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HEAT TRANSFER MEASUREMENT IN LIVING SKIN

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Measurements of temperature gradients and heat flow in the superficial skin layers are of importance in the study of body heat regulation. Though skin seems accessible, difficulty is found in making temperature measurements. Skin is very thin; often epidermis is less than 0·05 mm thick on the limb surfaces, there are large changes in skin properties in a small depth of tissue and rapid changes in vessel size and blood flow may follow minute damage. For these reasons an exploring thermocouple must be small compared with epidermis and should cause little physical change on insertion or local heat flow will be affected.

It is difficult to make couples to this standard from easily obtained materials, since commercial wires are usually from 0·01 mm upwards in diameter and the finer wires are too fragile and flexible to use without support. Usually they are platinum alloys with low thermo-electric e.m.f. The smallest couple which could be made is thus 0·02 mm in diameter, and larger if supported strongly enough for insertion into skin.

Previous work (Bazett & McGlone 1927; Bazett, 1941, 1949; Mendelsohn, 1936), while demonstrating the presence and general form of the temperature gradients, has suffered inevitably from these difficulties. Needle-mounted couples of 0·3–0·8 mm diameter had to be used. Conduction stem errors large enough to be calculated and of a similar order to the differences being measured have had to be allowed for in some cases. This calculation can only be done approximately or empirically, as the physical system is too complex to allow rigorous treatment. (It involves two media, both non-homogeneous, one of which may vary in time. These media interact in three dimensions.) Also, although stem errors near the surface may be allowed for, those occurring in deeper tissues, where the gradient is steep or changing in direction, cannot be estimated.

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Attempts have been made to measure temperatures in the most superficial 2 mm of skin with couples 0·3 mm thick with soldered junctions of the same order of length (Bazett & McGlone, 1927; Mendelsohn, 1936). Though every care has been taken to minimize skin damage and the gradients obtained were shown to differ in degree from those where damage was great, it seems likely that they must represent somewhat inflamed skin. The couples used had diameters many times those of the largest vessels in the outer layers. Another difficulty has been the estimation of skin heat flow exactly at the site and time of estimation of a temperature gradient. Pennes (1948) gives evidence from his own and other work of the great variation of surface temperature from point to point over small areas of skin. This has been fully confirmed by the method to be described later in this paper. For this reason, and also because skin temperature locally may change with time in a subject exposed for a long period to a constant environment, it is necessary to measure heat flow at the site of thermocouple entry. The couple should therefore not be inserted obliquely, as is sometimes done to avoid stem errors. Frequent readings of skin heat flow need to be taken during an experiment, for if it changes between gradient readings the apparent form of the gradient will be affected.

An attempt has been made to overcome these difficulties by devising a very small thermocouple surrounded by a heat-flow measuring device. This paper comprises an account of the construction and performance of this system.

METHODS

The thermocouple

The thermocouple (Vere, 1955) is designed to be very small yet rigid, with a stem conduction error smaller than the experimental error from other causes. It can be passed into a hair follicle, or a large sweat or sebaceous gland. Couples of 0·05–0·03 mm diameter may be passed into skin along the track of a puncture by a glass fibre of the same size causing relatively little damage.

General structure. The general arrangement of the couple is shown diagrammatically in Fig. 1. The couple is formed between a bismuth-antimony alloy in a fine glass capillary and an outer coating over this of Wood's metal. The exploring junction lies at the tip of the capillary. Thermoelectric currents are led away through copper wires joined respectively to the two alloys at the upper, broad end of the glass capillary. These junctions are surrounded by a constant-temperature bath and constitute the reference junctions. All metal surfaces are insulated electrically with a thin layer of rubber.

Method of construction. New and carefully cleaned soda glass tubing of about 6 mm diameter and 0·8 mm wall is drawn down to 1–2 mm diameter. Its composition seems to be critical, as good results have been obtained only with certain types of glass (Osram–G.E.C. 'Wembley' X8 soda glass). A little of one of the Hutchin's alloys (Bi 97, Sb3 parts; Firestone, 1930) is melted in a Pyrex boiling tube. While the drawn-down glass capillary is still hot some of this bismuth alloy is drawn into it with a rubber suction bulb. Before it cools the metal-in-glass capillary so made is further drawn down in stages till it is about 0·3 mm diameter. It can be heated to bright redness without damage. When it is 0·5 mm or less in diameter it may be allowed to cool with only a few small cracks occurring in the glass. Larger capillaries shatter on cooling. A few small cracks are unimportant; they seal over during the next stage. A fine tinned copper wire is melted into the alloy at one end of a suitable piece of capillary, which has been filled with alloy in the way described. The capillary is then heated, about 2 cm from the seal to the copper wire, in a microburner with a minute flame. When bright red hot the capillary is quickly pulled out into a very fine capillary, the broad end near the copper being returned quickly to the flame after this manœuvre and passed through the flame again rapidly towards the copper wire. In this way the alloy solidifies last at the broad end and forces due to solidification of the alloy do not crack the glass where the capillary diameter varies sharply.

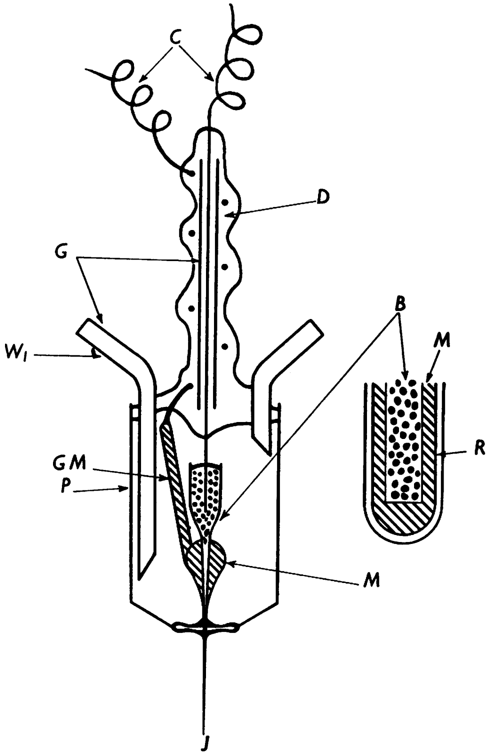

Fig. 1. Diagram of the general arrangement of the thermocouple. The rubber coat covering structures in the reference junction bath is omitted for simplicity. Inset, tip of couple enlarged. *B*, bismuth alloy in glass capillary; *C*, copper wires; *D*, 'Durofix' cement; *G*, glass tubes; *GM*, glass coated with Wood's metal; *J*, exploring junction; *M*, Wood's metal; *P*, paper reference-junction box; *R*, rubber; W_I, water inlet.

The fine end of the capillary is then placed in a drop of melted Wood's metal (m.p. 70° C) on a heated light alloy block. This block (2 × 1 × 0·5 cm) is surrounded by a copper shim apron to ensure even heating and avoid contact of hot fumes with the capillary. The capillary is broken off in its finest part, under the melt (to avoid exposure to air) and about 2 cm from its broader end. It is then pushed through the melt till its narrow end protrudes and its stem is coated with Wood's metal nearly up to the broad end but not over it. This is because small cracks in the glass here short-circuit the couple when the melt is carried over them. The exploring thermal junction is made at the capillary tip between the inner alloy and the Wood's metal coat. If a junction is not formed at once it is due to a fault in the alloy core. A little more capillary is then broken off in the melt and so on till a good junction is made. Oxide quickly forms on the melt, which must be cleaned frequently by drawing a razor blade across its surface.

The formation of the junction is simplified by connecting a microammeter between the light alloy block and the copper wire fused into the capillary. Formation of a good junction is shown on the meter by the large thermal current produced. Good junctions are not formed if the light alloy block is dirty or too cool, when crystals can be seen in the melt. If it is too hot the melt will not coat the glass. It should be just hot enough to melt all the crystals and not more. When a junction forms, the couple should be finished quickly, as sometimes if it is kept hot the resistance rises slowly and the junction becomes unstable. The capillary is pushed once or twice through the melt to coat it thoroughly and then withdrawn and cooled. Inspection in a good light shows any small irregularities as bright spots. They are removed by a few rapid passes through the melt. It seems likely that sputtering or evaporation methods would simplify this stage greatly, but they have not yet been tried.

The couples are completed by passing the copper wire inside a glass supporting tube (about 3 mm external diameter). A second copper wire, wound round this tube, is pushed into the end of a fine empty glass capillary which is led to the Wood's metal coat on the couple capillary (Fig. 1). This empty glass capillary is then covered with Wood's metal from the coat on the couple to the second copper wire. There are now three metallic junctions, one between the two alloys at the tip of the capillary and two others, the reference junctions, about 4 cm from the tip, each between one alloy and a copper wire. The glass support tube and the copper wires are coated and secured with 'Durofix' cement. A thin Perspex fin is mounted in the cement covering the glass supporting tube, to be gripped by a micro-manipulator. The connexions of the fine copper wires to the leads of a mercury switch are encased in a single block of 'Plasticine' to protect them from small temperature differences.

The whole couple up to the glass support is electrically insulated and water-proofed by dipping once in thin rubber solution. If the couple is held point up after dipping, only a very thin coat is left on the tip. A second heavier application of rubber is made over the reference junctions and broader parts of the couple. The couples are inspected and their diameters measured under the microscope. The metal coat should be smooth with only small variations in diameter (Fig. 2).

Couples last for many months if well made. They can be completed in 15 min with practice. Broken ones may be remade by cleaning the tip with petroleum ether and dipping again in Wood's metal after breaking a little off the tip with a razor blade.

Reference junctions. These are surrounded by a water-bath through which a steady flow of water is led from a constant-temperature vessel through a short, heavily lagged rubber tube. The bath is made of paper, 'Durofix' and plastic tubing (Fig. 1).

Properties of the couples

(1) They are very small, being easy to make over the range 0·05–0·005 mm in diameter.

(2) The thermo-electric e.m.f. is high (about 58 μV/° C). This overcomes in part the disadvantage of high internal resistance of small couples.

(3) The calibration (Fig. 3*a*, *b*) is almost linear over the range 10–40° C. Lower temperatures have not been explored. Above 45° C the junction may become unstable. Fig. 3*a* shows results over a wide range of temperature with a 400 Ω series resistor in circuit. Fig. 3*b* shows results over a smaller temperature range without a series resistor.

The couples are calibrated by dipping their tips into a glycerol bath in a large brass block containing a mercury-in-glass thermometer reading to 0·05° C directly and to 0·01° C by interpolation. The block is placed in stirred water in a Dewar flask. The normal practice of immersing a good length of the couple in the medium cannot be followed here. Great instability results from air convecting from the glycerol surface up towards the reference junctions. This is not a conduction stem error. It is completely removed by covering the exposed stem with cotton-wool. In

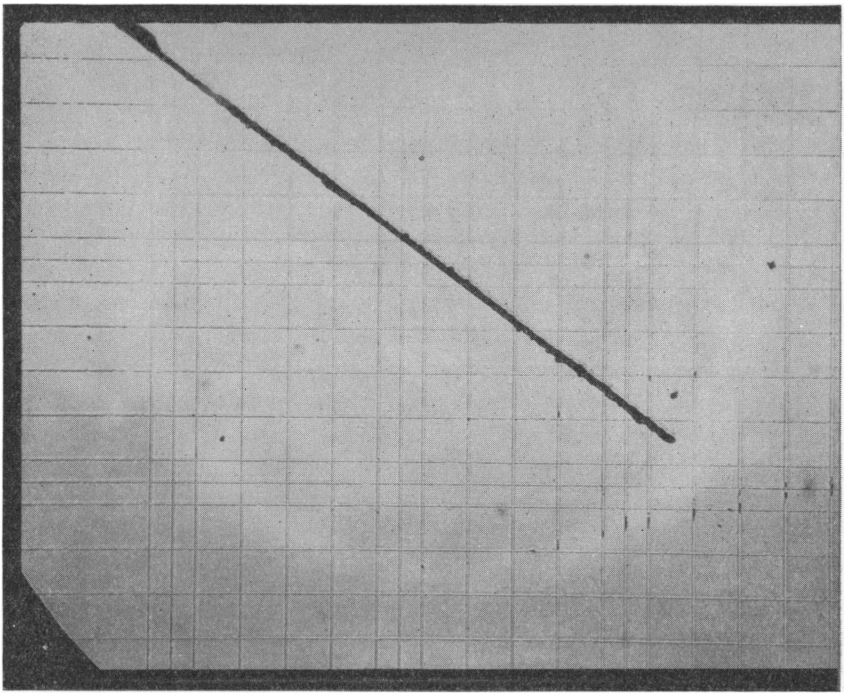

Fig. 2. Photograph of the tip of a thermocouple 0·006 mm diameter mounted on a red cell counting graticule.

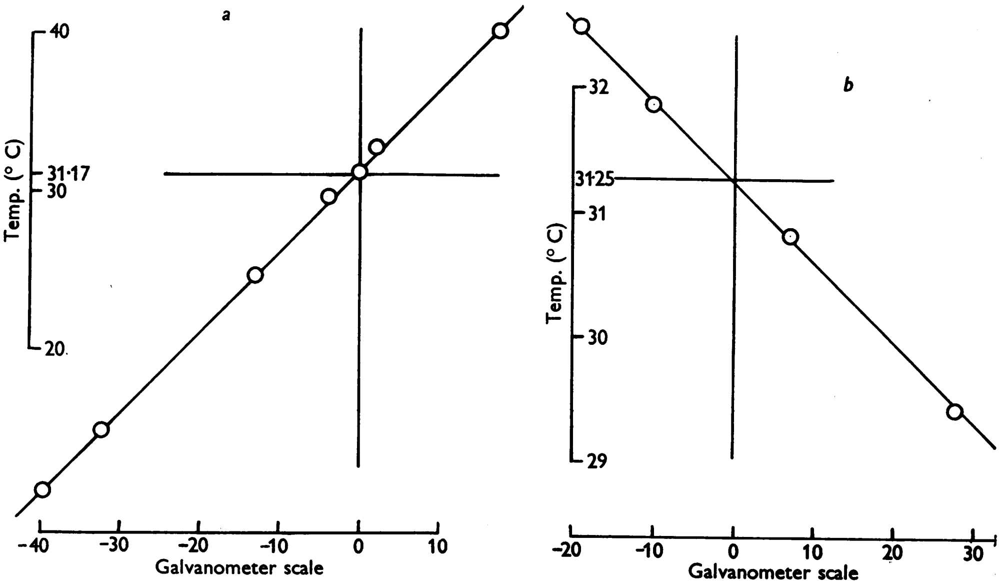

Fig. 3 (*a*) and (*b*). Calibration graphs for alloy thermocouples. The crossed lines represent the temperature of the reference junction bath and the galvanometer zero. The conditions of the experiments are given in the text.

use on skin this difficulty is overcome by surrounding the lower part of the stem with a water 'flow-box' to be described.

The apparatus used in this and all the other experiments described was as follows. The galvanometer was a 'Cambridge Spot' model. Its sensitivity was 7·2 μA for 100-scale division deflexion. One scale division was 1·6 mm. It could be read by interpolation to 0·1 scale division. Its internal resistance was 27 Ω and the suspension period 2·6 sec. Though the external critical damping resistance was 88 Ω, lower resistances were usually in circuit and readings were taken only in the steady state. All lead wires ran to a mercury switch, their soldered contacts all being in the same paraffin bath. The reference junction bath was supplied from a constant-temperature bath controlling the temperature to 0·01° C; water came from this at a constant pressure head and returned to it through a filter pump powered by compressed air.

(4) The structure is based on a glass cylinder. This gives great strength for lateral bending stresses. It is rigid and rapidly straightens after bending, which is not true of fine wires.

(5) The coaxial structure minimizes parasitic e.m.f. because surrounding fluids can reach only one metal and the two elements of the couple pass through almost identical electrical and thermal fields. However, an insulating coat is essential, as large contact potentials develop between Wood's metal and solutions.

(6) The exploring junction is planar and normal to the axis. There is no junction error such as occurs with long soldered junctions of wire couples where the exact site of generation of potential is uncertain.

(7) The thermal conductivities of all the couple materials are far lower than those of common metals, the Wood's alloy, glass and Hutchin's alloy having conductivity of 0·032, 0·002 and 0·02 cal/cm. ° C. sec respectively. This, together with the very small cross-section, minimizes stem conduction error.

The thermocouple stem errors. These are due to conduction of heat along the couple and are of first importance where only a short length of the couple stem is immersed. It was decided that calculation or even empirical determination of these errors was not an accurate way of allowing for them, and that it would be preferable to employ couples whose stem errors in use were smaller than the experimental error from other causes.

Stem errors were studied using a heated copper plate covered with soft paraffin 2·6 mm deep (k paraffin = 0·00044 cal/cm. ° C. sec) (Fig. 4). A temperature gradient of about 10° C was held across the paraffin by running water at constant temperature and rate of flow across the surface. This gradient was assumed to be linear. Thermocouples held in a micrometer clamp were inserted through the water into the paraffin.

Fig. 5 shows the results of two experiments from a number made with the apparatus in a room at between 24·5 and 25·5° C with no artificial air movement. The curve on the right shows results with a couple 0·090 mm diameter. A substantial stem error is seen (about 0·2° C at worst). As the couple passes deeper into the paraffin this error disappears and the points come to fall on a line which passes through the paraffin surface intercept. No such error is seen with a couple 0·025 mm in diameter (on the left of the figure), the point farthest from the regression line of all points in paraffin being 0·36 scale division (0·06° C) from it. This is a doubtfully significant deviation (standard deviation of all points is 0·15 scale division, $t_{22} = 2·4$; $0·05 > P > 0·02$), but may represent a minute stem error since the point concerned is at the depth where maximal error would be expected. The intercept with the paraffin surface is not significantly away from the lines ($t_{22} = 1·3$; $0·5 > P > 0·2$). In other similar experiments couples of 0·07 and 0·050 mm had demonstrable errors, but smaller than the 0·090 mm couple. A 0·022 mm couple showed no error.

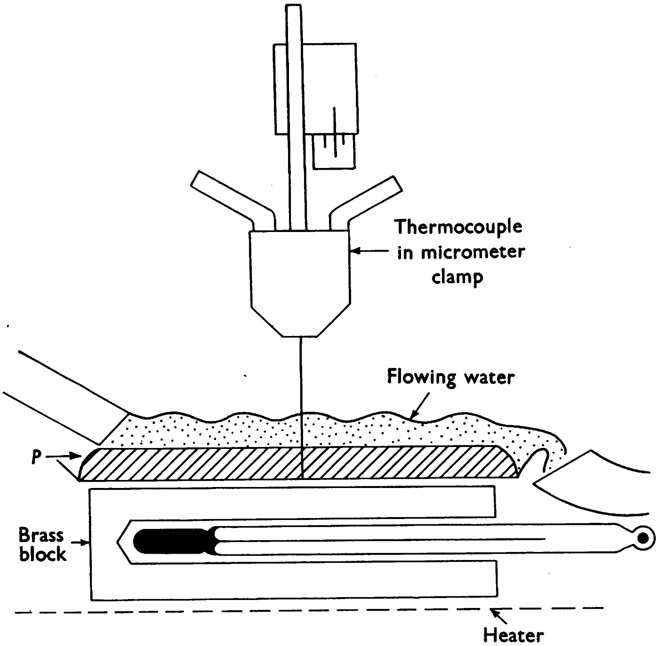

Fig. 4. Apparatus arranged for estimation of thermocouple stem errors. The thermocouple is lowered into a layer of paraffin, *P* (on copper plate), across which a constant temperature gradient is held; see text.

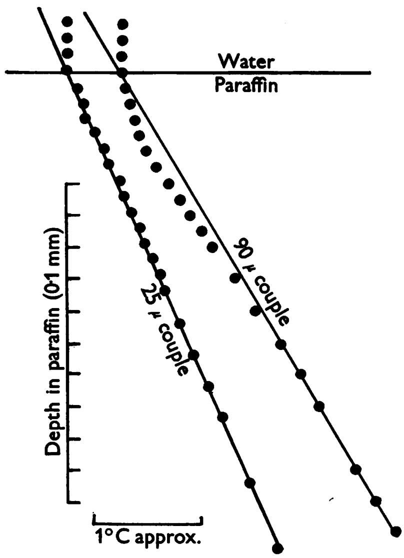

Fig. 5. Recorded gradients in the paraffin plate. The ordinates represent depths in paraffin and the abscissae galvanometer deflexions. The temperature scale indicating the order of errors is approximate, as the calibration of the galvanometer differed a little for the two thermocouples.

These conditions are much more stringent than those for skin, as its conductivity (discussed by Hardy & Soderstrom, 1938; Burton & Edholm, 1955; and Pennes, 1948), is greater than that of paraffin and its temperature gradient in ordinary conditions about one tenth that of these experiments. For these reasons 0·025 mm couples may be used in skin and their stem errors ignored for accuracies of 0·05 °C and 0·05 mm. It would probably be safe to use larger ones but this has been avoided where possible. It seems likely that a 0·040 mm couple would have a worst error of about 0·05° C in skin. The results of an experiment in paraffin covered by still air are shown in Fig. 6. The stem errors in air have not been as fully investigated as for water, as the couples were not to be used in air. Clearly stem errors should be assessed in every different thermal case and no couple can be considered free from error in all situations. Calculation of stem error by 're-laxation' methods and simplified heat-flow equations was attempted. The results in general agree with those from the paraffin plate, but the labour of calculation is prohibitive.

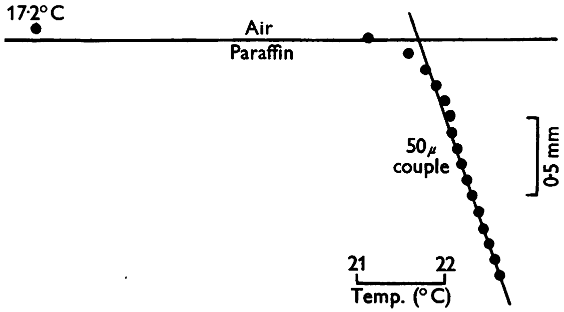

Fig. 6. Estimation of thermocouple stem errors by progressive immersion in paraffin. Recorded gradient with air above the paraffin plate.

The insulating coat. The rubber coat is very thin and seems to interfere little with thermal performance. Were it more thickly applied, however, it would probably worsen stem errors. The rubber is not entirely satisfactory as firm rubbing on skin may damage it, lowering the resistance. It was, however, found to be much superior to 'Durofix', Perspex in chloroform or polystyrene in ethyl acetate. It was difficult to measure the coat resistance directly, but Wood's metal rods coated in the same way as the couples and dipped into 1% saline solution had a coat resistance of about 7×10^5 Ω. Touching on skin did not lower this. Very firm repeated pressure lowered it to about 10^5 Ω and scraping roughly across the skin broke through the rubber completely.

Thermocouple resistance. Fig. 7 shows couple resistances plotted against diameters. The resistance depends mainly on the cross-section and length of the narrowest part, the latter being approximately constant. The resistance scale shown is reciprocal and the diameter scale represents a square function.

The thermocouples in use

It has been pointed out that during calibration the exposed stem of the thermocouple must be surrounded by cotton-wool to damp down air currents which cause instability. In the determination of temperature gradients in skin, however, the exposed stem is surrounded by a constant-temperature water-bath which is used to control and measure the heat loss from the skin surface. The temperature of the water in this bath (which will be called the 'flow-box' to distinguish it from the couple reference-junction bath) is adjusted till on touching the skin with the box no change in local skin temperature occurs. This is determined by a copper–constantan couple of Y shape lightly stretched over the skin so as just to indent its surface at the site of contact of the bath. This couple is similar to the design described by Bazett & McGlone (1927) and discussed by Pennes (1948) and Mendelsohn (1936). If the skin surface temperature remains the same it seems likely that no thermal change will occur in the tissue beneath it.

The flow-box is formed from a cylindical Perspex box (approx. dimensions: wall 1, external diam. 18, height 15 mm). Into the base is inserted a Hatfield-Turner heat-flow disk (Hatfield & Wilkins, 1950; Hatfield, 1950; Holti, 1955). Box and disk are divided along a vertical diameter into symmetrical halves. each half of the box holding one half of the disk: the thermo-electric e.m.f. from the latter is led from one half only.

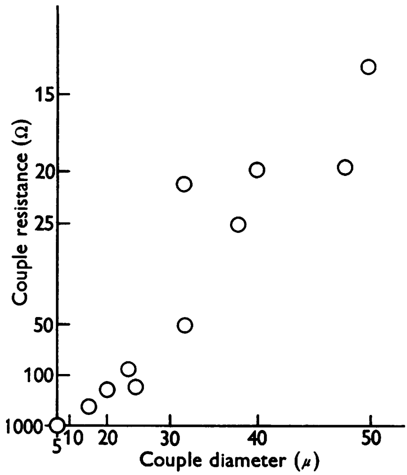

Fig. 7. Thermocouple resistance as a function of diameter. The lowest point represents 7000 Ω and 0·005 mm diameter. The resistance scale is reciprocal and the diameter scale represents a square function.

Each half of the box is provided with two arms projecting horizontally at the level of the upper end in the plane of division (Fig. 8*a*), for clamping the box to a Perspex plate on which the micromanipulator is mounted (Fig. 11). At one extremity the corresponding arms of each half are hinged together (Fig. 8*b*): the other pair of arms can be drawn together by a screw (not shown), thus approximating the two halves of the box. The slit in the centre of the lid is widened into a lanceolate aperture, on each side of which are two openings for the circulation of water. The inner wall of each half of the box is made of rubber hydrochloride 0·0015 in. (0·038 mm) thick. The two halves are held on the Perspex plate which forms the base of the micromanipulator, so as to embrace the stem of the thermocouple after it has been passed into the skin: the screw then approximates the two halves till they almost touch (Fig. 8*c*).

Water from the couple reference-junction bath is led through the box, holding it at constant temperature very close to that of the reference junctions. The rubber walls touch the stem of the couple over a large area. This ensures that heat loss up the stem occurs to a sink of constant known temperature, large size and known distance from the tip. Three thermocouples are used with the box. They are the heat-flow disk itself, a fine copper–constantan junction, calibrated before incorporation and placed in the water, and the movable Y-shaped junction already mentioned. It was found that a couple fixed under the box gave erroneous readings of skin temperature. This is discussed later. The flow-box couple was of 44 s.w.g. copper and 36-gauge constantan thinned for its last inch to 44 s.w.g. in nitric acid. The skin Y couple was of 32 s.w.g. wires. The leads were short and unjointed. The reference junctions were in a tube of liquid paraffin in the constant-temperature bath.

The advantages of the flow box are thought to be as follows:

(1) The heat-flow disk gives a most sensitive measure of heat flow from the skin at the site of thermocouple puncture.

(2) By covering the surface, air-flow errors are removed.

(3) Heat flow up the couple may be stabilized and estimated.

(4) Local conditions are stabilized for a time, allowing more accurate thermal gradients to be found.

(5) All the parameters may be found for direct measurement of the thermal conductivity of skin layers.

The disadvantage is that the presence of the box interferes with radiant heat exchange and evaporation from the skin, so that if sweating begins or ends during an experiment a false idea of total skin heat loss will be obtained. If sweating is occurring before the box is applied, the total heat loss will be unaffected by the presence of the box since the heat flow from the deep tissues to the surface is determined by the surface temperature and does not depend on the nature of the heat exchange at the surface.

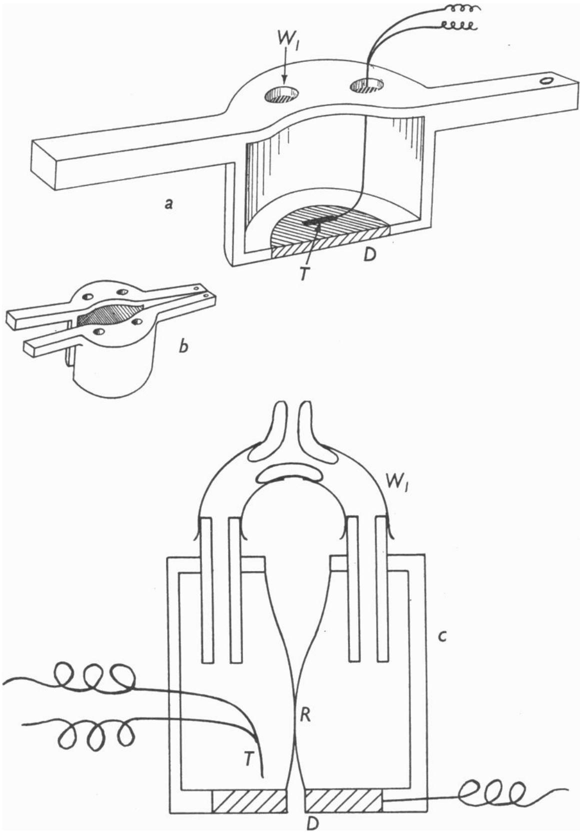

Fig. 8. The flow-box. *a*: one half of flow-box, with rubber membrane of inner wall removed; W_I, water inlet; *D*, heat-flow disk; *T*, flow-box water thermocouple, just above disk—in practice the wires to the water thermocouple lie in the water for over 2 cm of their length. *b*: the two halves assembled for use. *c*: section across two halves of box; *R*, rubber hydrochloride membrane.

The calibration of the flow-box was made in two ways. First the thermocouples were calibrated with known temperature differences between the box and its surroundings, and secondly with known heat flows through its base. The box was placed with the heat-flow disk just on the surface of a well stirred constant-temperature water-bath. The graph (Fig. 9) shows the calibration results with water at constant temperature flowing through the box. The regression coefficient of galvanometer readings on temperature difference across the plate was 58·7. On the stirred bath the plate is less stable than on skin. However, the standard deviation of the readings from the regression line shown is 0·045° C. On skin the standard deviation of repeated results over 10 min is of the order of 0·01° C. The regression coefficient for the calibration of the copper–constantan couple in the flow-box water was 11·9 scale divisions/° C. The standard deviation of one reading was 0·03° C under calibration conditions.

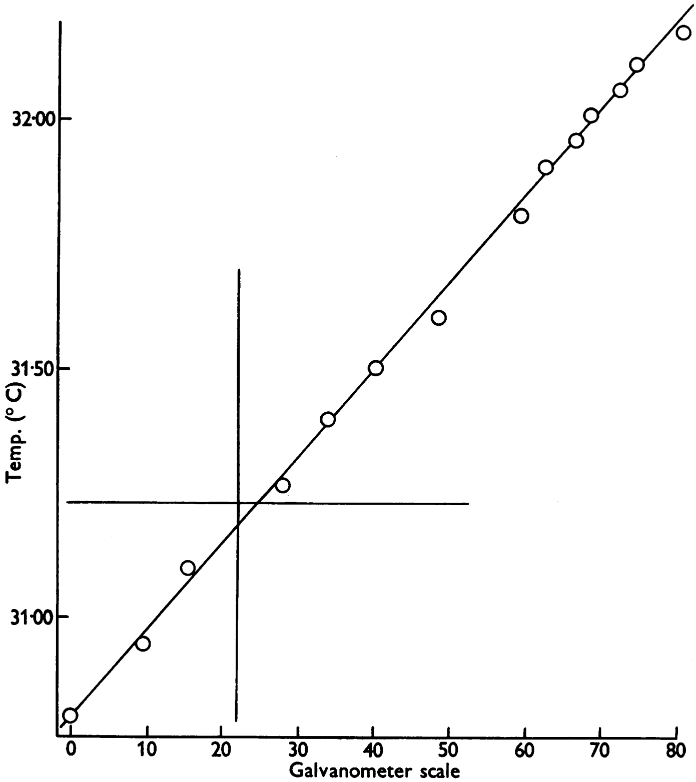

Fig. 9. Heat-flow disk calibration graph for differences of temperature across the disk. The crossed lines represent the temperature of the water in the flow-box and the zero of the short-circuited galvanometer.

Fig. 10 shows a similar graph but with temperatures recorded within the flow-box water. The box temperature is affected by heat flow through the base to a measurable amount only when the heat flow is large compared with that to be expected from skin in ordinary circumstances. (The results are offset a little from the origin owing to cooling of the water reaching the box after leaving the constant-temperature bath at 28·50° C.) Normally the water is only about 0·5° C below skin temperature. In spite of this rise in cooling water temperature it will be seen that there is no measurable non-linearity of heat-flow disk calibration over a range even beyond its normal use.

To calibrate the box with known heat flows a second Hatfield heat-flow disk was used. This was mounted to coincide with the disk in the base of the box. A layer of thin cloth soaked in glycerol made good thermal contact between the disks. The water flowing through the box was held at a steady temperature while readings were taken with the heat-flow disk of known calibration placed in circuit with the unknown disk and the galvanometer. The known disk was turned over during each experiment so that for each temperature setting of the box a sum and a difference of the e.m.f. produced by the disks was obtained. From these and the galvanometer zero the ratio was obtained between the currents from the two disks for a given heat flow identical for both. The calibration of the box disk was 4·23 μV for a heat flow of 10^{-4} cal/cm^2.sec.

The full assembly for a skin experiment is shown in Fig. 11. After the box temperature has been set, the Perspex plate is strapped in position on the skin with adhesive plaster. Then the thermocouple is inserted into the skin with the fingers via a hair follicle or glass-fibre puncture after the micromanipulator has been aligned with its direction of insertion. The couple is then clamped in the micromanipulator. (The micrometer used was graduated in 0·05 mm.) The flow-box is then placed round the couple. The exposed thermocouple stem is surrounded with cotton-wool above

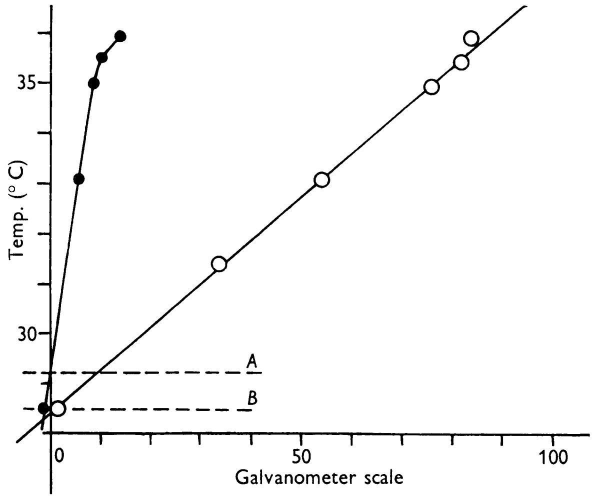

Fig. 10. Graph showing readings of the heat-flow disk (○) and flow-box thermocouple (●) plotted against temperature of lower surface of box. *A* represents the usual working temperature of skin, *B* the usual temperature of box water during experiments.

the flow-box. The couple is racked out of the skin as readings are taken. The point on the recorded gradient corresponding to the skin surface is assessed by the point at which the previously measured skin temperature occurs, by direct inspection of the site of the couple tip after the experiment, racking it down till it coincides with the lower edge of the box, and by inspection of the shape of the gradient. The part of the gradient produced when the tip is between the halves of the heat-flow disk is linear; the part when the tip is in skin has a characteristic curve. There is a small gap between the two parts in the curve (Figs. 15, 16).

RESULTS AND DISCUSSION

The performance of the apparatus

All the experiments have been made in a room with wet- and dry-bulb temperatures controlled to $\pm 0{\cdot}6°$ C and a constant air movement of about 50 ft./min. The wall temperature was quite variable, but changes occurred very slowly; they may therefore cause differences between but not within experiments.

With the apparatus on the skin it seemed likely that major contributions to error would be made by room climate change, subject–instrument errors and a residual error due to galvanometer reading and small circuit e.m.f. due to unavoidable physical effects. A simple semifactorial experiment was attempted to study this complex error. In addition to the skin Y thermocouple, a fourth thermocouple was fixed below one half of the box with 2 cm of its lead wires wound in the same plane to see whether this would give better

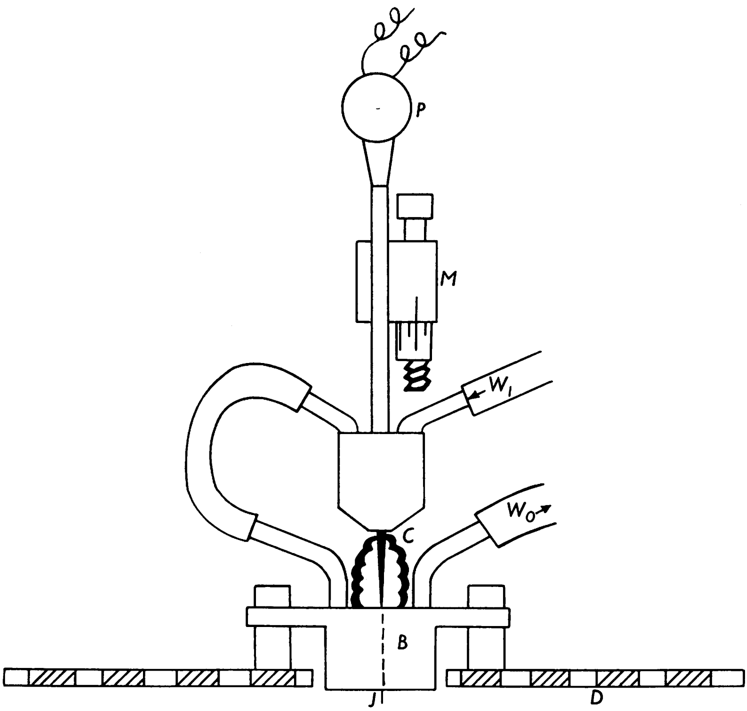

Fig. 11. The full thermocouple assembly. *P*, 'Plasticine' round soldered junctions to thermocouple leads; *M*, micrometer clamp holding thermocouple; W_I, W_O water inlet and outlet; *C*, cotton-wool round stem of thermocouple; *B*, flow-box; *D*, drilled Perspex plate; *J*, exploring junction of thermocouple, in skin.

estimates of local skin temperature. Reference junctions were in the water-bath, whose temperature could be read to 0·01° C and was shown never to vary by more than 0·05° C and seldom more than 0·02° C during an experiment. Equal numbers (fourteen) of readings were taken from the heat-flow disk and the copper–constantan couples at intervals during a measured time. For readings on skin the box was adjusted so as not to alter local skin temperature. The site was front of thigh and the conditions identical with the skin gradient experiments except in the mounting of the box on the thigh—the box rested lightly on the skin. During measurement of temperature gradient in skin the box was more securely mounted, a change of method suggested by these error experiments. Four series of readings were made.

Series	Purpose
(*a*) Apparatus just on the surface of water in constant temperature bath. Results taken over 2 min.	To eliminate skin (S) and room (R) changes leaving other errors (O)
(*b*) As (*a*) but over 20 min.	To eliminate (S) but not (R) changes leaving ($R+O$)
(*c*) Resting on skin, 2 min.	To eliminate (R) but not (S) leaving ($S+O$)
(*d*) On skin, 20 min.	To include all errors ($S+R+O$).

The room temperature charts showed a slow regular cyclic variation of about $\pm 0{\cdot}3^\circ$ C with a periodicity of about 3 hr. A skin gradient estimation usually takes 10–20 min to make.

The series of results was inspected. Clearly if there were a slow variation in the skin–instrument relationship this would only show in (*d*) and the factorial design would be vitiated. This in fact did occur, the variance of the (*d*) readings being ten times that of the (*c*) group, though all the standard deviations were small ($S_{(S+R+O)} = 0{\cdot}026^\circ$ C). This large error was sought and found to be due to movements and small pressure changes between the box and the skin, to which the heat-flow disk was most sensitive. This effect is discussed in the next section. It is a most important source of error. The box was then remounted on skin in the way described above for a skin gradient experiment, this method being worked out as a result of the error observations made with the box only resting on the skin. With the box strapped in place the variance fell markedly in a repeated series of readings. The variance of no series now differed significantly from series (*a*) ($P > 0{\cdot}2$ in each case for variance ratios). The most sensitive test for room changes was taken to be $\frac{V(S+R+O)}{V(S+O)}$. This now gave a not significant variance ratio ($P > 0{\cdot}2$). It was concluded that the room and subject–instrument errors do not differ significantly from the observer and residual errors and are in any case of an acceptable order, the standard deviation of one heat-flow disk reading for a long duration experiment on skin being about $0{\cdot}01^\circ$ C provided the site and pressure on the skin are fixed.

The error of the couple in the flow-box was of a similar order. The skin temperature couple fixed beneath the box gave variable readings which tallied badly with heat-flow disk results. Its readings showed a steady change during the experiment. Longer series of readings were made to decide whether the plate and box water combination of couples or the skin couple fixed beneath the box gave the better estimate of skin temperature. As the box water couple does not change significantly, Hatfield disk readings alone were used. Multiple regressions on room-temperature change and reading order in time of both the 'skin' couple and the heat-flow disk were made. These showed that while the Hatfield disk was independent of both ($0{\cdot}3 > P > 0{\cdot}2$ in each case) the skin couple was independent of room temperature only ($0{\cdot}7 > P > 0{\cdot}5$). It showed a very clear dependence on the order of making readings ($P = 0{\cdot}001$). Thus the readings of a skin temperature couple fixed under the box drift slowly with time and depend on no other parameter. This appeared to be due to a progressive indentation of the epidermis by the couple, which can be seen for some time when it is lifted from the skin. In this way it shares to a variable extent the temperatures of the skin and box temperatures during the experiment. It was rejected as a measure of skin temperature, the heat-flow disk and box couple readings being used instead. The standard deviation of disk and box couple readings in 55 successive readings was 0·014° C in each case.

That small movements of the box are very important was confirmed by further experiments during which the box was deliberately moved a very little on the skin, so as to lift it but not to change its site, between two sets of readings. The deviation produced by the movement was very significant for the heat-flow disk ($t_{16} = 5{\cdot}28$, $P < 0{\cdot}001$) but not for the box couple ($t_{16} = 0{\cdot}08$, $P > 0{\cdot}9$).

An experiment with the largest observed room temperature change (21·45–21·72° C) showed the slight but not significant dependence of box temperature on room temperature ($t_{10} = 1{\cdot}23$, $0{\cdot}3 > P > 0{\cdot}2$ for the regression sum of squares). The heat-flow disk showed no significant dependence ($0{\cdot}7 > P > 0{\cdot}5$).

During an experiment with the full assembly and an alloy thermocouple the readings of the latter showed a standard deviation of 0·026° C for 16 min while its tip was at a fixed depth in the skin.

It was concluded that when used in the way described the method had an error within the desired 0·05° C. The main source of error will not be in temperature measurement but in estimating depth in skin.

The effects of pressure of the box on the skin

The effects of pressure made by the box on the skin were studied by loading it with small weights. These were placed on it for 15 sec in each case, with a 15 sec unloaded period between loads. Fig. 12 shows the readings of the heat-flow disk during the experiment. The area of the box base was 250 mm². Thus the box loadings equivalent to capillary, diastolic and systolic pressures would occur roughly at 85, 270 and 410 g respectively. Fig. 13 shows the effect of firm digital pressure on the box. In these experiments reactive hyperaemia developed progressively as the pressure increased, being visible as a red colour when the box was lifted and persisting for a prolonged period afterwards. The colour remained red and did not fade after the experiment for many minutes. The temperature given by the hyperaemic skin after maximal pressures was in each case equal to or a little higher than that recorded during the pressure if the pressure was short in duration but very heavy. More prolonged heavy pressure resulted in progressive cooling during compression.

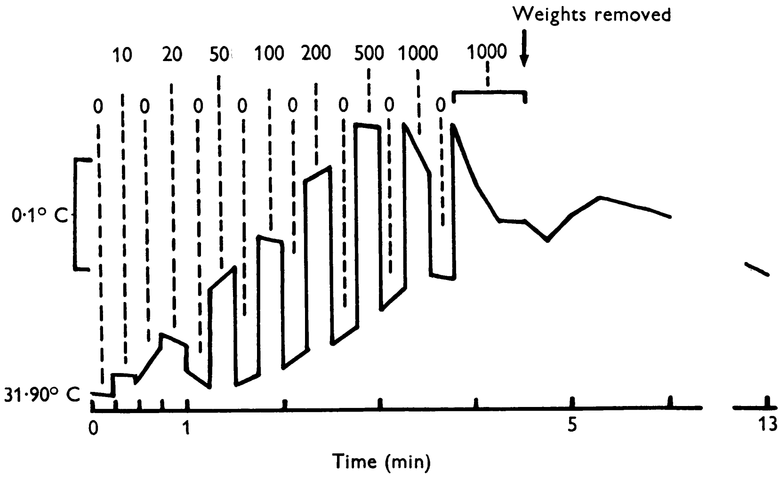

Fig. 12. The effect of weighting the flow-box on recorded skin surface temperature. The figures above the diagram represent grams weight applied to the box.

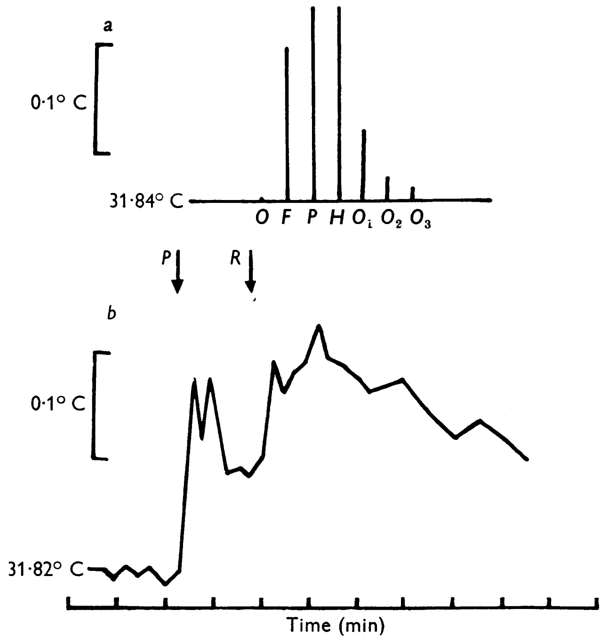

Fig. 13. The effect of digital pressure on the flow-box on temperature of skin surface recorded by the box thermocouples. (*a*) Skin temperatures under various conditions of pressure: *O*, resting; O_1, O_2, O_3, successive readings at rest; *F*, firm digital pressure; *P*, firmest possible pressure; *H*, reactive hyperaemia. (*b*) Skin temperatures plotted against time during and following digital pressure on the flow box; *R*, pressure released.

While prolonged very heavy pressure may empty all vessels locally with a consequent fall in temperature, it may be that pressure heavy enough to empty veins but not arteries or a short very heavy pressure gives a skin temperature elevation of the highest order found by Lewis (1927) in reactive hyperaemia but not as high as that due to full arteriolar dilatation with maximal skin blood flow. It is possible that in the former case the skin temperature may approximate to that of local arteriolar blood. This is uncertain, but the results do show the very large effects of pressure, even though quite

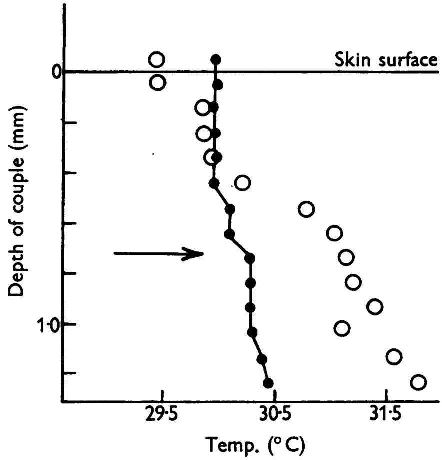

Fig. 14. A skin thermal gradient during which movement of the flow-box occurred. ○, thermocouple readings; ●, coincident heat-flow disk readings. The arrow indicates the depth of the thermocouple at which the box movement occurred. Readings were made at regular intervals of depth, in order, from the point of deepest insertion.

light, on local skin temperature. For these reasons frequent heat-flow readings should be made while estimating a skin thermal gradient, for a change in the site or pressure of the apparatus may cause a discontinuity in the gradient which might be attributed to other causes such as local vascular anatomy. A gradient in a hair follicle showing this effect, due to a small change in position of the box, is shown in Fig. 14. Visible veins were not included in the area beneath the box in skin heat-flow experiments as their cooling or heating effects are most variable.

Thermal gradients in hair follicles

It was found easy to insert a thermocouple into a hair follicle, after removal of a hair from the skin on the front of the thigh, although the follicle often entered at an angle necessitating tilting of the pillar of the thermocouple clamp. A typical result is shown in Fig. 15. Depths are measured along the axis of the follicle which lay at 40° to the normal. It soon became clear when skin puncture experiments were made that the follicle gradients differed from the direct puncture results. The form of the follicle gradients differs from that of skin puncture measurements and would be affected by the known conical shape of follicles and the specialized vascular plexus surrounding them (Johnston & Whillis, 1949). This may account for the absence of large temperature peaks and marked changes of gradient found by Bazett (1949) in punctured skin and ascribed by him to the pattern of blood distribution in the dermis. However, small temperature peaks can be seen at 0·3 and 0·55 mm depths.

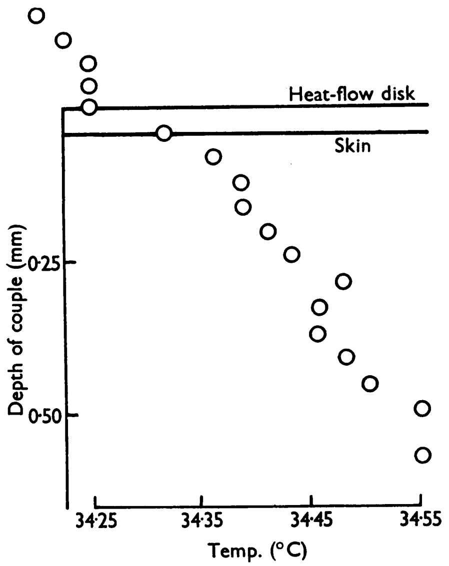

Fig. 15. A skin thermal gradient in a hair follicle. The two parallel lines at the 'skin surface' represent the limits of confidence of depth measurement.

The local skin anatomy was difficult to assess. The figures given by Spalteholtz (1927) were not directly applicable, as they refer to palm, sole and buttock skin and not to front of thigh. Epidermal thickness at the site of the experiments was estimated to be 0·12 mm by measuring the excursion of a microscope focused first on the skin surface, marked with ink and cleared with liquid paraffin, and then on the summits of the capillary loops. The readings varied from 0·10 to 0·15 mm with a mean of 0·12 mm. To assess the relative depths of skin structures skin was taken from the front of thigh of an adult male cadaver of similar build to the experimental subject. Paraffin sections were made after fixation in formol saline. The depth of capillary loops below the surface was from 0·045 to 0·090 mm, indicating shrinkage of the section to one half or one third of the thickness in life. The horny layer of the epidermis was 0·015–0·036 mm deep, the stratum lucidum 0·015 mm and the prickle cell layer 0·018 mm deep over the dermal papillae and 0·060 mm between the papillae which were neither deep nor numerous. Minute vessels occurred within 0·009 mm of the base of the epidermis, but larger vessels with muscular coats first appeared at 0·12–0·15 mm below the surface. Hair follicles penetrated to 0·8 mm at an angle of about 45° and had broad conical mouths filled with horny material.

In the experiment shown the couple was 0·025 mm in diameter, giving a galvanometer deflexion of 4·3 divisions/° C. The heat-flow disk reading was 0·0056 cal/cm^2.sec (200 kcal/sq.in. hr). The room temperature was at 26·44° C and the subject's skin temperature locally was 34·2° C. Calculated thermal conductivities of skin were 0·00086 cal/cm.° C.sec for the outer 0·3 mm of skin thickness and 0·00043 for the slope of the outermost 0·05 mm of the gradient. These figures are higher than for the punctured gradient. Possible reasons for this, making these results of doubtful significance, are the peculiar anatomy of the follicle, the fact that the subject was sweating sensibly a little and that a larger heat flow than usual was induced to magnify the gradient.

Direct skin puncture results

The skin was punctured between the halves of the box with a glass fibre 0·04 mm in diameter. A little ink on the fibre stained the puncture to assist insertion of the thermocouple. It was found that couples smaller than 0·025 mm would only enter the outer epidermis. Repeated attempts to push them further failed. Couples 0·030 mm in diameter would penetrate epidermis. However, they would not pass further. Couples stiffened with glass fibres to within their last 2 mm would not go further but actually depressed the skin. The glass fibre used in the initial puncture met with as much resistance on its second passage as at first. It seemed that a layer in the dermis rapidly closed after a puncture had been made. One couple only, from the large number used, did probably penetrate the dermis. Others, though not penetrating so deeply, gave closely similar results. Fig. 16 shows the gradient observed. The couple diameter was between 0·035 and 0·040 mm. The subject was seated with the right leg unclothed, wearing two layers of light cotton clothing over the body and arms. After the disturbance caused by cleaning the thigh with alcohol there was a waiting period of 1 hr to allow recovery of equilibrium. The room temperature rose slowly from 22·22 to 22·45° C during this period, falling again to its first value. During the experiment it rose from 22·22 to 22·26° C. The water-bath supplying the apparatus was at 31·57° C. The skin temperature beneath the box was about 32·2° C. The heat-flow disk readings before and after the skin gradient readings were 39·8 and 39·9, corresponding to a heat flow of 0·00204 cal/cm^2.sec (73 kcal/sq.in. hr). No local inflammation was noted with the first puncture. Later attempts to reintroduce the couple caused visible inflammation. The skin temperature then rose at the puncture by 1·5° C.

This gradient gives insufficient evidence on which to base any general conclusion, representing as it does one site on one occasion. However, it does show the form of a skin temperature gradient, with suggestive evidence of a rise in temperature in the dermis (Bazett, 1949). Even allowing for a shrinkage of the control section of skin to one third of the *in vivo* thickness the measurements suggest that this thermocouple reached the subpapillary plexus of muscular vessels. Though a small rise in temperature is recorded in the dermis

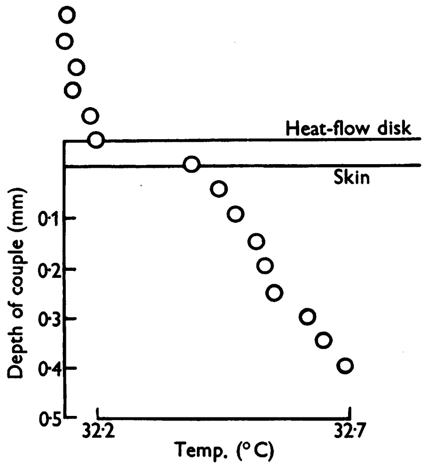

Fig. 16. A skin thermal gradient by direct puncture. The two parallel lines at the 'skin surface' represent the limits of confidence of depth measurement.

it is much smaller than the changes described by Bazett (1927, 1941). This suggests that the gradients described by Bazett, though representing the various vascular networks, may be produced partly in response to trauma, and that normal temperature variations with depth in skin are not so marked. The depths of structures involved in skin punctures are difficult to assess without further exact work on the anatomy of the sites of puncture.

This gradient represents a value of 0·00032 cal/cm. ° C. sec for the thermal conductivity estimated from the line giving the mean slope in the outermost 0·3 mm of skin (Fig. 16). Slopes for the tissue between 0·2 and 0·3 mm deep and for the outermost 0·05 mm give conductivities of 0·00058 and 0·00019 cal/cm. ° C. sec respectively. These figures compare interestingly with those discussed for whole skin and epidermis by Burton & Edholm (1955), being rather lower for epidermis. They suggest that the conductivity falls markedly as the surface is approached, and that the over-all conductivity for skin or epidermis depends on how deep the measurements are taken. The accuracy of the whole estimate is limited to about ±20% by the depth measurements. Thus the obvious step in temperature which occurs at the heat-flow disk–skin interface in each case may be due either to a surface film of air or to a layer of very low conductivity in the keratinized layer itself or both. In any case the low conductivity of the outermost epidermis suggests that air is included in it. This step in the results at the skin surface emphasizes that it is here that error is maximal both in depth and temperature measurement. In both Figs. 15 and 16 there is a fall at this point of the order of 0·1° C. The results of Grayson (1952) on water content of tissue seem not to be applicable to epidermis, the conductivities found being too low to coincide with the scale for internal organs. The results may represent either a falling water content or increasing air content as the surface is approached. The water content of human epidermis is stated to be about 65% over-all, but to fall variably in the horny layer (Zheutlin & Fox, 1950). Many more experiments would be needed before firm generalizations could be made on these points. These results are presented as preliminary to further work.

SUMMARY

1. A method is described of measuring temperature gradients and heat flows in living skin with minimal local disturbance. Its advantages and disadvantages as compared with other methods are discussed. A very small thermocouple is used.

2. A number of preliminary results is presented. They show the great importance to temperature measurement of small pressures made by apparatus on the skin.

3. Temperature gradients in hair follicles differ from those obtained by direct skin puncture, probably because of differences in local anatomy.

4. Direct-puncture gradients are extremely difficult to obtain. One result is discussed.

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