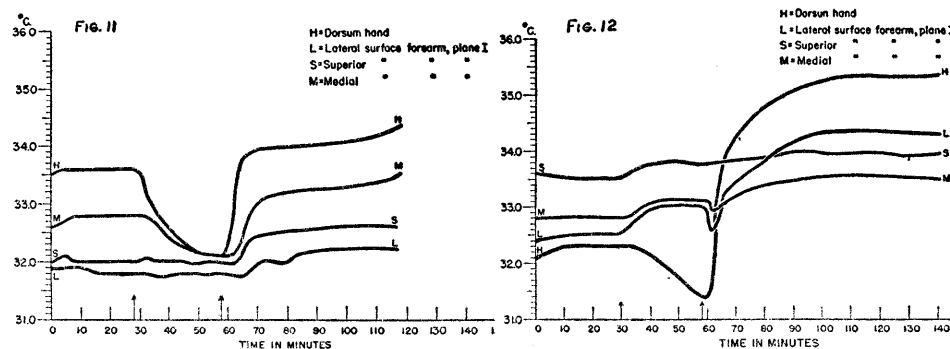


Fig. 11. COMMON TYPE OF RESPONSE to circulatory occlusion, distal forearm, on skin temperature of proximal forearm and hand.

Fig. 12. UNUSUAL TYPE OF RESPONSE to circulatory occlusion, distal forearm, on skin temperature of proximal forearm and hand.

(anterior and lateral). This compares with the value of 1.2° given above; however his measurements were taken with the forearm apparently in supination and in contact with the bed along its entire length (10).

IV. *Effect of circulatory occlusion at distal forearm and upper arm on proximal forearm and hand temperatures*

If the temperature differences around the circumference of the proximal pronated forearm are caused only by local variations in cutaneous flow patterns, then interruption of the arterial inflow should disturb this non-isothermal state. Occlusion of the distal venous return should also have an effect if this circulatory variable is contributory.

A. EFFECT OF CIRCULATORY OCCLUSION AT DISTAL FOREARM: VENOUS RETURN FROM DISTAL FOREARM AND HAND INTERRUPTED; FLOW THROUGH EXPERIMENTAL SEGMENT INTACT

This procedure, performed in 11 subjects, produced the following effects on forearm temperatures. a) Five subjects had no significant change ($\pm 0.1^{\circ}$ or less) at any of the three skin areas, *L*, *S* and *M*, during occlusion periods lasting 24 to 40 minutes. Of these, 2 showed no effect on readmission of the circulation to the distal forearm and hand; 1 had a rise in temperature at all three areas; 2 had temperature rises at one or more areas, *L*, and *L* and *M*. b) Five subjects had temperature decreases at one or more skin areas during

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the circulatory arrest. Of these, 2 showed drops at *L*, *S* and *M* of 0.9° , 0.5° and 2.0° and 0.7° , 0.4° and 0.7° , respectively, for occlusion periods lasting 38 and 36 minutes; on readmission of the circulation temperatures rose quickly to, but not above, their original levels. Two subjects showed decreases at *M* only of 1.3° and 0.7° for occlusion periods lasting 32 and 30 minutes; on release of occlusion, temperature rose above its original level at *M* in the first, and at *L*, *S*, and *M* in the second (fig. 11). One subject responded with a decrease at *L* and *M* of 0.7° and 0.3° for a 40-minute occlusion, with significant rises above control levels at both these areas on release of occlusion. c) One subject showed a rise in temperature at *L*, *S*, and *M* of 0.5° , 0.3° and 0.3° during 28 minutes of circulatory arrest (fig. 12).

During the period of occlusion, temperature of the hand fell progressively. The higher the temperature of the hand, the steeper the initial rate of cooling. When initial hand temperatures were between 34.0 to 35.0° , the total drop ranged between 2.0 and 2.6° for occlusion periods ranging from 28 to 40 minutes. With initial hand temperatures between 32.0 to 34.0° , the drops ranged from 0.6 to 0.9° ; with an initial hand temperature of 30.6° , the total drop was only 0.2° for a 23-minute period of occlusion.

In the 5 subjects who had a decline in temperature at one or more forearm points during distal occlusion, the dorsum of the hand was 0.2° , 0.5° , 0.7° , 0.7° and 1.0° warmer than the warmest area at plane I. Figure 9 indicates that a relatively warm dorsum of the hand is accompanied by a higher temperature of entire distal forearm as compared with proximal forearm. This suggests that the temperature declines in these 5 subjects were initiated by removal of a warming influence of the venous return from the distal extremity. However, of the 5 subjects without significant response during circulatory arrest, 3 had hand temperatures 0.6° , 0.7° and 1.4° higher than that of the warmest area of plane I, and 2 had hand temperatures 0.5° and 0.6° cooler than the coolest area. The one subject showing a rise in temperature during occlusion had a hand temperature 0.4° lower than the coolest area of plane I. Lack of uniformity in response may well be caused by the important probability that change in volume flow to proximal forearm *above* the occluding cuff was a complicating factor.

After the release of distal occlusion 8 of the 11 subjects showed considerable rises in forearm temperature above control levels at one or more areas; no subjects showed drops in temperature in the period after release of occlusion. Hand temperatures in all subjects rose very sharply on readmission of the circulation to exceed the original level; in general, the lower the initial hand temperature before occlusion the greater the increment of temperature over this level on restoration of the circulation. The rises in proximal forearm skin temperature were undoubtedly caused by flooding of this skin by

the increased volume return of venous blood from the distal forearm and hand during their reactive hyperemia period. During the early part of this period, reddening of the skin about the basilic vein was quite marked together with a slight swelling of this vessel. Changes over position *S*, during or after occlusion, either did not occur or (with the exception of one instance) were less marked than at *L* or *M* (fig. 12); this correlates with the relative scarcity of large veins on the superior aspect of the forearm.

Just prior to the release of occlusion of the distal circulation, the temperature at plane I was remeasured around the entire circumference in each subject. In subjects not responding during the occlusion period, the non-isothermal condition that was initially present was naturally not affected. In responding subjects, the contours of the temperature distribution were altered with usually small ($0.2-0.3^{\circ}$) reductions in the maximum thermal difference at plane I, but uniform temperature was not achieved (fig. 13, *left*). During occlusion, the circulation to forearm above the cuff was maintained since the proximal margin of the cuff was 5.0 to 7.0 cm. distal to plane I; therefore, flow in the superficial veins at this plane must have continued.

The effect of distal flow in subcutaneous veins on skin temperature has been recognized. Lewis and Love found large differences in temperature of skin over and immediately adjacent to the radial vein with the hand immersed in ice water (11). Grant and Pearson found that the warming of forearm skin in response to warming the body could be prevented if the circulation to the hand of that side were arrested (12).

B. EFFECT OF CIRCULATORY OCCLUSION AT UPPER ARM: FLOW THROUGH ENTIRE FOREARM BELOW ELBOW INTERRUPTED

Results were virtually identical in 3 subjects. The first effect of arrest of the arterial inflow was a cooling at all three areas of plane I and hand, the initial rates of cooling being steepest at areas of highest temperature. After prolonged ischemia (35-40 minutes), measurement around the entire circumference at plane I revealed an isothermal state to within $\pm 0.1^{\circ}$ (fig. 13, *right*). Irregular temperature distribution around the circumference of the forearm with circulation intact must be caused by circulatory inequalities on the arterial or venous side. The difference in responses between the area over the basilic vein *L* and medial forearm *M* as compared with the superior aspect *S* of the forearm, as described in section IV A, suggests quite strongly that the pattern of local subcutaneous venous flow is the contributory factor. Of significance is the fact that the asymmetrical relationship of bone and soft tissue in proximal forearm did not prevent attainment of an

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isothermal distribution at plane I in the closing minutes of interruption of the arterial inflow.

At the conclusion of such periods (35-40 minutes) of interruption of the arterial inflow, the subjects experienced much pain in the arm, marked weakness of fingers and wrist with marked hypesthesia of the extremity up to the lower cuff border; these changes could be evaluated only fleetingly but grossly corresponded to those described by Lewis, Pickering and Rothchild (13).

V. Comparison of rectal, brachial arterial and deep forearm temperatures

In the analysis of the effect of blood flow on the temperature-depth curves of figure 15a, b and c, knowledge is required of the temperature of the blood in the brachial artery at the elbow and of maximum forearm temperature. In contrast to the pronated forearm position used in all other subjects, the forearm was in complete supination to facilitate arterial puncture; the elbow and dorsum of the hand rested on small linen pads and the rest of the forearm was in air. To determine maximum tissue temperature, three needle thermocouples were inserted vertically into the superior aspect of the forearm; one needle was at the midpoint of the transverse axis and the

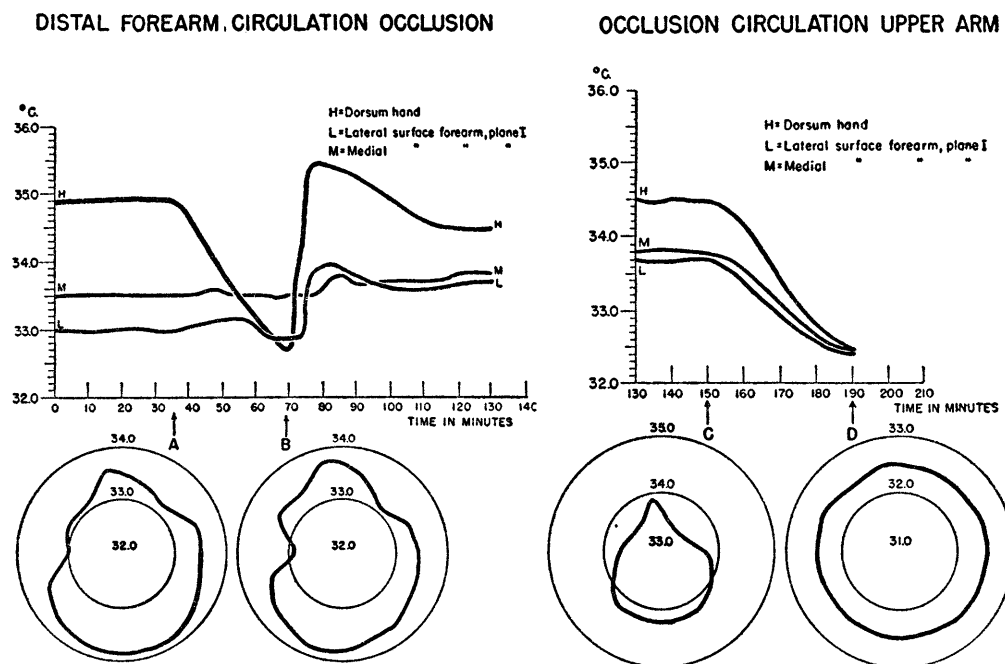


Fig. 13. COMPARISON OF EFFECTS of occlusion of circulation at distal forearm and at upper arm, in same subject, on skin temperature of the proximal forearm and hand. Note only minor changes in surface temperature distribution between A and B at conclusion of period of occlusion at distal forearm. Virtual isothermal state at D at conclusion of period of occlusion upper arm.

others 0.5 cm. on each side. Needles were advanced either until bone was reached or the temperature curve passed its maximum. The two outer needles were then withdrawn and reinserted 1.0 cm. on each side of the mid-point and the process repeated with these. A final withdrawal and insertion were then made 2.0 cm. to each side of the midline.

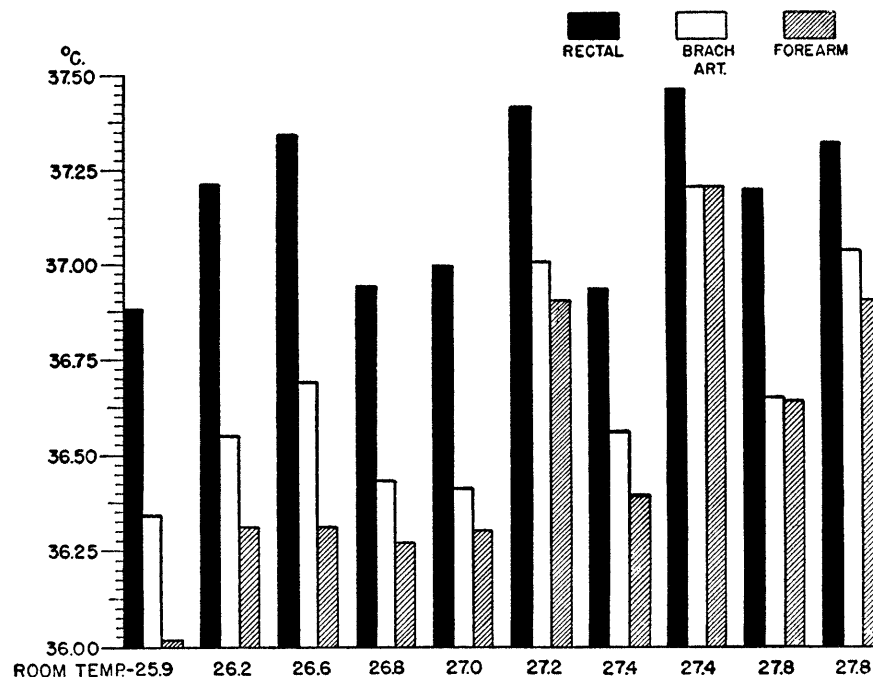


Fig. 14. COMPARISON OF RECTAL, brachial arterial blood, and deep forearm temperatures in 10 subjects.

Brachial arterial blood either equaled or exceeded the deep forearm in temperature in all subjects (fig. 14). The differences ranged from 0.00 to 0.36° with a mean of 0.16°. Mean arterial blood temperature was 36.68°; mean maximum forearm temperature was 36.52°. The arterial inflow to the forearm must act as a warming system for the tissues extending from the skin into the geometrical axis of the limb at plane I if the arterial blood has the same temperature at the elbow and 8.0 cm. below the elbow (plane I). At the range of environmental temperatures covered in these experiments, the difference in temperature between blood in the brachial and radial arteries found by Bazett *et al.* should be minimal; therefore change in temperature of arterial blood between elbow and plane I should be negligible (14). This fact is of importance because the analysis of the contribution of circulation to the observed deep tissue temperature curves of figure 15 is considerably simplified if a unidirectional transfer of heat occurs between blood and tissue throughout the entire tissue.

Foged reported two brachial artery temperature determinations in

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man of 39.1° and 37.3° compared with rectal temperatures in the same subjects of 37.3° and 37.6° , respectively, at room temperatures of 22.0 to 22.3° (15). Wright and Johnson found radial artery temperatures 1.2 to 3.1° lower than oral temperatures in 4 subjects at 20.5 to 24.5° room temperature (16).

VI. *Depth-temperature distribution along the transverse axis of the proximal forearm*

The form of the thermal gradients through the entire transverse axis of the forearm was determined with Y-model thermocouples by the technique described and illustrated in figures 1a, 3, 4 and 5. At least one hour was allowed to elapse between the insertion of the thermocouple and the

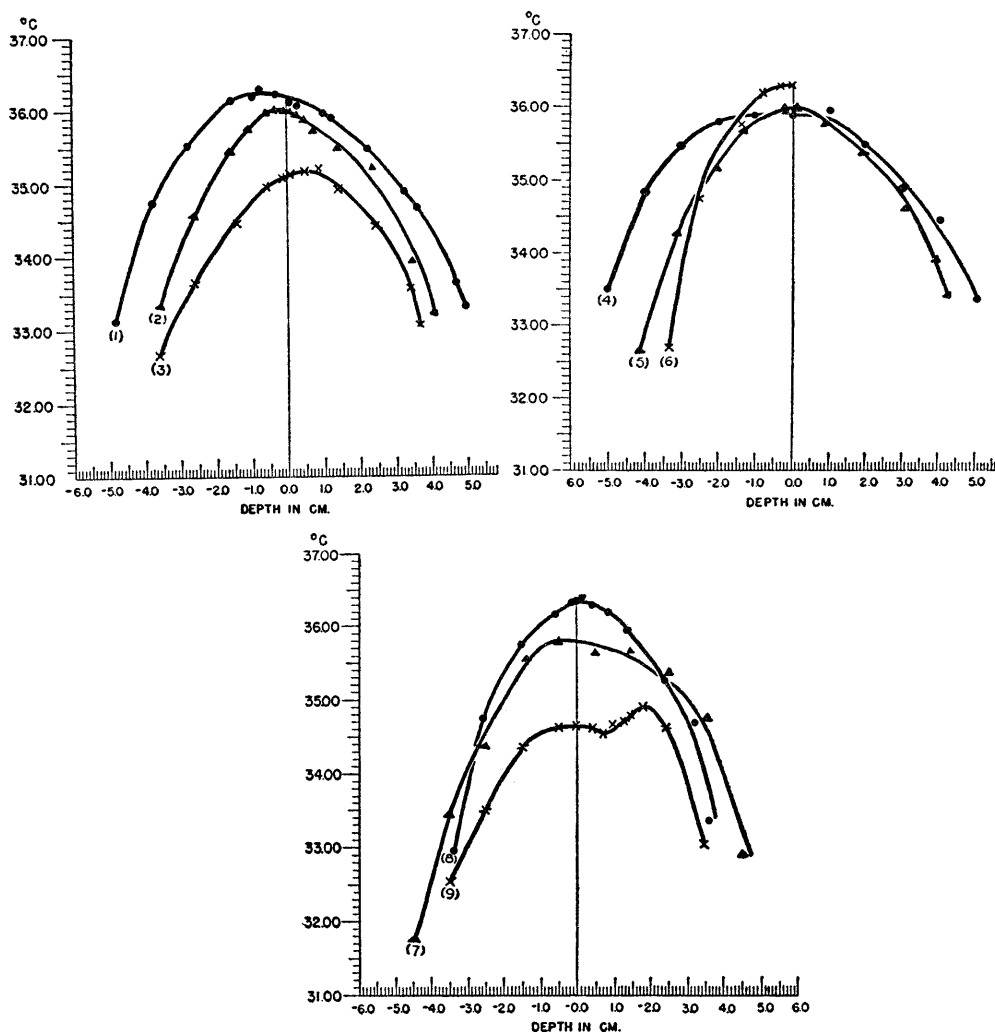


Fig. 15. TISSUE TEMPERATURE-DEPTH CURVES in 9 subjects; plane I, transverse axis of forearm. See text section VI. Room temperatures: curve 1, 26.5° ; 2, 26.6° ; 3, 26.1° ; 4, 26.7° ; 5, 26.3° ; 6, 27.4° ; 7, 26.3° ; 8, 26.7° ; 9, 27.1° . The negative abscissa values represent the lateral side of the forearm, and the positive values the medial side.

beginning of readings. Skin temperatures could not be determined accurately with these models because the long axis of the junction, 0.1 to 0.2 mm. in length, was oriented perpendicularly to the skin surface and therefore must have been influenced by air and skin temperatures simultaneously before finally entering the tissue completely. For this reason the skin temperatures in figure 15a, b and c were determined with the radiometer placed over the point of entrance and exit of the wire after the thermocouple was momentarily released from the clamps. Readings in tissue at a given point were taken for two minutes. If the temperature remained steady to $\pm 0.05^\circ$, the junction was moved to a new position; if not, readings were repeated until a stable figure was obtained. If the readings did not become steady the junction was brought back to the skin surface for a new start. After one complete passage through the forearm, the path of the junction was reversed and readings taken at the same points as on the original passage. The curves of figure 15 are in subjects in whom the temperatures at the same point in the two trips by the junction coincided to $\pm 0.1^\circ$. Correspondence of temperatures at the same point on the two passages was always excellent near the axis of the limb and the deviations between the two curves were most marked near the periphery. The curves of figure 15 are for junction passage from the lateral to the medial side of the forearm.

The significant features of the curves of figure 15a, b and c are: 1) In all cases the temperature reached its maximum near the geometrical axis of the limb. This is in accord with the previous findings with needle thermocouples in the human biceps (2). 2) The curves did not possess perfect circular symmetry. Maximum temperature was asymmetrical with respect to the axis by distances varying from 2.0 to 10.0 millimeters without predilection for either side of the arm. In 6 of the 9 subjects, the skin temperature on the medial side was higher than on the lateral side; this corresponds with the detailed results of section III. Since the circumference of the limb was in all probability not at uniform temperature (see section III), each curve must give only the temperature distribution along the experimental axis; the isothermal surfaces inside the forearm cannot be concentric cylinders (approximately) but must possess irregular contours dependent on surface contours. 3) The curves tended to superimpose toward the axis of the limb (except curve 9). Forearm tissue temperature was therefore more uniform centrally than peripherally. Mean maximum forearm temperature was 36.09° . 4) A biphasic curve was found once (curve 9) showing one maximum 4.0 mm. lateral to the axis and a second maximum 1.9 cm. medial to the axis. This distribution of temperature was undoubtedly caused by some local variation in vascular pattern. The path of the needle in all cases was selected to provide maximum distance from ulnar and radial arteries but

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the location of the medial peak in curve 9 would seem to correspond to the position of the radial artery, at least with respect to horizontal distance from the axis (fig. 3c).

Logarithmic plots on the lateral and medial limbs of all the curves (except 9) were made by applying two methods: with the zero at the geometrical axis of the limb and with the zero at the point of maximum temperature. Although satisfactory straight lines could be obtained for most of the data points in a majority of subjects, the slopes of the lines in most instances varied considerably with the two methods of plotting, even though the shift of zero was only several millimeters. Exponents ranged in value from 1.57 to 2.83 with a mean value of 2.01 for all plots by both methods. The mean curve of all the data except curves 3 and 9 is plotted in figure 16 for a forearm of average radius of 4.0 cm. Maximum temperature for this curve was at the axis of the limb but again the medial side is at a higher level than the lateral side in accord with the usual findings. Logarithmic plot of the temperature difference between the axis and more distal points against the distance gave a satisfactory straight line for the lateral side with a slope of 2.16; on the medial side the points could not be fitted satisfactorily with a single line.

Analysis. The mean curve resulting from a plot of all the data (fig. 16) will be analyzed by an application of the analytic theory of heat flow in homogeneous, isotropic conductors. The symbols are defined as follows:

θ = tissue temperature, °C.	E = Newton cooling constant in grams cal. per cm. ² per sec. per °C.
θ_a = arterial blood temperature, °C.	h_m = rate of tissue heat production in grams cal. per cm. ³ per sec.
θ_v = venous blood temperature, °C.	h_b = rate of heat transfer from blood to tissue in grams cal. per cm. ³ per sec.
r = normal to cylindrical isothermal surface (radial distance from axis), cm.	V = Volume flow of blood through tissue in grams per cm. ³ per sec.
R = radius of cylinder, cm.	s = specific heat blood in grams cal. per gram per °C.
K = specific thermal conductivity tissue in grams cal. per cm. ² per sec. per °C. per cm.	

The following assumptions will be made in the analysis. *a)* Since a cross-section of the pronated proximal forearm is almost perfectly cylindrical, the general differential equation of heat flow will be used in cylindrical coordinates. In reality the cross-section is always elliptical with the two axes differing in length by 0.5 to 1.0 cm. The use of elliptical coordinates would involve a degree of complexity in the solution which is probably not justified by the underlying physiological complications.

b) The tissues of the forearm must contain two heat sources: heat produced by tissue metabolism and heat transferred from blood to tissue at each point in the forearm. For simplicity of analysis, the rate of heat production

by tissue will be considered uniform throughout the forearm. According to Hill, the temperature coefficient of the resting rate of heat production by the inexcitable frog sartorius is 2.64 to 2.74 which is about the same order of magnitude as other biochemical or vital processes (17). Therefore, tissue heat production near the surface of the forearm should occur at a lower rate than near the axis because of the presence of the temperature gradient. The rate of heat production by skin and subcutaneous fat is presumably of a low order of magnitude. The presence of radius and ulna in the supero-lateral quadrant of the forearm should disturb the gradients if heat production and thermal conductivity in bone, together with the relationship of blood and bone temperatures, differ from those of the soft tissues. Since the two limbs of the mean curve of figure 16 have approximately the same level and shape, the effect of bone is not evident; therefore the bone will be treated mathematically exactly as the soft tissues.

c) In the absence of evidence to the contrary, the volume flow of blood per unit volume of tissue per second (V) will be considered uniform throughout the forearm. The rate of heat transfer from blood to tissue obviously cannot be considered uniform. According to the familiar Fick principle:

$$\text{Eq. 1} \quad h_b = V \cdot s(\theta_a - \theta_v)$$

θ_v , the temperature of the venous blood leaving the tissue at a point must be some function of the tissue temperature at that point. No data are available on the extent of thermal equilibration between capillary blood and surrounding tissue; presumably the physical conditions of the capillary circulation favor almost complete equilibration. After the introduction of an equilibration constant, k , which is assumed uniform throughout the tissue:

$$\text{Eq. 2} \quad \theta_v = \theta + k(\theta_a - \theta) \quad 0.0 \leq k \leq 1.0$$

Substituting in *equation 1*:

$$\text{Eq. 3} \quad h_b = V \cdot s(k - 1)(\theta - \theta_a)$$

Equation 3 states that the rate of heat transfer from blood to tissue at any point is proportional to the difference between arterial blood and tissue temperature at that point, since $V \cdot s(k - 1)$ is a constant in the steady state. θ_a is considered uniform throughout the tissue; the introduction of mean capillary blood temperature into *equations 2* and *3*, although physically indicated, would render the analysis incapable of being tested with the experimental data. However, the more complete the equilibration between capillary blood and tissue, the closer k approaches 1.0 as its limiting value. If equilibration is complete, then *equation 3* reduces to the following exact expression:

$$\text{Eq. 4} \quad h_b = V \cdot s(\theta_a - \theta)$$

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d) The tissue specific thermal conductivity K will be taken as uniform throughout the forearm. This is supported by the value of 0.0005 found by Hardy and Soderstrom for beef muscle and fat (18) and the same value obtained by Lomholt for skin (19). K for most materials has a measurable temperature coefficient. The data of Lomholt at the physiological range of temperature indicate that this coefficient is negligible (19). According to Bordier, the spongiosa of bone has a conductivity which is approximately 1.7 times that of muscle (20) so that the presence of bone in the forearm makes the assumption of uniform conductivity only partially true.

e) The Newton cooling law will be applied to the heat transfer between forearm skin and environment. The data of Hardy and Soderstrom indicate that this law is followed by the nude, basal body lying on a mesh hammock in still air at calorimeter temperatures of 23.0 to 28.0° and relative humidity of 25 per cent (18). Heat loss from the forearm skin by conduction must have been a negligible factor in this study because the limb was in air except for the contacts at the elbow and hand. Since the environmental temperature range in the laboratory was small, the Newton cooling law is not being made to apply over a wide range of environmental factors, but merely to apply to the experimental conditions. The value of the cooling coefficient will be taken as 0.0001 from the data of Hardy and Soderstrom (18); the evaporation heat loss from forearm skin will be taken as 21 per cent of the total heat loss, the figure obtained for the whole body by these authors (18).

The general differential equation of heat conduction is in cylindrical coordinates:

$$\text{Eq. 5} \quad \text{cp} \frac{\partial \theta}{\partial t} = -K \left[\frac{\partial^2 \theta}{\partial r^2} + \frac{1}{r} \frac{\partial \theta}{\partial r} + \frac{1}{r^2} \frac{\partial^2 \theta}{\partial \phi^2} + \frac{\partial^2 \theta}{\partial Z^2} \right] + h_m + h_b$$

Since this analysis deals only with the steady state, the left hand side becomes zero. The gradient along the long axis of the forearm has been shown to be negligible (see section II), eliminating $\frac{\partial^2 \theta}{\partial Z^2}$; the angular gradient

$\frac{\partial \theta}{\partial \phi}$ will also be taken as zero in view of the approximate circular symmetry of the mean curve of figure 16. The equation to be solved becomes:

$$\text{Eq. 6} \quad -K \left[\frac{d^2 \theta}{dr^2} + \frac{1}{r} \frac{d\theta}{dr} \right] = h_m + h_b$$

If both h_m and h_b were uniform throughout the cylinder, the distribution of temperature would be parabolic and given by the functions (after appropriate boundary value substitutions):

$$\text{Eq. 7a} \quad \theta = \theta_0 - \frac{(h_m + h_b)}{4K} r^2$$

where θ_0 = temperature at the axis; or by

$$\text{Eq. 7b} \quad \theta = \left[\theta_s - \frac{(h_m + h_b)}{4K} R^2 \right] - \frac{(h_m + h_b)}{4K} r^2$$

where θ_s = temperature at surface of cylinder. Since h_b is given by *equation 3* as a function of θ , the differential equation to be solved is (instead of *equation 6*):

$$\text{Eq. 8} \quad \frac{d^2\theta}{dr^2} + \frac{1}{r} \frac{d\theta}{dr} + a\theta = b$$

which is a Bessel's equation of zero order in which

$$a = \frac{V \cdot s(k - 1)}{K} \quad b = V \cdot s \frac{(k - 1)\theta_s - h_m}{K}$$

and both a and b are numerically negative constants. The physically pertinent solution of *equation 8*, after appropriate boundary condition substitution, is:

$$\text{Eq. 9} \quad \theta = \frac{\left(\theta_s - \frac{b}{a} \right) J_0(i \sqrt{a} r) + \frac{b}{a}}{J_0(i \sqrt{a} R)}$$

in which J_0 is Bessel's function of an imaginary variable, of zero order and the first kind, $i = \sqrt{-1}$, and the absolute value of a is used in the expression \sqrt{a} . In order to plot this function, θ_s (surface temperature) must be obtained from the Newton cooling law, which is:

$$\text{Eq. 10} \quad -K \frac{d\theta}{dr} = E(\theta_s - \theta_E)$$

where θ_E = the environmental temperature (the air and walls of the laboratory being at the same temperature). Applying *equation 10* to *equation 9* and solving for θ_s :

$$\text{Eq. 11} \quad \theta_s = \frac{b}{K\sqrt{a} [-iJ_1(i\sqrt{a}R)] + 1.21EJ_0(i\sqrt{a}R)\theta_E} \cdot \frac{K\sqrt{a} [-iJ_1(i\sqrt{a}R)] + 1.21EJ_0(i\sqrt{a}R)}{K\sqrt{a} [-iJ_1(i\sqrt{a}R)] + 1.21EJ_0(i\sqrt{a}R)}$$

in which J_1 is Bessel's function of an imaginary variable of the first order and first kind.

In figure 16, the lowest curve has been plotted for a forearm in which blood flow is assumed to be absent and in which the only heat source is local tissue heat production (h_m). The value of h_m had been calculated as 0.0001 from the data of Asmussen *et al.* and Holling on the O_2 consumption of

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skeletal muscle in resting man, taking the respiratory quotient as 0.82 (21, 22). Equation 7b was used in construction of the plot with h_b equal to zero; θ_s was calculated by the Newton cooling law. By use of equations 9 and 11 in which $h_m = 0.0001$ the dotted curves of figure 16 were plotted to give as close an approximation as possible to the mean experimental data. The arterial blood temperature, not being measured in these subjects, was

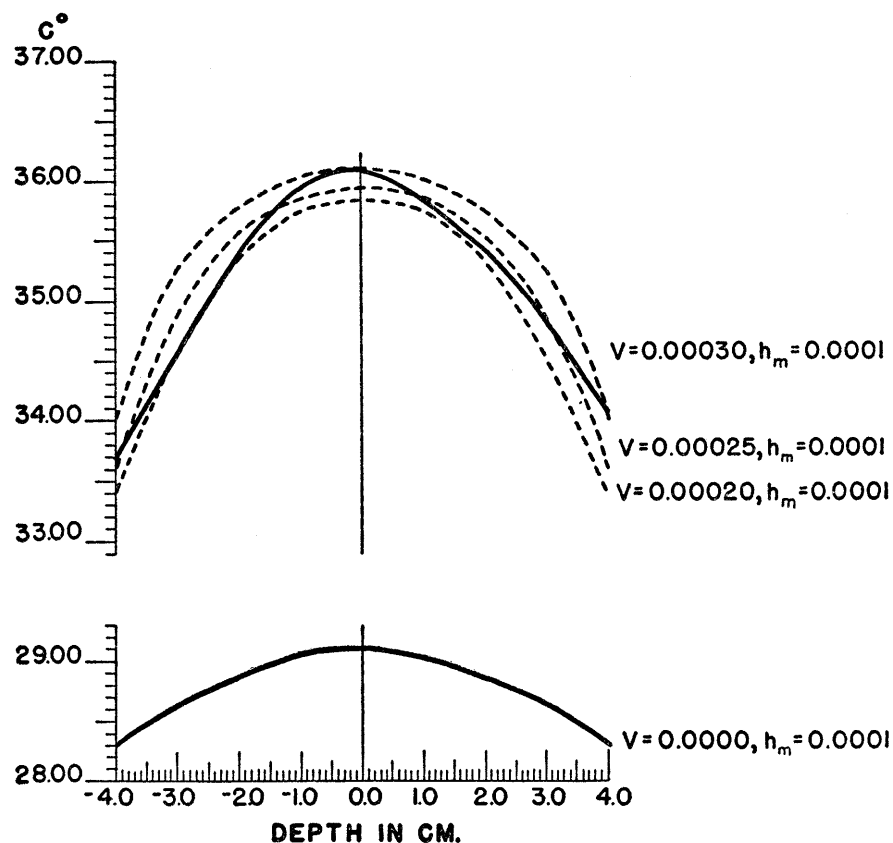


Fig. 16. MEAN EXPERIMENTAL and theoretical curves.

taken at 36.25° or 0.16° higher than the mean maximum tissue temperature in correspondence with the subjects of section V; mean room temperature of 26.6° was used in equation 11; full equilibration ($k = 0.0$) between blood and tissue was assumed. The experimental curve was most closely approximated when the blood flow V was assigned values from 0.0002 to 0.0003 gram per cm^3 per second. These necessary values of V correspond quite closely to the range of 0.00025 to 0.0005 found by Abramson *et al.* (23) and Barcroft and Edholm (24) using plethysmographic technique on the forearm. If partially incomplete equilibration is assumed between blood and tissue ($k = 0.25$), then the values of V most nearly satisfying the mean curve become 0.0003 to 0.0004; in the unlikely event that equilibration is very

incomplete ($k = 0.50$), V becomes $0.0004-0.0005$ gram per cm^3 per second. The causes of the deviation between the mean experimental curve and the theoretical curves must be numerous. The assumed uniformity of h_m , V and k must be contributory but experimental check on these assumptions is not possible with existent techniques. It is possible that the venous return from the distal portion of the extremity modified the deep tissue temperature distribution considerably.

DISCUSSION

Hardy and Soderstrom (18) and Gagge, Winslow and Herrington (25) have analyzed the relationship between rectal and mean skin temperatures and total heat loss from the body surface in calorimetric experiments on man. In their analyses, the calculated thermal conductance of tissue is considered to be a function of the peripheral blood flow, the physical thermal conductivity of the tissue (and the depth of gradient in the theory of Gagge *et al.*, 25). These authors' conclusion that the peripheral blood flow cannot be a significant factor in heat loss from the skin at the experimental range of room temperatures is not supported by the present analysis. Granted that the values of human skeletal muscle O_2 consumption given by Asmussen *et al.* (21) and Holling (22) are even approximately correct, then the rate of tissue heat production is much too small to sustain the level of the observed temperature distribution in the forearm. On the basis of the above analysis, a blood flow of 0.0002 to 0.0004 gram per cm^3 per second is needed to raise the level of the theoretical distribution to that of the experimental curve; moreover, the values of the blood flow calculated by theory coincide very closely with those obtained by others experimentally (22, 23). With a flow of 0.0003 at full thermal equilibration and a rate of tissue heat production of 0.0001 , only 25 per cent of the total heat lost from the surface of the proximal forearm would be that produced by local metabolism.

The conclusions drawn from calorimeter experiments are based on mean data for the body surface and the particular thermal relationships found for the forearm do not necessarily apply elsewhere. Gagge *et al.*'s calculation (25) of a mean depth of gradient of 2.2 cm. likewise does not find experimental confirmation in the forearm. An important feature of that calculation, namely the assumption of a peripheral blood flow of zero, obviously is one major source of difficulty. The theoretical blood flow-tissue metabolism curves of figure 16 are almost true parabolas because the infinite power series defining the Bessel's function of zero order and first kind converge so rapidly at the physiological range of values of the constant

$a = \frac{V_s(k-1)}{K}$ that all terms after the r^2 term become negligible. These

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theoretical curves deviate most from a perfect parabolic distribution at the periphery of the cylinder, i.e., as r increases. Burton and Bazett (26) explained the 'paraboloid' character of Bazett and McGlone's data (1) on the basis of *equation 5a* or *5b*, but the above analysis of the blood flow effect leads to a more complete interpretation. The curves of Bazett and McGlone (1) taken in cool environments show a lower level and in addition a steeper initial slope than those taken in warmer environments. This may be accounted for in theory by the fact that reduction in blood flow has the effect of causing an increase in slope at the periphery as well as a reduction in level of the entire curve; in other words, as the blood flow increases the calculated curves become flatter and approach arterial blood temperature but cannot exceed that temperature.

It is apparent that if the blood flow be known, the determination of the tissue temperature distribution and brachial arterial temperature would permit a tentative calculation of the rate of forearm heat production which is subject, however, to the important assumptions already discussed. These assumptions, principally the uniformity of heat production and blood flow, cannot be explored experimentally at present. More extensive analytic study of these assumptions would involve the solutions of differential equations in which both the local rate of tissue heat production and blood flow become functions of the distance from the axis of the limb. Elimination of the necessity for use of the Newton cooling law could be attained by immersion of the forearm in a constant temperature water bath; this would also possess the advantage of rendering the skin surface virtually isothermal with possibly better circular symmetry of the individual curves. In addition, interruption of the distal venous return might also yield individual curves more susceptible to analysis. However, until such simplifying steps are taken, a further complicating theory in the analysis of the curves is not justified.

SUMMARY

The cutaneous topography of temperature in the upper extremity has been determined with reference to the presence of gradients and to the effects of blood flow on the proximal forearm.

Simultaneous rectal, brachial arterial blood, and deep forearm temperatures have been measured. Under the condition of these experiments the blood flow acts as a warming agent not only to the superficial tissues but to all the forearm tissue between skin and axis of the limb.

Steady-state tissue temperature-depth distributions have been determined and the analytic theory of heat applied to evaluate the effects of local heat production and circulation.

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