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Thermocouples for Temperature Measurements on Skin Surfaces and in Living Tissue.

By J. S. ELDER, of the Department of Public Health, temporarily attached to the Division of Veterinary Services at Onderstepoort.

I. Skin Surface Instrument.

The suitability of various methods of thermometry for the determination of skin surface temperatures has been discussed by previous authors, among others, Rudolf Cobet (1926), Bedford and Warner (1934), Hardy (1934) and Pfleiderer and Büttner (1935), (1937). The general conclusions are that the most accurate method is that of the measurement of the radiation emitted by the skin, but that the most convenient method is the use of a thermocouple placed in contact with the skin. Some investigators have used resistance thermometers, but the thermoelectric method appears to be preferable and more accurate.

The author has employed the thermoelectric method, and is of the opinion that, with suitably designed instruments, the accuracy of this method compares very favourably with that of the radiation method. The apparatus required is much simpler, and the method can be applied to the skin of animals covered with hair or wool, whereas the radiation method can be applied to uncovered skin only.

The difficulties associated with the accurate determination of skin temperatures are of a special nature, since the instrument used is subjected to the disturbing influence of air and wind on one side, and the temperature of the skin itself is liable to be altered by the instrument. The methods by which different investigators have sought to circumvent these difficulties have varied greatly, and the result has been a wide variety in design among the instruments developed. Not all the designs appear to have been satisfactory. Proper design of the instrument is of the utmost importance if reliable readings are to be obtained, and for this reason a good deal of space will be devoted to a discussion of the various sources of error in skin temperature measurements, and their elimination.

(1) *The Thermoelectric Effect.*

This effect is observed whenever, in an electric circuit composed of two or more metals (or alloys), the different junctions between the metals are at different temperatures. An electromotive force is set up, the magnitude of which depends on the particular metals used, and which is proportional to the difference in temperature between the two junctions, over small temperature ranges. This system of two dissimilar metals is known as a thermocouple, and is illustrated in Fig. 1.

The junction of metals " A " to " B " is heated, and " B " to " A " cooled. Under these conditions an e.m.f. (electromotive force) exists in the circuit, and this can be measured if the circuit is broken at any point such as " C " and a measuring instrument interposed. This e.m.f. will be a measure of the difference in temperature between the hot and cold junctions.

In practice, one of the junctions is kept at a known temperature by immersing it in liquid in a thermos flask. This junction will be referred to as the contra-element.(1) The other junction, which will be referred to as the application element, is applied to the skin. The reading obtained gives the difference in temperature between the skin and the water in the flask, and, as the latter is known, the skin temperature can be deduced.

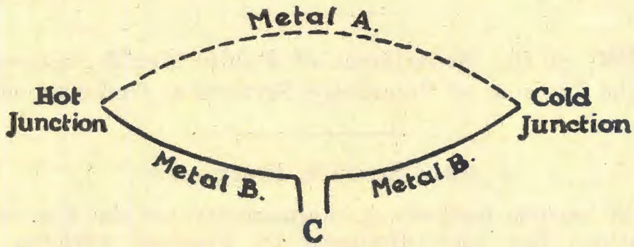

Fig. 1.—Principle of the thermocouple.

The best method of measuring the e.m.f. is by means of a potentiometer, which gives the e.m.f. of the thermocouple in terms of a standard cell. The reading obtained with a potentiometer has the advantage of being independent of the electrical resistance of the circuit. This is not the most convenient method, however, as the apparatus required tends to be cumbersome. A simpler method is the use of a galvanometer to indicate the current in the circuit. The current will be proportional to the e.m.f. and therefore to the temperature difference, but it will also depend on the resistance of the circuit and the current sensitivity of the galvanometer. Should these quantities vary, due to changes in temperature of the wires or galvanometer or any other cause, the sensitivity of the system will vary. Such variations can be rendered negligible by suitable design of the circuit, and under these circumstances the accuracy obtained by the galvanometer deflection method is adequate for ordinary requirements.

One source of error which must be guarded against carefully is the existence of stray thermoelectric effects in the circuit. These are avoided by ensuring that there are no contacts between dissimilar metals in the circuit, other than the hot and cold junctions. To accomplish this it is necessary to modify the circuit of Fig. 1, since the galvanometer winding introduces a third metal, copper, into the circuit. (For reasons discussed below, it is desirable that both metals " A " and " B " should be of some other material than copper.) Thermoelectric effects due to the presence of copper are avoided by connecting the galvanometer leads (also of copper) to the thermocouple circuit at the contra-element, as shown in Fig. 2. With this arrangement both the junctions at which copper is present are at the same temperature.

There remains the possibility of stray thermoelectric effects in the galvanometer itself, the various parts of which are made of different metals. These effects will arise only if different portions of the galvanometer are at different temperatures. To prevent this the author found it necessary to avoid sudden exposure of the galvanometer to large changes of air temperature, and to shade it from direct sunlight.

(1) Frequently, though sometimes incorrectly, referred to as the " cold junction ". A better term, which has come to the notice of the author since the above was written, is " reference junction ".

The circuit shown in Fig. 2 has the further advantage that, owing to the low resistivity of copper, the galvanometer leads may be several yards long without materially increasing the resistance of the circuit.

Any galvanometer of suitable current and voltage sensitivity can be used. For maximum efficiency, the galvanometer resistance should be of the same order as that of the rest of the circuit, usually ± 4 ohms. A current sensitivity of 2 microamperes/division is adequate for ordinary requirements; portable pointer galvanometers of this sensitivity are obtainable, and have been found highly satisfactory for indoor and outdoor use.

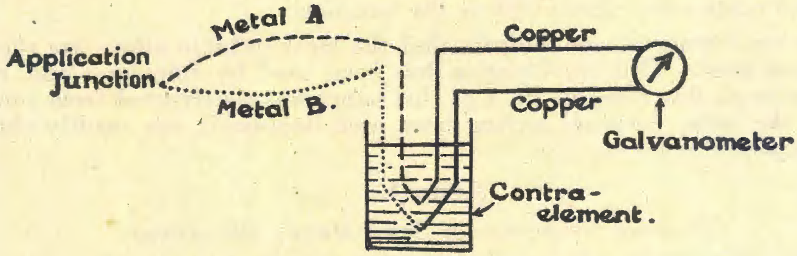

Fig. 2.—Modified thermocouple circuits.

(2) *Choice of Metals.*

The metals " A " and " B " used for the construction of the thermocouple must be chosen to have suitable thermoelectrical, thermal, mechanical and chemical properties.

Thermoelectric Properties.—The various metals and alloys can be arranged in a series according to the magnitude of their thermoelectric effects when used in conjunction with any arbitrary standard metal. Any two metals which are far apart in this series will show a large thermoelectric effect when used together in a thermocouple. In the interests of sensitivity, therefore, the metals should be chosen from opposite ends of the thermoelectric series.

One alloy which is very widely used for thermocouples on account of its general, all round suitability is constantan. This alloy is situated near one end (the negative end) of the series. Metals such as copper and iron and alloys such as brass, steel and manganin are situated towards the positive end of the series, and therefore produce a large thermoelectric effect when used with constantan.

Thermal Conductivity.—As will be discussed in greater detail in section (3), the thermocouple should conduct as little heat as possible away from the skin. This requirement immediately rules out copper and silver, whose thermal conductivity is very high. The thermal conductivities of the various alloys and metals under consideration are shown in Table 1. It will be seen that the thermal conductivity of steel, in particular stainless steel, is low, that of iron somewhat higher, and brass higher still. Nevertheless the conductivity of brass is less than one third of that of copper, so that brass, though less suitable than steel, is by far preferable to copper. Constantan has a very low thermal conductivity, and therefore satisfies this requirement admirably.

Mechanical Properties.—The importance of mechanical strength depends on the design of the instrument. It will be shown in the section on " Sources of Error " that the wires should be as thin as possible but freely supported, either by their own rigidity, or by being stretched across an open frame. Copper has been found to yield too easily under tension but constantan and a particular form of brass have been found to stand up well to continuous handling. In this respect steel is eminently suitable. The author has not investigated the suitability of manganin, but according to Pfleiderer and Büttner (1935) the brittleness of this alloy is a disadvantage.

Chemical Properties.—As the wires will be subjected repeatedly to the corrosive action of moisture on the skin, the materials used should be chemically resistant. Stainless steel is obviously ideal from this point of view. Constantan and brass have been found to remain clean and bright after several months' use, but iron and copper are clearly out of the question.

The above considerations indicate that the most suitable alloys are constantan and stainless steel. This combination has been used by Pfleiderer and Büttner. The thermocouple described in Pt. I of this paper was constructed from constantan and brass, the latter material having been used because it was readily obtainable in a very convenient form.

TABLE 1.

Physical Properties of Some Metals and Alloys.

	Thermal Conductivity at 18° C. in Cal./cm./sec./1°C.	Electrical Resistivity at 18° C. in ohms cm.	Temperature Coefficient of Resistance per 1° C.	Thermoelectric Power Relative to Platinum in Microvolts/1° C.
Aluminium	0·48	$3{\cdot}2 \times 10^{-6}$	·004	+ 4
Copper	0·90	$1{\cdot}7 \times 10^{-6}$	·004	+ 7
Brass	0·15–0·30	$4\text{–}9 \times 10^{-6}$	·0016–·004	+ 3 to + 5
Iron	0·14–0·17	$9\text{–}15 \times 10^{-6}$	·006	+ 18
Chrome Steel (stainless)	0·03–0·06	—	—	—
Nickel Steel (Krupp's 30% Ni)	0·03	—	—	+ 1 to + 5
Lead	0·08	21×10^{-6}	·004	+ 4
Platinum	0·17	11×10^{-6}	·004	0
Silver	1·01	$1{\cdot}6 \times 10^{-6}$	·004	+ 7
Constantan	0·054	49×10^{-6}	·0000	− 35
Manganin	0·052	42×10^{-6}	·0000	+ 7

(3) *Sources of Error in Skin Temperature Measurements.*

The errors discussed in this section may be described as " thermal " errors, since they include only those errors which are due to the application junction being at a different temperature from that of the undisturbed skin. Other sources of error, e.g. random errors of observation of the galvanometer, or changes in the sensitivity of the system will be discussed in section (7).

These " thermal " errors appear to be due to three main causes:—

(i) Physical disturbances of the heat exchanges between the skin and its surroundings. The temperature of the skin may be altered by the application of the instrument, either as a result of heat conducted away from the skin by the wires or the holder, or of the disturbing effect of the instrument on the air, wind and radiation to which the skin is exposed. (The latter influence has been referred to by Pfleiderer and Büttner (1935) as disturbance of " local climate "). Errors of this type may be either positive or negative, according to whether the instrument binders or assists loss of heat from the skin

(ii) The difficulty of ensuring that the junction is at the same temperature as the skin. Only one side of the junction can be placed against the skin, and the other side will be in contact with air or other material which may not be at skin temperature. Errors due to this cause will almost invariably be negative, as the skin is practically always warmer than the surrounding air.

(iii) Physiological reactions caused by the contact, pressure or irritating effect of the instrument, or even by changes of "local climate". Among the possible effects are vasomotor actions and stimulation or inhibition of the sweat glands or hair arrector muscles. Any of these actions would change the temperature of the skin, but whether the change would be an increase or a decrease is difficult to predict, as it would depend on the nature of the reactions.

Errors due to (i).—Under natural conditions the skin may be freely exposed to air, wind and radiation, or covered with hair or wool. It is obvious that these conditions should be disturbed as little as possible by the instrument, and in addition, the instrument itself should not conduct heat away from the skin at the point where the temperature is measured.

The removal of heat from the skin by the lead wires is liable to be a serious source of error in a crudely designed thermocouple, this error being at its worst with the arrangement shown in Fig. 3.

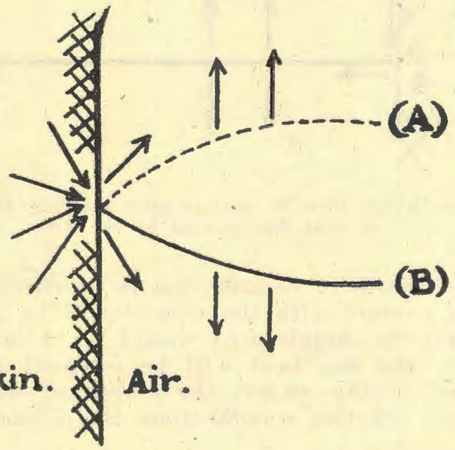

Fig. 3.—Heat flow from the skin due to contact of wires.

The arrows indicate the flow of heat from the skin, along the wires, and thence to the surrounding air. This removal of heat will be considerable, as the heat conductivity of even poorly conducting metals is much greater than that of air, and must cool the skin appreciably. The magnitude of the error will depend on the conditions, being small when air temperature is close to skin temperature, and large at low air temperatures combined with high wind velocities.

This error is minimised by allowing the wires to lie in contact with the skin for some distance on each side of the junction as indicated in Fig. 4. This figure indicates the distribution of heat flow which is reached after the first few seconds required for the wires to heat up to steady temperatures.

With this arrangement any heat that is conducted away from the skin by the lead wires is removed at points remote from the junction. For some distance on each side of the junction the temperature of the wires will be practically uniform, so that the flow of heat along them will be negligible. This state of affairs is attained in the " bridge " form of construction which appears to have been originated by Kunkel (1889), and adopted by Luczak (1932), Cobet (1926) and Pfleiderer and Büttner (1935, 1937). The " hairpin " shape used by Benedict (1925, 1928), and Aldrich's design (1928), also satisfy this requirement.

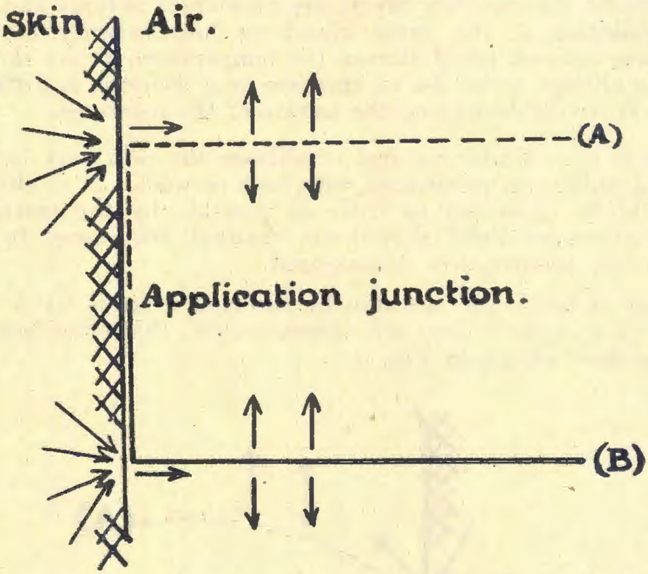

Fig. 4.—Bridge form of construction showing distribution of heat flow caused by the wires.

For the " bridge " form of construction to be effective, it is necessary that the length of wire in contact with the skin should be large compared with its diameter, and also that the metals used should be of low thermal conductivity. The thinner the wire, the less heat will be removed from the skin. In the thermocouple described in this paper, the length of wire in contact with the skin on each side of the junction was 80 times the diameter of the wire.

Apart from conduction along the wires or holder, there are other ways in which the temperature of the skin may be disturbed. It is obvious that the proximity of any instrument will modify the natural surroundings of the skin, or interfere with the hairy or woollen covering. The normal exchanges of heat by means of conduction, convection, emission and absorption of radiation, and evaporation will inevitably be disturbed, therefore the problem is to design an instrument whose disturbing effect is negligibly small. The effect would be great if large masses of solid material were placed against, or close to the skin; this appears to have been a disadvantage of the instruments of Cobet and Benedict (the latter placed cotton wool behind the junction). These authors claim to have obviated errors due to this cause by sliding the instrument slowly across the skin, so that the junction was brought into contact with fresh, undisturbed areas continually. Sliding the instrument is not always practical, e.g. in the case of animals covered with hair or wool (for which Benedict's and Cobet's instruments were not designed), and in addition there is the risk of heating the junction by friction.

The most satisfactory arrangement appears to be one in which the junction is freely suspended in air from a holder which does not approach the skin anywhere near the junction. This arrangement was adopted by Büttner, whose "Gleit-element" is a modification of the "Bridge" form, in which the junction is suspended from wires stretched across the end of a short ebonite tube. This very neat and effective design is, however, unsuitable for measurement in sheep's wool, for which it is not designed.

The design adopted by the author (also an application of the "bridge" form) is shown in Fig. 6. The holder was cut from a sheet of insulating material ($\frac{1}{4}$ inch Sidanyo Board). It will be seen that the junction was well isolated from any solid material, and also that any effect which the instrument had in sheltering the skin from the free play of wind or radiation must have been very small, on account of the open nature of the holder. The instrument could also be used in sheep's wool, by parting the wool between two staples, introducing the instrument and then closing the wool over and around the holder.

Errors due to (ii).—Even if the temperature of the skin is not altered by the instrument, an error may arise due to the junction being at a different temperature from that of the skin. For this reason, again, it is essential that the junction should be freely suspended in air, and not supported from behind by solid material; otherwise the temperature of the junction would be determined as much by the support as by the skin.

When the junction is placed against the skin it touches the skin on one side only, and is exposed on the other side to air which is at a different temperature. The temperature of the junction will be between that of the skin and the surrounding air, but it will be much closer to that of the skin, as will be shown from the following considerations:—

Heat always flows from higher to lower temperatures, i.e. whenever heat is conducted in a given direction, there must be a fall of temperature, or negative temperature gradient in that direction. A bad conductor of heat would require a larger difference of temperature to produce a given flow of heat through it, than a good conductor. More precisely, for a given heat flow, the temperature gradient is inversely proportional to the thermal conductivity of the medium.

Except under extremely hot conditions, the air is at a lower temperature than the body. Heat is conducted from the body through the skin to the air, and the temperature of the skin surface is lower than that of the tissues. The air immediately next to the skin is at the same temperature as the skin surface, but away from the skin the temperature decreases progressively until it becomes equal to normal air or room temperature at points remote from the body. This decrease of temperature is found to be linear close to the skin, where the air is not in turbulent motion.

The relative magnitudes of the temperature gradients in air and skin are of importance. Air being gaseous is a very bad conductor of heat, but the skin which is composed very largely of liquid is a much better conductor. Consequently the temperature gradient in the air will be much steeper than in the skin. This is shown in Fig. 5 (*a*), in which temperature is plotted *vs.* distance from the skin surface. The temperature gradients in air and skin are indicated by the slope of the graph in those media. A value of 2° C. per mm. was chosen for the temperature gradient in air, this being a possible value when the skin is exposed to cold air temperatures. The temperature gradient in skin was deduced on the assumption that the conductivity of skin is 20 times that of air.(1), (2).

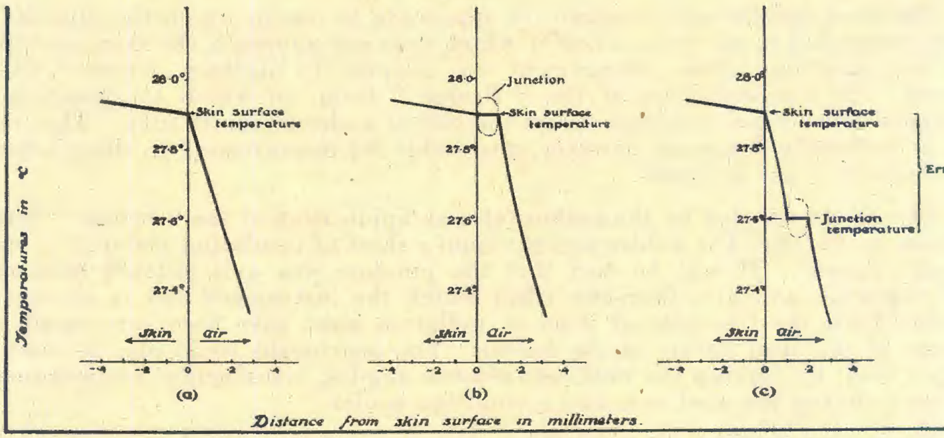

Fig. 5.—Temperature gradients, in air, skin and thermoelectric junction.

Fig. 5 (*b*) represents the temperature distribution when the junction is placed in good contact with the skin. All metals are good conductors of heat; even constantan, which is a poor conductor compared with other metals, has a thermal conductivity about a thousand times that of air. Consequently the temperature gradient required to maintain the flow of heat through the junction will be very small; this is indicated in the figure by the temperature graph being practically horizontal inside the metal. Assuming the temperature gradient in the junction to be ·002° C. per mm., and the width of the junction 0·1 mm., the total fall of temperature across it will be only ·0002° C.(3) The average temperature of the junction will therefore differ from that of the skin in contact with it by a negligible amount.

Fig. 5 (*c*) represents a case in which the junction is not in good contact with the skin, owing, e.g. to the presence of occasional hairs under the wire. The result is that the junction is separated from the skin by a thin layer of air.

(1) Approximate values of the various thermal conductivities are:—

Air: 0·00006 cal./cm./sec./1° C.

Skin (human): 0·001-0·004 cal./cm./sec./1° C. (varying according to depth below surface, and blood supply). K. Büttner (1938).

Constantan: 0·054 cal./cm./sec./1° C.

(2) The slope of the graph inside the skin will be increased if allowance is made for the heat lost by radiation from the skin surface. According to Büttner (1938) the amount of heat lost by radiation is generally somewhat greater than that lost by conduction. Even allowing for this, the temperature gradient in the skin will still be small compared with that in air.

(3) Strictly speaking the temperature gradient in the junction and its immediate vicinity will be increased by a factor between 1 and 2, as a result of the crowding of the lines of heat flow into the metal. Even allowing for this the fall of temperature across the junction remains negligible, but the increase in the temperature drop in the skin near the junction is somewhat greater. This error varies with the depth to which the junction is pressed into the skin, becoming zero when half the width of the junction is below the level of the skin surface. It is concluded, however, that this error is also negligible, since experimental evidence indicates that the readings obtained with the instrument described in this paper are practically independent of pressure of application.

The fall of temperature across this air film may be appreciable on account of the steepness of the temperature gradient in air, and may give rise to an error of 0·5° C. or more.

The above considerations show that it is important that good contact should be obtained between the skin and the junction; they also indicate that, when good contact is obtained, errors due to a temperature difference between the junction and the skin [cause (ii)] are negligible.

Errors due to (iii).—There remains the possibility that the temperature of the skin may be altered by physiological reactions in the thermoregulatory mechanism or vascular system caused by contact of, or irritation due to the instrument. To avoid such reactions the disturbing influence of the instrument on the skin must be kept small. Here again the use of fine wires and a small junction is an advantage, and in addition the junction should be smooth so as not to scratch or prick the skin. The instrument should not feel hot or cold to the touch; this is achieved by the use of a holder of thermally insulating material.

In practice, the readings themselves obtained by the author indicated that errors due to physiological causes were absent or negligible. If such temperature changes had occurred, they would not have been apparent immediately, but would have developed gradually, and the instrument would have indicated a steady change of reading. In tests which were made on sheep and human skin, it was found that after about 3 seconds, required for the galvanometer to reach a steady deflection the reading remained constant for two minutes or more, showing that in that time there was no measurable change in the temperature of the skin. The time taken for ordinary routine readings was only about 5-10 seconds, and chances of temperature changes is this short time were extremely small.

Some authors have stressed the importance of always using the same force when applying the junction to the skin, as they have found that the readings varied wih the pressure of application. The experience of Pfleiderer and Büttner (1935) (which has been verified by the author) was to the contrary. Tests have indicated that with the thermocouple described in this paper the reading was independent of pressure over a wide range. It was therefore possible to obtain reliable readings with light pressures, and this reduced the risk of mechanical irritation.

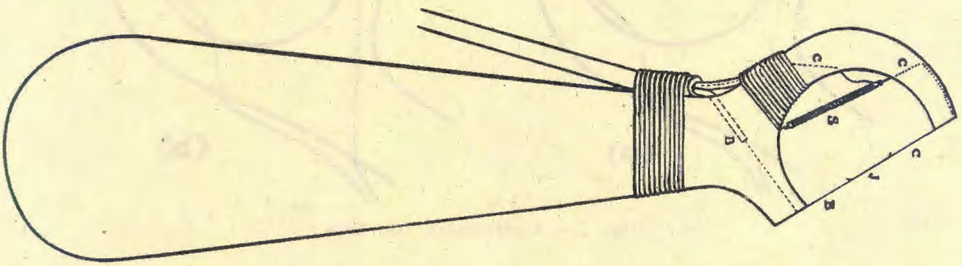

Fig. 6.—Skin surface thermocouple. B, brass wire; C, constantan wire; J, application junction; S, steel spring.

(4) *Constructional Details of Skin Surface Thermocouple.*

The finished instrument is shown in Fig. 6. The holder was cut from ¼ inch Sindanyo board, but any electrically and thermally insulating sheet material suitable for machining could have been used. The holes drilled for the wires are indicated by dotted lines.

The brass wire used was a stranded type of fishing line known as " wire gimp ". It consisted of 15 strands of No. 40 S.W.G. brass, of diameter ·0048 in." or ·12 mm. The stranded nature of this wire was an advantage, because it was possible to use a single strand for the junction, but to use all the fifteen strands as lead wires, thereby reducing the resistance of the circuit. At the same time stray thermoelectric effects were avoided, since the strand used for the junction was of the same composition as the rest of the wire. As this wire was manufactured for fishing purposes it possessed considerable tensile strength and resistance to corrosion by fresh or salt water.

The other lead wire consisted of No. 24 S.W.G. constantan (diameter ·022 inch or ·56 mm.) to which was soldered a short length of No. 40 S.W.G. constantan for connection to the application junction. The two gauges were supplied by the same firm, and were of very nearly the same composition, as was indicated by tests described in section (6).

The connections between the thin junction wires and the metal leads were made with soft solder, and were located in the holes drilled in the holder. This was done to shield the joints from radiation, and so prevent local differences of temperature; otherwise the presence of solder might have given rise to stray thermoelectric effects at the joints. As regards the connection between the single brass strand and the remaining strands of the gimp, special care was taken to ensure that the solder adhered to each strand, so that variations of resistance due to uncertain contacts were avoided.

The application junction was soft soldered after the rest of the wiring had been completed. The method adopted was as follows:—

The wires were cleaned with fine emery paper, straightened, and then given a very slight downward kink at the end, as shown (exaggerated) in Fig. 7 (*a*), and smeared with flux.

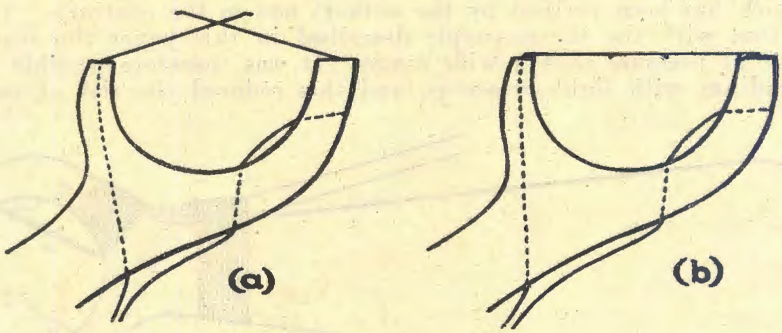

Fig. 7.—Application junction.

The instrument was then grasped in the hand in such a way that the wires could be pressed down with the fingers, so as to lie side by side and parallel to each other. In this position they were dipped momentarily into a film of molten solder on a soldering bit. The solder immediately ran round the wires and held them together by surface tension, forming a smooth, flat joint as shown in Fig. 7 (*b*).

The small kinks at the ends of the wires prevented the ends from scratching or pricking the skin. Joints made in this way were so smooth that they could hardly be felt when the surface was stroked with the finger. The length of the junction was about 3 mm., the width, 0·25 mm., and the length of wire on each side of the junction, 1·0 cm.

To keep the wires under tension, a small coil spring was attached to the constantan wire, as shown in Fig. 6. This was necessary, as it was found that it was difficult to ensure good contact with the skin if the wires were slack.

The leads from the application element to the contra-element were 1 yard in length, and were covered with thin rubber tubing (cycle valve tubing) for insulation purposes, and the two together covered with thicker rubber tubing. The leads from the contra-element to the galvanometer consisted of 5 yards of 5 amp. untinned copper flex. At the contra-element the constantan and brass leads were each soldered to one of the copper leads, care being taken to ensure adherence of the solder to all the conducting strands. The two joints were then bound together with a layer of cardboard between them for insulation purposes, and the whole coated with tallow to render it waterproof.

Galvanometer.—A Weston, model 440 portable moving coil pointer galvanometer was employed and found highly statisfactory. The current sensitivity was approximately 2·2 micro-amperes per scale division, the resistance 3·5 ohms, and the period of swing approximately 2 seconds. The external resistance required for critical damping was 11 ohms.

As the resistance of the thermocouple and leads was about 4 ohms, the galvanometer was overdamped when the thermocouple was connected directly to it. Under these circumstances about 7 seconds was required for the deflection to reach a steady value. The time spent on each reading was therefore not excessive. With this arrangement a sensitivity of 3 galvanometer divisions per degree Centigrade could be obtained.

Usually it was found preferable to make the galvanometer read directly in degrees Centigrade, by including a series resistance of suitable value in the circuit. Fractions of a degree were then estimated to the nearest tenth. By this means the working out of results was simplified enormously, especially when large numbers of readings were taken.

With this resistance in the circuit it was found that the galvanometer was very slightly underdamped, so that the pointer moved rapidly to its final position. This was an advantage, not only because a reading could be obtained in about 3 seconds, but because it was possible to judge the quality of the contact between the junction and the skin. When the contact was good the pointer moved rapidly, but with bad contact the movement was sluggish.

The series resistance was wound from manganin wire. This alloy was chosen on account of its closeness to copper in the thermoelectric scale. It had the additional advantage that its resistance did not vary with temperature.

Another advantage of the use of the series resistance was that, owing to the increase in total resistance of the circuit, any small change of resistance (due to temperature changes or other causes) had a smaller percentage effect on the sensitivity. The only portions of the circuit affected by air temperature were the copper and brass portions, and these accounted for only a quarter of the total resistance.

Method of Calibration.—The instrument was calibrated (in terms of a mercury thermometer) by placing the contra-element in warm water (40° C. or over) in a thermos flask, and immersing the application junction in water at room temperature (usually below 30° C.). Under these conditions the application junction was at a lower temperature than the contra-element, whereas in actual measurements the reverse was usually the case. This made no difference to the magnitude of the current produced, but merely altered its direction. To compensate for this the galvanometer leads were reversed during calibration.

The water surrounding both junctions was kept well stirred. The temperature was read close to each junction on a mercury thermometer, and the galvanometer deflection noted. The ratio of the temperature difference to the galvanometer deflection gave the sensitivity of the system in degrees Centigrade per galvanometer scale unit.

(5) *Method of Application.*

Readings could be taken by a single observer, but the procedure was much simpler when two observers worked in collaboration. One observer handled the instrument and also carried the thermos flask, which was strapped to the chest so as to leave both hands free for manipulation of the instrument. The other observer read the galvanometer and noted the readings.

In the case of exposed skin, such as human skin, which is generally covered with a relatively small amount of hair, all that was necessary was to place the application junction against the skin. The presence of hair under the wire was avoided as far as possible. Very light pressure was found to be sufficient to give a reliable reading.

With animals possessing a thick hairy coat, such as cattle, it was necessary to expose the skin first. This was easily accomplished by pushing a thin, blunt pointed rod of wood (or other bad conductor of heat) under the hair and along the skin, lifting the hair momentarily, and placing the junction and wires along the line of skin exposed. The hair was immediately smoothed down over the wire, so as to minimise the disturbance of the natural heat exchanges, and the reading taken after a few seconds, when it had reached a steady value.

The temperature of the water in the flask was read on a mercury thermometer at the beginning and end of each series of measurements, and at intermediate times if required. This temperature was made fairly close to that of the skin so that large deflections were avoided, and errors due to percentage changes in the sensitivity of the system thereby reduced.

With the instruments described by some authors [Benedict (1925), Cobet (1926)] it was recommended that the junction should be warmed by being applied to the cheek or forehead prior to taking readings, in order to reduce the time required for the instrument to reach the temperature of the skin. With the instrument used by the author this was unnecessary as the reading reached its final value very quickly.

It was also unnecessary to slide the instrument, as it was found that no appreciable change of temperature due to disturbance of " local climate " took place when the instrument was kept in one spot (see following section).

(6) *Test of Accuracy of Readings.*

The methods of minimising " thermal " errors have been discussed in section (3). A series of tests was conducted for the purpose of determining whether the application of these methods had reduced the errors to negligible proportions. These tests were carried out mainly at low air temperatures, for reasons indicated below.

Errors of the first two types (those due to physical disturbance of the heat exchanges and those due to bad contact) are determined by the heat flow from the skin. Consequently they should be roughly proportional to the difference in temperature between the skin and its surroundings (in the absence of solar radiation). A similar variation might be expected, qualitatively, of errors due to those physiological reactions which follow the disturbance of "local climate". The greatest errors were therefore expected at low air temperatures.

The consistency with which readings could be repeated was evidence of the absence of errors of type (ii). Had the contact been unsatisfactory, it is extremely unlikely that the same readings would have been obtained repeatedly, since the quality of the contact would not have been the same each time. The consistent nature of readings taken at the same spot is illustrated in Table 2, column 1, which shows readings obtained on the human forearm at an air temperature of 0° C. After each reading the instrument was removed and then applied again to the skin. The uniformity of the readings indicates that errors due to bad contact may be excluded, even at this low air temperature.

TABLE 2.

Temperatures Read at a Fixed Point on the Human Forearm Exposed to Calm Air at 0° C.

°C. Repeated Contacts.	Time in Seconds.	°C. Contact maintained for 1 Minute.		°C. Light Pressure.	°C. Heavy Pressure.	°C. Light Pressure.
28·6	5	28·5	New point on arm selected.	24·9	25·0	25·1
28·6	10	28·6		24·9	25·1	25·0
28·7	15	28·6		25·0	25·1	25·0
28·7	20	28·6		24·9	25·2	25·0
28·8	25	28·7		24·9	25·3	25·0
28·8	30	28·7		24·9	25·3	24·9
28·8	35	28·7		24·9	25·3	24·9
28·8	40	28·7		24·9	25·3	24·9
28·8	45	28·7		24·9	25·4	24·9
28·8	50	28·7		24·9	25·4	24·8
28·7	55	28·7		24·9	25·4	24·8
28·7	60	28·7		24·9	25·4	24·8

Evidence against the existence of errors of types (i) and (iii) (i.e. those due to physical or physiological disturbances of the heat exchanges) is provided by the constancy of the galvanometer deflections. Had there been any large disturbance of heat flow, the temperature of the skin would have altered gradually until equilibrium was established at a new temperature. It was found, however, that if the junction was kept in contact with the skin for any length of time without undue pressure, then after the first 3 to 5 seconds the reading remained constant almost indefinitely. This is indicated by the readings in Table 2, column 3, which were taken at five second intervals on a human forearm exposed to air at 0° C., the junction being kept on the skin throughout the readings. Only the first reading differs from the mean by more than 0·1° C.

Tests were carried out to investigate the effect of pressure of application. This was done by taking a reading with very light pressure (that due to the weight of the instrument only) and then increasing the pressure so that the wires made a furrow some mm. deep in the skin. It was found (both at high and low temperatures) that increasing the pressure did not cause any *immediate* change of reading greater than 0·1° C. at the most, even when the pressure was so great that the wires left a red impression on the skin. Hence the readings may be regarded as independent of pressure, within wide limits.

If such extreme pressure, as that described above, was maintained for any length of time, a gradual rise of temperature was indeed observed. This is indicated in Table 2, columns 4, 5 and 6 and Fig. 8. At an air temperature of 0° C. an initial rate of increase of 0·1° C. in five seeconds was noted. Such a variation would have been expected as a result of the reduction of the heat flow from the skin inside a fold. This effect would not have introduced an error into the routine observations, firstly because extreme pressure was avoided, secondly the time spent on each reading was less than 10 seconds and thirdly because most observations were made at much higher air temperatures.

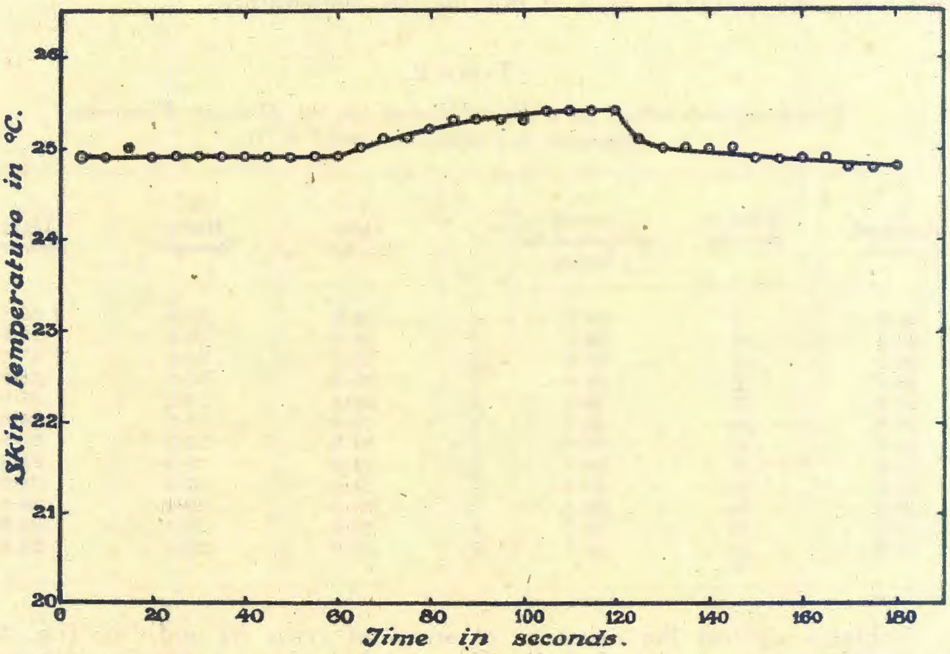

Fig. 8.—Effect of increasing pressure of application.

The fact that the readings were independent of application pressure suggests that errors due to mechanical irritation were absent and also that good thermal contact could be obtained with light pressures. The experience of some authors, who state that their readings varied with pressure, seems to indicate that their instruments were subject to errors determined by the quality of the contact.

A further test of the absence of errors (i) and (ii) consisted of a comparison of the readings obtained with the above instruments with those obtained on a thermocouple of a totally different design. On this latter instrument the conduction of heat away from the skin was prevented by a balancing method. The thermocouple could be warmed with a heating coil until it was at the same temperature as the skin. Under these circumstances no heat was removed from the skin by the instrument, so that error (i) was eliminated; moreover the quality of the contact between the instrument and the skin was of no importance, since there was no flow of heat across it which could produce a fall of temperature [error (ii)].

The balancing thermocouple consisted of a constantan rod with two copper wires soldered to it, one at the end and the other 1 cm. from the end, forming the junctions J_1 and J_2 (see Fig. 9). The copper leads from these junctions were connected to a galvanometer G_2, so that the deflection on this galvo indicated the difference in the temperatures of J_1 and J_2. Another galvanometer, G_1, was connected to J_1 and a contra-element, so that the temperature of J_1 could be determined.

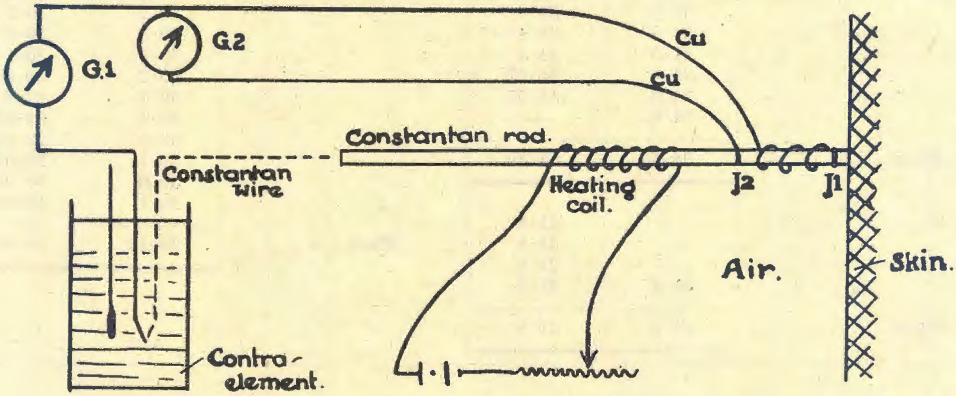

Fig. 9.—Balanced thermocouple.

In use the heating current was adjusted so that G_2 read zero. This indicated zero temperature gradient along the constantan, and hence no flow of heat to or from the skin. Under these conditions the reading on G_1 was noted and hence the temperature of J_1 relative to the contra-element deduced.

The instrument was surrounded with cotton wool to insulate it thermally, except for a length of about 1 mm. in the neighbourhood of J_1. This was left bare since it was argued that the skin under J_1 would normally have been exposed to air.

The balancing thermocouple was found, in practice, to be tedious in operation and unsuitable for routine observations. Very careful adjustment was necessary to keep the flow of heat balanced for any length of time. The instrument was therefore used only as a means of testing the accuracy of non-balanced instruments.

The readings obtained on " balanced " and " bridge " types of thermocouple at different air temperatures under calm conditions are shown in Table 3. In each case the random deviations from the mean are of the same order of magnitude for both instruments, which suggests that these variations may be due partly to actual changes in the temperature of the skin. The mean values show that there is a tendency for the " bridge " type to give slightly higher readings than the " balanced " type; the discrepancy is very small, however, the greatest difference obtained being 0·1° C. at an air temperature of 16° C. Considering the great difference between the two methods of measurement the agreement is strikingly good.

TABLE 3.

Comparison of "Bridge" and "Balanced" Types of Thermocouple, on Human Skin.

Air Temperature.	Skin Temperature.		Air Temperature.	Skin Temperature.	
	"Bridge" Instrument.	Balanced Instrument.		"Bridge" Instrument.	Balanced Instrument.
	°C.	°C.		°C.	°C.
30 °C.	34·4	34·4	16 °C.	30·0	29·8
	34·6	34·6		30·2	30·1
	34·4	34·4		30·3	30·1
	34·5	34·4		30·3	30·1
	34·6	34·57		30·2	30·05
	34·6	34·57		30·1	29·8
	34·6	—		30·1	29·93
				30·0	29·83
MEAN	34·53	34·49		30·1	30·03
				30·0	30·03
				30·1	30·03
0·5 °C.	—	21·8			
	—	21·8	MEAN	30·12	30·02
	—	21·8			
	21·8	21·8			
MEAN	21·8	21·8			

(7) *Additional Sources of Error.*

Apart from thermal errors, other errors may arise due to causes discussed below.

(i) *Stray Thermoelectric Effects*, due to non-uniformity of strands of brass wire or the two gauges of constantan wire. One of the advantages of using a stranded brass conductor was that a single strand of the same material could be used for the application junction. To ascertain whether there was any appreciable difference in the composition of various strands, the following test was conducted:—

Two lengths of intact wire gimp were connected to the terminals of a galvanometer, and the circuit completed by means of a single strand obtained from a sample of the same material (see Fig. 10). One of the junctions between the intact wire and the single strand was placed in boiling water, and the other kept at room temperature. If the composition of the strands had been uniform there would have been no deflection, but in practice a very small deflection was obtained with each of the fifteen strands.

The effect was very small, however. In the worst case it could have given rise to error of 0·05° C. when there was a difference of 30° C. between the application junction and the lead wires. The average effect, taken over all the strands, regardless of sign, was half the above value. Consequently the effect was negligible, even at the lowest air temperatures experienced.

The thin and thick gauges of constantan were tested in the same way. The results were not quite as favourable. It was found that there was a stray thermoelectric effect which could have given rise to an error of −0·1° C. for every ten degrees difference between the application junction and the connection between the thin and thick constantan wires. This effect might have been significant at low temperatures, but if the air temperature was known it could be corrected for.

(ii) *Variation of Sensitivity with Temperature.*—Variations of sensitivity of the whole system were caused by changes in the current sensitivity of the galvanometer and changes in the resistance of the circuit. The two effects worked in opposition. The first caused an increase of 0·1 per cent. per 1° C., and the second a decrease of 0·05 per cent. per 1° C. in a circuit of 19 ohms resistance. The combined effect was to increase the sensitivity by 0·5 per cent. for every ten degrees rise in air temperature.

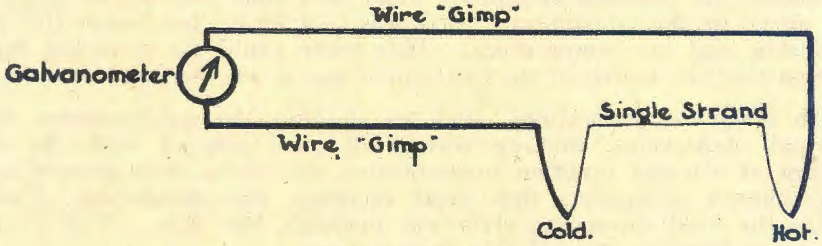

Fig. 10.—Circuit used in testing for thermoelectric effects among strands of wire gimp.

The error due to changes of sensitivity with air temperature was proportional to the galvanometer deflection, i.e. to the temperature difference between the two junctions. Consequently it could be made negligible by keeping the deflections small, by having the contra-element at a temperature within, say, 5° C. of that of the skin. In addition, the instruments were calibrated from time to time at the various air temperatures prevailing during the experiments. Even if the air temperature during readings had differed by 10° C. from that at which the thermocouple was calibrated, the error in a deflection corresponding to 5° C. would have been only 0·025° C.

An additional change of sensitivity was caused by the fact that the thermoelectric power of a thermocouple varies with temperature. This effect was dependent on the average temperature of the junctions, i.e. of the skin and contra-element, and not on the temperature of the leads. The magnitude of this effect was of the order of +1·5 per cent. per 10° C., and the error again was proportional to the deflection. It was reduced to negligible proportions by keeping the galvanometer deflections small, and also by calibrating the thermocouples at a mean junction temperature within 5° C. of that existing during readings.

(iii) *Broken Strands in the Lead Wires.*—The effect of broken strands was to increase the resistance of the circuit, and thereby to lower the sensitivity. Errors due to this cause were guarded against by recalibrating the instrument after about every 250 readings. On one occasion when an instrument was inspected after about 2,000 readings, two broken strands were found in the wire gimp lead. In spite of this, the sensitivity was still within 1 per cent. of its original value.

Summary of Various Errors.

(i) *Random Errors.*—These were encountered in reading the galvanometer and the mercury thermometer in the flask. In each case the accuracy was estimated at ±0·1° C., the combined error being ±0·14° C. Errors of this nature would tend to cancel each other when many observations are taken.

(ii) *Systematic Errors.*—Under this heading are included thermal errors, stray thermo-electric effects and changes in sensitivity with temperature. All are determined by air temperature (directly or indirectly).

The tests for the presence or absence of thermal errors suggest that these were small, as no discrepancies were obtained which were beyond the limit of accuracy imposed by random errors. It therefore appears that thermal errors were not greater than $\pm 0 \cdot 14°$ C. at an air temperature of 0° C.

Reasons have been given for neglecting the effect of changes of sensitivity, when precautions were taken to keep the deflections small.

Probably the greatest systematic error was that due to the stray thermo-electric effect in the constantan; this was $-0 \cdot 1°$ C. for every 10° difference between skin and air temperature. This error could be corrected for on the assumption that the holder of the instrument was at air temperature.

With adequate precautions, such as shading the galvanometer terminals, using small deflections, making certain of good contact with the skin and calibrating at air and junction temperatures similar to those prevailing during the experiments, it appears that great accuracy was obtainable. Under these conditions the total systematic error was probably less than $-0 \cdot 2°$ C. for every 10° difference between air and skin temperature.

Note on Robustness of Instrument.

The obvious disadvantage of an instrument in which the application junction is made of very thin wire is its delicate nature. In practice this was not found to be a serious drawback, and the ease with which reliable and accurate readings could be obtained was considered to outweigh this disadvantage. Moreover, with careful handling the junctions lasted well; in one case at least 3,800 readings were taken on animals which were sometimes restless, without breakage of the wire. When breakage did ultimately occur, it occurred not at the junction but at the point where the spring was attached to the constantan wire.

II. Hypodermic Instrument.

The thermoelectric effect has been found convenient as a means of thermometry inside living tissue. The main advantage of this method is that the thermocouple can be constructed in the form of a needle which can be introduced into tissue with a minimum amount of injury. Such thermo-needles have been used by Becquerel and Breschet (1839), Sonne (1921), Schultze (1926), R. Büttner (1935) and others.

The problem of temperature measurements inside living tissue is much simpler than that of measurements on skin surfaces, since the instrument is almost completely surrounded by fluid media at temperatures which are more or less uniform and constant. The existence of large, local temperature differences in tissue is impossible as such differences would soon be equalized by heat conduction and blood circulation. Only where heat is being produced rapidly, or removed continuously (e.g. just below the skin or in the respiratory system) can large temperature gradients exist.

The chief precaution to be observed is that the thermo-element should be well embedded in tissue, and remote from the point at which the needle enters the skin. At this point the conduction from tissue to air, via the needle, will be at its maximum; it is also probable that the skin and subcutaneous tissue round the point of entry will have been cooled considerably by the antiseptic (such as ether) applied before the insertion of the needle.

The circuit used for the hypodermic instrument was the same as in the case of the surface thermocouple, and the same remarks regarding the choice of metals apply. The importance of low thermal conductivity combined with mechanical strength is, however, somewhat greater; in the case of the surface instrument, loss of heat was minimised by using very thin wires, but with the hypodermic instrument the needle had to possess sufficient strength to penetrate animal skin or hide. For this reason needles made of brass were avoided, and a needle made of Krupp steel was selected. Needles made of this alloy conducted very little heat away from the tissue, firstly because the strength of the material made possible the use of needles with thin walls, and secondly because the thermal conductivity of Krupp steel is very low. The other alloy used was constantan.

Elimination of Stray Thermoelectric Effects.

A ready made hypodermic needle was used. One of the chief difficulties was the finding of a material that could be used as a lead wire from the needle to the cold junction. This wire had to match the needle thermoelectrically, otherwise a stray thermoelectric effect might have existed at the junction between the lead wire and the needle.

A large assortment of steel hypodermic needles and different kinds of wire was tested until a suitable match was obtained. The method of testing was as follows:—A needle and a sample of wire were selected, and the wire soldered or otherwise connected to the needle near the point. The syringe end of the needle and the free end of the wire were connected by a length of copper flex to a galvanometer. The junctions between the copper leads and the needle and wire were kept at the same temperature by immersing them in water in an inverted test tube, as shown in Fig. 11. This prevented any thermoelectric effect due to the presence of copper in the circuit.

The point of the needle was then dipped into hot and cold water successively, the reading on the galvanometer being noted each time. In most cases there was a deflection, showing that there was a thermoelectric effect between the two metals. The magnitude of this effect was estimated (in arbitrary units) by dividing the difference between the deflections in hot and cold water by the temperature difference. In this way it was possible to test all the needles and samples of wire against one chosen as a standard, and to arrange them in a series according to their thermoelectric effects. It was found that one particular needle and a sample of wire gimp were very close in this series and therefore these two materials were tested directly against each other by the above method, to verify whether the difference between them was appreciable.

No measurable e.m.f. was obtained, however, even when the needle was dipped into boiling water; this indicated that the two metals could be used together in the circuit without the slightest risk of a stray thermo e.m.f. at the junction between them.

Details of Construction.

The dimensions of the needle were:—Length of shaft, 5 cm.; external diameter, 0·8 mm. The application thermo-element was situated inside the needle close to the point. This was achieved by soldering a thin constantan wire (No. 40 S.W.G.) internally to the needle, the actual soldered joint extending for about 5 mm. from the tip. Behind the junction the constantan was insulated from the needle by a double silk covering impregnated with shellac varnish.

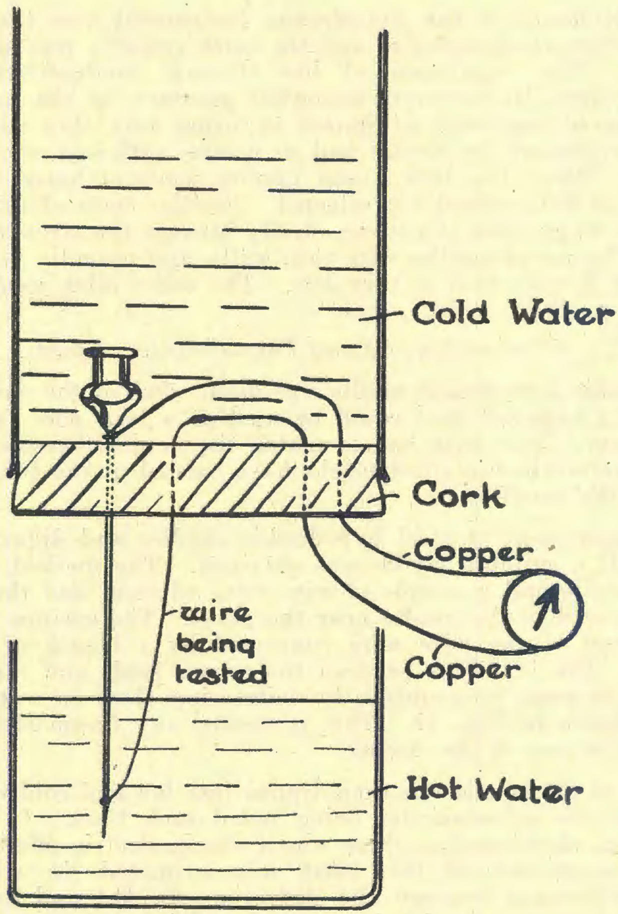

Fig. 11.—Method of comparing thermoelectric properties of needles and samples of wire.

The soldering was accomplished as follows:—The needle was first cleaned internally by pulling moist thread charged with emery power through it, and a small quantity of flux introduced. The inside of the needle was then "tinned" by placing a short length of copper wire coated with solder inside the point, and warming the needle carefully until the solder flowed. A short length of No. 40 S.W.G. double silk covered constantan was soldered to a length of No. 24 S.W.G. constantan (for a lead). The fine wire was cleaned and tinned for about 5 mm. from the tip, the rest being varnished with shellac in order to protect the silk covering. The constantan wire was then placed in position inside the needle, which was then warmed until the solder flowed, and a small amount of solder added at the point of the needle to seal it. Great care was taken to avoid heating the needle beyond the melting point of solder, so as to avoid softening the steel.

The junction between the fine and thick constantan was embedded in sealing wax * introduced, while molten, into the conical hollow at the syringe end of the needle. The wire gimp forming the other lead was soldered to the shaft of the needle just in front of the collar. The two leads were insulated from each other with cycle valve tubing. The contra-element and the rest of the circuit were the same as in the case of the skin surface thermocouples, and the same method of calibration was employed.

Method of Application.

The needle and the skin were cleaned. The needle was then inserted into the issue to a depth of at least 4 cm., so that the junction was well isolated from the cooling effect of air or cleansing agent on the exposed portion of the needle. When the region at which the temperature was required was less than 4 cm. below the skin surface (e.g. in subcutaneous temperature measurements), the needle was inserted through the skin some distance away and then pushed under the skin to the point required. Under these conditions the point at which the temperature was measured was well away from the region of the skin cooled by antiseptic agent.

Sensitivity of Instrument.

With the thermocouple connected directly to the galvanometer, the sensitivity was 0·4° C. per scale division. A series resistance was not added in this case, as it was considered preferable that the sensitivity should not be reduced.

Test of Accuracy of Hypodermic Thermocouple.

The importance of having the thermo-element at a point remote from the region where the needle entered the skin, in order to avoid cooling influences of air or antiseptic, has been mentioned. The following test was conducted in order to determine to what depth it was necessary to insert the needle in order to avoid this error:—

The temperature inside the body cavity of a newly killed rabbit was measured by inserting the needle to different depths. The following readings were obtained at an air temperature of 27·3° C.:—

Length Inserted.	*Deflection.*	*Temperature.*
4·5 cm.	11·2	40·08° C.
3·5 cm.	11·2	40·08° C.
2·5 cm.	11·1	40·04° C.
1·2 cm.	10·0	39·60° C.

Above 3·5 cm. the readings were constant, and with 2·5 cm. inserted the reading was only ·04° C. lower. This might have been due to an actual temperature difference inside the body.

The above readings, which are typical of those obtained in routine measurements, clearly indicate that with 3·5 cm. inserted, there was no appreciable error due to conduction of heat away from the tissues. However, more striking

* NOTE.—A disadvantage of sealing wax was its solubility in alcohol. When the cleansing agent contained alcohol, care had to be taken to avoid wetting the wax while cleaning the needle.

evidence of the absence of a cooling effect was obtained by cooling the exposed portion of the needle to about 0° C. with ether; even under these conditions, no reduction of the temperature at the point of the needle was indicated.

Summary of Errors.

(1) *Random Errors of Observation.*—The galvanometer deflections were estimated to the nearest tenth of a scale unit, which corresponds to an accuracy of ±0·04° C. The mercury thermometer was read to the nearest 0·1° C.; the combined random error was therefore of the order of ±0·1° C. in the case of the hypodermic instrument.

(2) *Systematic Errors.*—The previous section indicates that the only thermal errors likely to occur in the case of the thermo-needle, namely, those due to conduction of heat along it, were negligible.

Owing to the lower circuit resistance, the effect of changes of resistance with temperature was 2½ times as great as in the case of the skin surface instrument, amounting to about −1·25 per cent. for every 10° rise in temperature. This was practically offset by the increase of current sensitivity of the galvanometer of 1 per cent. per 10° rise in temperature. The combined error was negligible, particularly since the deflections were kept small.

Stray thermoelectric effects were tested for, but none were found. Such errors must have amounted to less than 0·1° C. for every 10° temperature difference between the point and the syringe end of the needle, otherwise their presence would have been detected.

Summary and Conclusions.

Details have been given of the construction of thermocouples suitable for temperature measurements on skin surfaces and in living tissue. The sources of error have been discussed, and tests of the accuracy of the method have been described. It is concluded that, with adequate precautions, the following degree of accuracy was attained:—

Skin Surface Instrument.—Random errors, ±0·14° C.; systematic errors, less than −0·2° C. per 10° C. temperature difference between skin and surroundings.

Hypodermic Instrument.—Random errors, ±0·1° C.; systematic errors, less than 0·1° C. per 10° C. temperature difference between tissue and air.

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