ON METHODS OF MEASURING SKIN TEMPERATURE.

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(With 10 Figures in the Text.)

CONTENTS.

I. Introduction.

Measurements of skin temperature are of considerable importance in physiological studies as well as in clinical investigations, and of late years many observations have been made and various methods of measurement have been employed. Amongst these methods are the application to the skin of:

(1) Some type of mercury-in-glass thermometer;
(2) Thermo-junctions in various types of holders;
(3) Electrical resistance thermometers.

Radiation thermopiles have also been used.

In the measurement of a surface temperature two principal difficulties arise. These are (1) that where an object of any considerable size is applied to the surface the normal loss of heat from the covered area is immediately disturbed; and (2) exposure of the thermometer bulb, thermo-junction, or other measuring apparatus to the air influences the temperature reading obtained, since the temperature of the thermometer or thermo-junction is the resultant of the effects of contact with the surface and with the air. In the presence of a strong air current this latter difficulty is liable to assume considerable importance. From the physical and engineering standpoints these difficulties are discussed, and the literature reviewed by Othmer and Coats (1928) and Colburn and Hougen (1930). Bailey (1932) showed that when a bare thermometer is applied to a rigid surface the thermometer records only 72 per cent. of the temperature difference between air and surface. In measuring the temperature of the skin it is also essential that the pressure with which the measuring instrument is applied be kept as constant as possible. It is necessary to ensure good contact with the skin, but excessive pressure will hamper the cutaneous circulation.

II. Apparatus for measuring skin temperatures.

The method of measuring skin temperature now most widely used is the application of a thermocouple to the skin; indeed Benedict, Coropatchinsky and Finn (1929) say that this is the only method that seems at all practical and accurate. Benedict and his associates make use of a junction mounted on a hard rubber block, with a wad of cotton-wool beneath the actual junction. The method of mounting is illustrated in Fig. 1, which is redrawn from the paper just referred to.

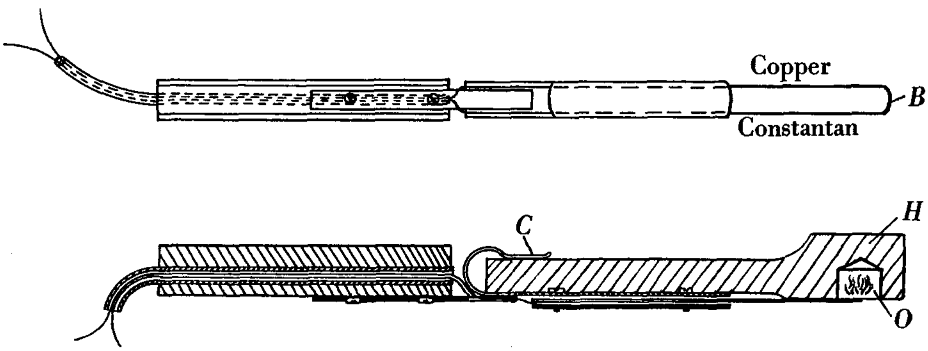

Fig. 1. Application thermo-junction showing hairpin loop and hard rubber holder for protection of junction. (Redrawn after Benedict, Coropatchinsky and Finn, 1929.) *B* shows the hairpin loop formed by the junction; *C* is the clip attaching the thermo-junction clamp to the hard rubber block, *H*; *O* shows the hole in the hard rubber block which is filled with a wad of cotton wool.

The observer keeps his thumb over the junction when it is not in contact with the subject's skin and keeps his hand fairly well closed over the hard rubber holder; thus, it is said, the temperature of the rubber is approximately uniform and not so far from that of the skin as to affect the junction temperature. The arrangement of the holder ensures that both of the wires from the junction are in close contact with the skin for a length of 2 or 3 cm., and thus thermal disturbance by conduction along the leads is minimised. It is claimed that in the 6 sec. or so for which the junction is applied to the skin the covering of the skin has no sensible influence on the skin temperature.

In order to avoid possible error consequent on covering an appreciable area of skin about the point at which the temperature is required and to ensure a constant, light pressure on the skin, other workers have designed apparatus in which, at the point of measurement, only the junction itself is in contact with the skin. The application junction designed by Strauss (1928), and which is shown in Fig. 2, is typical of these forms.

In this instrument the junction projects about 1 mm. beyond the thin tubular holder through which the leads pass; thus the junction itself is subject to the effects of wind, and, as the tube containing the leads is at air temperature, there must be a disturbance of the temperature of the junction owing to heat conduction along the leads.

Other observers have used forms of apparatus more or less similar in principle to that of Strauss, in which the junctions are uncovered and which may therefore permit of heat-loss through conduction. The apparatus used by Aldrich (1928) and by Bloomfield, Ives and Britten (1930) is illustrated in Fig. 3.

The apparatus used by Winslow and Greenburg (1932) consists of a supporting ring attached to a suitable wooden handle, and an inner concentric

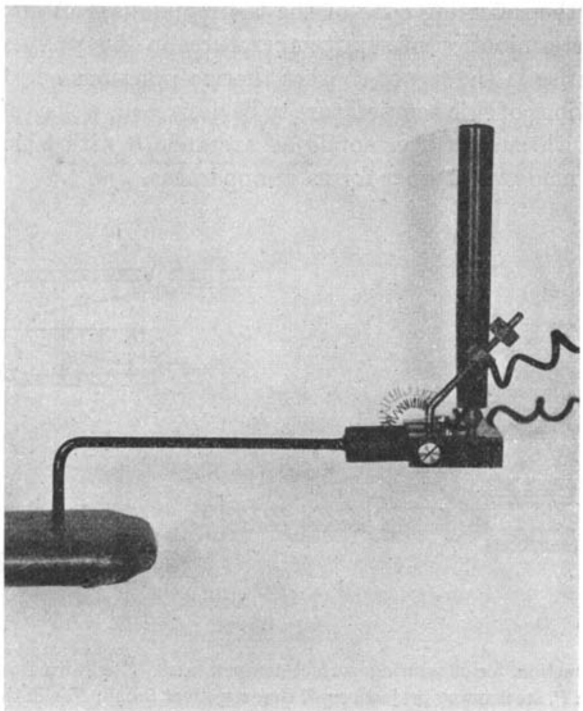

Fig. 2. The Strauss thermo-junction for skin temperature measurements.

floating ring carrying the thermo-junction. Reichenbach and Heymann (1907) used a three-footed holder, with a spring to keep the pressure of the thermo-junction on the skin constant. Since these thermo-junctions are calibrated by immersion in some liquid, it follows that if the air temperature differs from that of the skin, and particularly if the air movement be considerable, estimations of skin temperature will be subject to error.

Over forty years ago Stewart (1891) used electrical resistance thermometers for measuring skin temperatures. The resistance was a grating of lead paper mounted on a glass coverslip or on thin cardboard. In a recent paper Stewart (1930) describes resistance thermometers constructed of thin platinum wire or of lead paper, the resistances being fastened to a bakelite base.

Various workers have found that the human skin radiates approximately as a black body [Stewart (1891), Cobet and Bramigk (1924), Aldrich (1928), Vernon, Bedford and Warner (1930), Bohnenkamp and Pasquay (1931)], and we have lately made further observations which confirm this. The radiation from the skin is easily and rapidly measured by means of a suitable form of radiation thermopile, and such a thermopile is therefore a convenient instrument for measuring the temperature of exposed areas of the skin. When the "hot" junctions of the thermopile are screened (*e.g.* by a rock-salt window) even strong winds do not influence the results obtained. With slight or moderate air movement the reflecting cone of the thermopile is in itself sufficient protection. The determination of skin temperatures in this way avoids the difficulties which arise in the use of contact thermo-junctions and thermometers. In the observations of skin temperature to be described, we have used measurements made with such a thermopile as a standard with which to compare measurements made with other forms of apparatus.

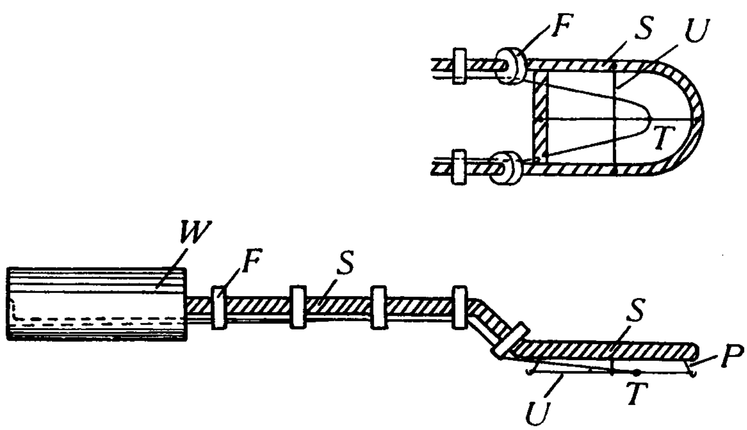

Fig. 3. Thermo-junction for measuring surface temperatures. (Redrawn from Aldrich, 1928.) *F*, fibre rings; *P*, steel spring projection; *S*, German silver frame; *U*, silk thread; *W*, wooden handle; *T*, thermo-junction.

III. A comparison of different types of thermo-junction.

(*a*) *Surface temperatures of a copper bath.*

A comparison was made of three types of thermo-junction, (*a*) one of the Benedict type, (*b*) one of the Strauss type, and (*c*) a junction described by Lewis (1930) in which the wires (0·28 mm. diameter) were twisted into a spiral for about 6 mm. from their ends, and the tip of the spiral lightly soldered to form the junction, the remaining length of the wire being carefully insulated. The constant temperature junction was kept in a vacuum flask of water at air temperature, and the application junctions were calibrated by immersion in water of known temperature.

After calibration the junctions were used for estimating the temperature of the outside of a thin-walled copper bath containing water; the water in the bath being agitated by means of compressed air. As a check on the surface temperature one junction of a thermo-couple was lightly soldered to the surface of the bath, and the leads were cemented to the bath surface for a distance of about 4 cm. from the junction. Tests showed that, up to a temperature of 45° C., with a room temperature of 24–25° C. and with calm air, the E.M.F. given by the soldered couple was the same as that given by a couple immersed in the water. There was no sensible difference between the surface temperature of the bath and the temperature of the water in the bath. The Benedict and Strauss junctions were applied to the bath in the usual manner, care being taken to ensure a good contact. The Lewis spiral junction (*c*) was stuck to the surface by means of a strip of surgical tape, the actual junction and the leads for a length of about 2 cm. being covered by the tape.

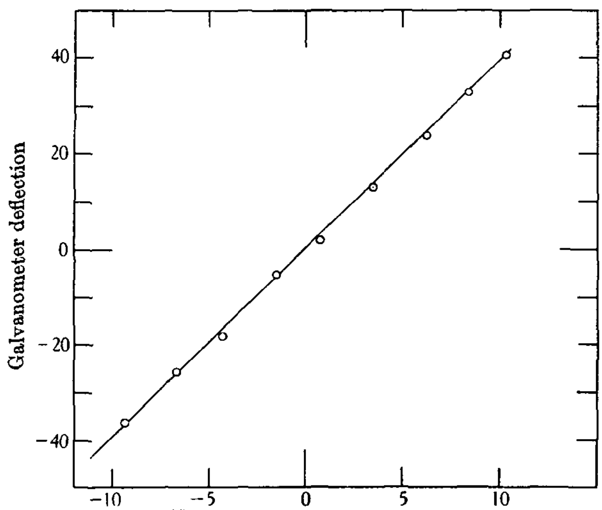

Fig. 4. Calibration curve for Benedict thermo-junction.

Fig. 4 shows the immersion calibration curve of the Benedict couple. The points plotted on the diagram show the results of observations with the junction applied to the surface of the bath. These points lie very close to the calibration curve. Evidently there was no appreciable error in estimating the surface temperature by means of this junction. These observations were made under ordinary room conditions, when the air velocity was of the order of 10 ft. per min. In a further series of observations the stream of air from a fan was passed over the surface of the bath, the air velocity being about 500 ft. per min. Even this strong air movement had no marked influence on the accuracy with which the surface temperature was measured.

The next diagram (Fig. 5) shows the results of observations made with the Strauss model. It is evident that the air temperature had a marked influence on the temperature of the junction, and this effect was enhanced when the air velocity was increased to 500 ft. per min. The extra cooling in the high air velocity observations was not due to the effect of the wind on the actual surface temperature of the bath, for observations made with the couple soldered to the bath showed that with such a wind, and with 20° C. difference between air and bath temperatures, the bath surface temperature was only 0·4° C. below the temperature of the water in the bath. It can be seen from the diagram that when estimates of surface temperature are based on the immersion calibration an actual temperature difference of 15° C. is estimated at 10·5° C. in calm air, and at about 8° C. in a wind of 500 ft. per min.

The spiral (Lewis) couple with its protection of surgical tape gave results which were much more accurate than those just referred to, but they were not as good as those obtained with the Benedict couple. In calm air a temperature difference of 15° C. was estimated at about 13·3° C.

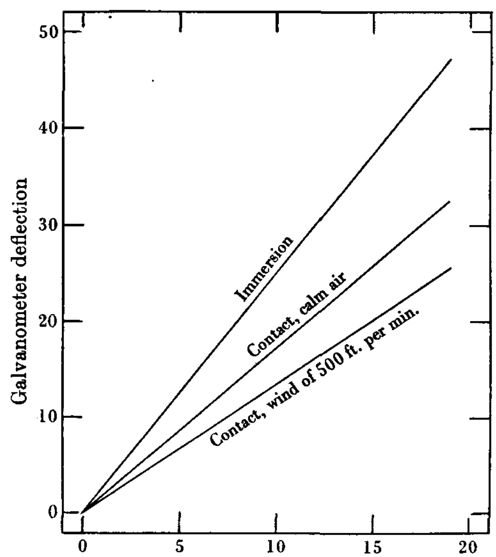

Fig. 5. Immersion and contact calibration curves for Strauss thermo-junction; standard temperature junction in bath at air temperature.

(*b*) *Skin temperatures.*

It was realised that these results might be somewhat different from those that would be obtained in actual skin temperature measurements, for on a yielding surface such as that provided by the skin the junctions might be expected to make better thermal contact than on a rigid metallic surface. Some further observations were therefore made in which temperatures of exposed areas of skin were measured.

In the first series observations were made of the forehead temperature of a clothed, resting subject. The spiral junction was affixed to the forehead 3·5 cm. to the left of the middle line, and the Strauss junction was placed 1 cm. below the spiral junction. These junctions remained in position throughout the experiment. The Benedict junction was applied to a position 3·5 cm.

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to the right of the middle line; this junction was removed from the skin after each observation and held in the hand so as to keep the holder approximately at skin temperature. In the centre of the forehead, observations were made by means of a Moll radiation thermopile, used in conjunction with a Cambridge unipivot galvanometer. The exposed junctions of the thermopile were protected by a rock-salt window. Observations with each of the three thermojunctions and with the thermopile were made each minute, the cycle of observations taking about 40 sec. After 3 min. observations in quiet room con-

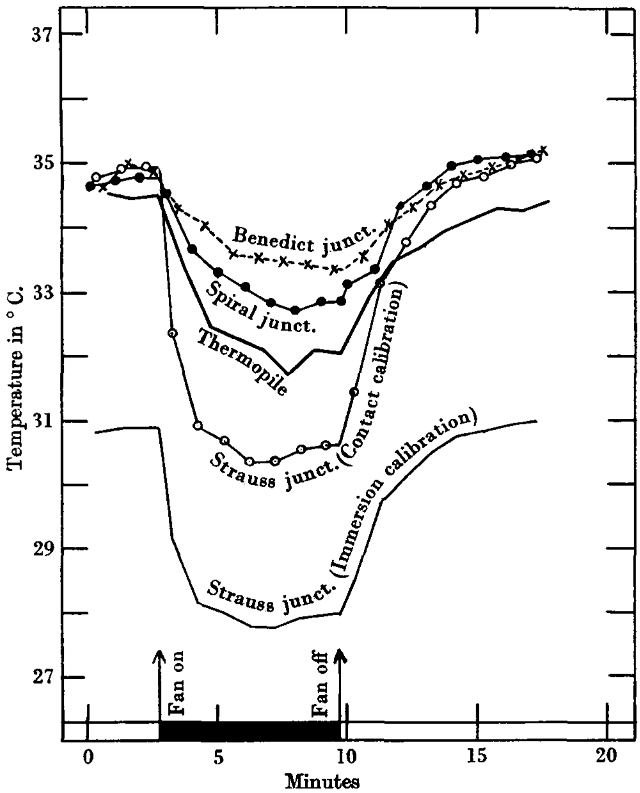

Fig. 6. Forehead temperatures as estimated by different methods.

ditions (air velocity about 10 ft. per min.) an electric fan was turned on, and a wind of about 350 ft. per min. passed over the subject's forehead. When the fan had run for 7 min. the skin temperature was almost steady, so the fan was stopped and the rise of skin temperature observed. Fig. 6 shows the mean results obtained in two similar experiments at an air temperature of 22° C. There was fairly close agreement between the results obtained with the Moll thermopile, and those given by the Lewis spiral junction when the readings with the latter were interpreted on the basis of the calibration by immersion. In calm air the Benedict couple gave results which were very similar to those given by the spiral junction, but the readings made in the presence of wind

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suggest that, even in the 6 sec. or so for which the junction was applied, the hindrance of the heat-loss from the skin affected the skin temperature.

In Fig. 6 two curves are shown for the results obtained with the Strauss junction. The lower of these is based on a calibration by the usual method of immersion. We have not seen a description of Strauss's method of calibration, but data published by him (Strauss and Schwarz, 1932) lead us to the conclusion that he used the method of immersion. The other curve in the diagram is based on a calibration made by applying the test junction to the surface of a copper bath containing water of known temperature, the constant temperature junction being immersed in water at room temperature. If the

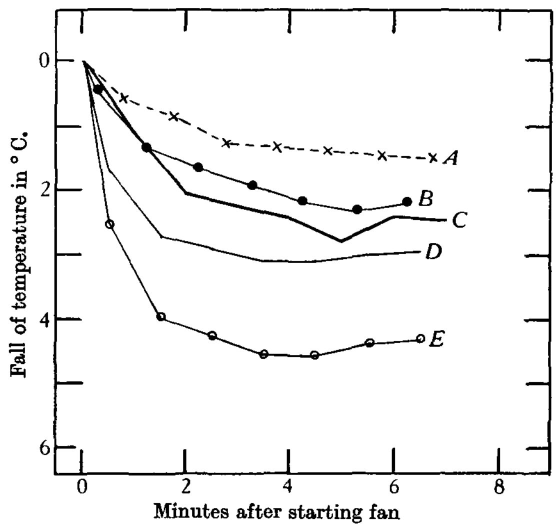

Fig. 7. Fall of forehead temperature due to wind of 350 ft. per min., as estimated by different methods. Curve *A*, Benedict thermo-junction; curve *B*, spiral thermo-junction (Lewis); curve *C*, Moll thermopile; curve *D*, Strauss thermo-junction (immersion calibration); curve *E*, Strauss thermo-junction (contact calibration).

results be interpreted on the basis of the surface contact calibration, the forehead temperature is estimated fairly accurately under still air conditions, but the fall of temperature in the wind is much exaggerated. With the immersion calibration the skin temperatures estimated are about 4° C. below those given by our radiation measurements.

The effect of the wind on the skin temperature as estimated by the different methods is shown in Fig. 7. The fall of temperature as estimated by the Lewis spiral junction is practically the same as that indicated by the thermopile measurements. The temperature drop shown by the Benedict junction is only about 1·5° C. as compared with the 2·4° C. given by the radiation method. In the case of the Strauss junction, interpretation of the results on the basis of the immersion calibration shows a temperature reduction of 3° C., while calculations from the surface contact calibration give a fall of temperature of 4·4° C. as compared with the 2·4° C. estimated from the thermopile readings.

The data just quoted show a fairly close agreement between the estimates of forehead temperature obtained with the Benedict thermo-junction and with the radiation thermopile, but in some other observations made in almost still air the Benedict junction yielded results which differed by 1–2° C. from the values obtained by means of the thermopile. The observations were always made by the method prescribed by Benedict and mentioned earlier in this paper; in the intervals between observations the junction and its hard rubber holder were held in the hand so as to keep the apparatus at hand temperature. It was thought that these discordant results might be caused by variations in hand temperature, and observations were made to test this point.

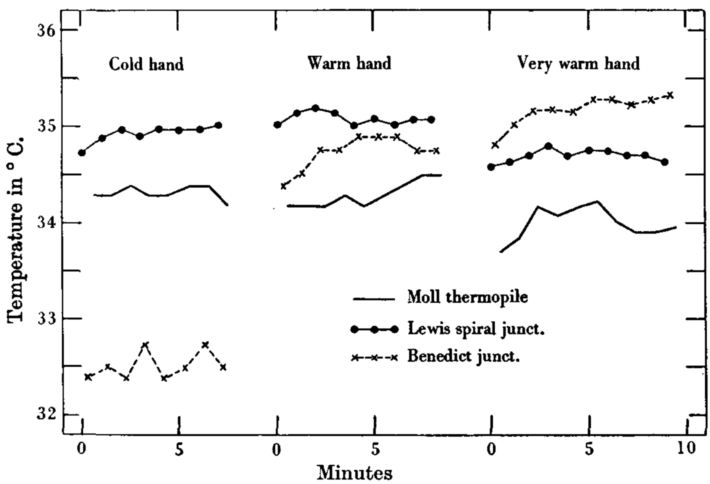

Fig. 8. Effect of observer's hand temperature on skin temperature estimates made by means of Benedict thermo-junction.

Fig. 8 shows the results of three sets of observations, made (*a*) when the hand holding the thermo-junction had been previously chilled by immersion for some minutes in very cold water, (*b*) when the hand was comfortably warm, and (*c*) when the hand was very warm. For comparison the curves obtained by means of the Lewis junction and the Moll thermopile are also given. When the hand was cold the Benedict junction gave a temperature about 1·6° C. below the thermopile value, while with the hot hand the estimate was about 1° C. above that given by the thermopile. When the Benedict form of thermo-junction is used it is evidently desirable that the temperature of the observer's hand should be approximately the same as that of the skin to be tested.

Further comparisons were made of the Benedict and Strauss forms of apparatus with the Moll thermopile in estimating the temperature of the skin at different points on the naked chest. Observations were made (*a*) under quiet room conditions, and (*b*) with a wind of about 350 ft. per min. The air temperature was 22° C. The results are summarised in Table I.

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Table I. *Mean difference between skin temperature of chest as estimated by means of (a) Moll radiation thermopile, and (b) thermo-junctions.*

Type of thermo-junction	Method of calibration	No. of observations	Temperature difference in ° C. (Thermo-junction *minus* thermopile) In still air	In wind
Benedict	Immersion	60	+0·60	0·00
Strauss	,,	78	−2·34	−3·01
,,	Surface contact	78	+1·65	−0·43

Compared with the thermopile values the temperatures given by the Strauss junction were relatively higher than in the observations on forehead temperature described earlier. On the basis of the immersion calibration the values were 2·3 and 3·0° C. below those given by the thermopile in still air and wind respectively, while in the measurements of forehead temperature the difference was about 4° C. When the junction was applied to the chest it became more deeply embedded than when applied to the more rigid surface of the forehead, and was thus more screened from the cooling effect of the surrounding air.

A summary of all the observations made on the chest and forehead is given in Table II, where the results are given as errors of estimation when the thermopile values are taken as standard.

Table II. *Mean errors of estimation of skin temperature, thermopile measurements taken as standard.*

		Still air			Wind of 350 ft. per min.		
			Mean error in ° C.			Mean error in ° C.	
Type of thermo-junction	Method of calibration	No. of obser-vations	Having regard to sign	Without regard to sign	No. of obser-vations	Having regard to sign	Without regard to sign
Lewis	Immersion	126	+0·48	0·51	38	+0·79	0·79
Benedict	,,	162	+0·35	0·74	62	+1·15	1·30
Strauss	,,	124	−3·01	3·01	62	−3·52	3·52
,,	Surface contact	124	+0·81	1·17	62	−0·86	0·97

The Lewis and Benedict models both gave results which were somewhat higher than those given by the Moll thermopile, but on the average the difference was only half a degree in calm air. In moving air the differences were rather greater, reaching over a degree in the case of the Benedict couple. The Benedict junction under-estimated the cooling effect of the wind on the skin by about 0·8° C. Serious error arises from the use of the Strauss junction. With the immersion calibration the temperatures are under-estimated to the extent of 3–3·5° C. Using the contact calibration the estimated temperature was too high in still air and too low in moving air; the effect of wind being exaggerated to the extent of 1·7° C. The most reliable of the three thermo-junctions tested by us seems to be the simple spiral junction of Lewis, though reasonably good results were also given by the Benedict couple. The single layer of surgical tape used for covering the Lewis junction ensures good thermal contact with the skin and protects the junction from the cooling effect of the air, while it does not appear to cause much interference with the normal heat-loss from the skin.

Interesting confirmation of the close correspondence between estimates of temperature made by means of the Lewis thermo-junction and the Moll thermopile (unprotected except by its reflecting cone) has been given us by Dr G. P. Crowden. Some two years ago in a study of the effects of vibration he measured the finger temperatures of a subject in still and moving air, the

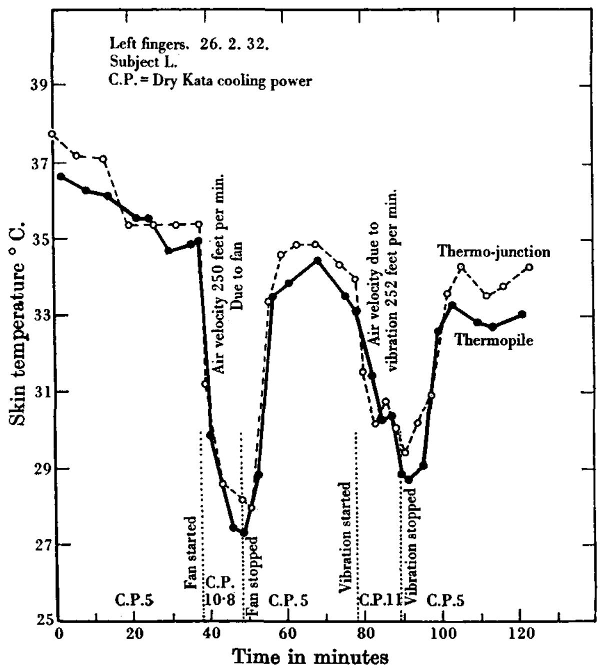

Fig. 9. Comparison of skin temperature measurements by Lewis contact thermo-junction and radiation thermopile in still and moving air (Crowden).

air movement being created in one case by a fan and in the other by mechanically induced vibration of the hand. Dr Crowden's hitherto unpublished observations are shown in Fig. 9. It will be seen that the two methods of measurement agree to within $\frac{1}{2}$° C., and that the Lewis junction accurately measures the great cooling effect of wind on the skin of the fingers.

IV. Electrical resistance thermometers.

Some observations of forehead temperatures were made by means of an electrical resistance thermometer. The resistance was a grid of lead-foil (as described by Stewart), mounted on an ebonite holder and carefully insulated. Comparative readings were made with the Moll thermopile.

In a few preliminary observations the resistance thermometer was applied straight away to the area of skin where the measurement was required. Before a steady galvanometer reading was obtained the surface of the ebonite holder had to be warmed to skin temperature, and it was found that this took about 3 min. Temperatures estimated in this way were all lower than the corresponding values obtained with the thermopile, the average error being 0·62° C. It seemed likely that this discrepancy was due to the skin being cooled by contact with the ebonite holder. In later observations the thermometer was first applied to the skin for about 3 min. on an area adjacent to that at which the temperature was required, and then moved into position for a further 10 or 15 sec. before the galvanometer was read. In these observations the mean error of the temperatures estimated with the resistance thermometer, taking the thermopile values as standard, was only 0·24° C.

These observations were made under quiet room conditions, with an air temperature of 17° C. When the thermometer is warmed on another area of skin before being applied to the observation point it is clear that in steady conditions a resistance thermometer of the type used by us is capable of yielding estimates of skin temperature which compare favourably with those obtained by means of thermo-junctions. Further observations were made at a room temperature of 22° C., in which the skin temperatures were first estimated in still air and then in a wind of 350 ft. per min. In the still air observations of this series the temperature as estimated by the resistance thermometer averaged 0·58° C. below the thermopile value, while in the wind the two averages were the same. The mean error of individual estimations was 0·74° C. in still air, and 0·47° C. in the wind.

V. Mercury thermometers.

Over a hundred years ago Davy (1814) used a mercury thermometer for measuring skin temperatures, and various workers have since used this method. Benedict, Coropatchinsky and Finn (1929) object to the use of mercury-in-glass thermometers for measuring skin temperature on the ground that such a thermometer when pressed on the skin obstructs the cutaneous circulation. They also say that no mercury thermometer with which they are familiar is rapid enough to measure the true skin temperature. Campbell and Angus (1928), at the suggestion of Leonard Hill, measured skin temperatures by *rolling* the bulb of a thermometer over the skin for 1–1½ min., and compared the values thus obtained with the results yielded by a Benedict thermo-junction. They found that the results agreed very well. The mean error was 0·3° C., and the average difference taking due regard of sign was 0·15° C. Vernon and Warner (1932), working at high air temperatures, made a comparison of the skin temperatures estimated with a mercury thermometer and with a thermopile. At an air temperature of 30° C. the average results by the two methods were the same, but at 38–39° C. the thermometer readings averaged 0·7° C. higher than the radiation values.

We have made measurements of the skin temperature on the face and chest by rolling a thermometer on the skin, and have compared our results with those given by radiation measurements. Readings were taken both in still air and in wind with a room temperature of 22° C. In fifty observations the mercury thermometer gave an average temperature only 0·15° C. below that given by the thermopile, and the mean error was 0·35° C. These results agree with the findings of Campbell and Angus.

Stewart (1930) describes a method of using a clinical thermometer for the accurate measurement of skin temperatures. The bulb of the thermometer is inserted into a cylindrical opening bored in the narrow edge of a small wedge of cork. When in position on the skin the bulb is completely protected against exposure to the air. Using a "one-minute" thermometer Stewart generally allows 2 or 3 min. for the thermometer to register its maximum, but he points out that an erroneous result will be obtained if an arbitrary time of contact is taken. The thermometer is applied to the skin with a uniform gentle pressure.

Using a "one-minute" clinical thermometer in the way described by Stewart, we have made measurements of forehead temperatures and compared the results with those obtained by means of the thermopile. The observations were all made in practically still air at a temperature of 17° C. The average of twelve readings of the clinical thermometer was 0·10° C. higher than the average of the thermopile measurements, and the mean error was 0·27° C. Estimates made in this way have the same order of accuracy as those made by rolling a thermometer on the skin, but with Stewart's method the observations take longer. By rolling a thermometer an observation can be made in about $1\frac{1}{2}$ min., whereas Stewart allows 2–3 min. for his clinical thermometer. We found that the clinical thermometer took at least 4 min., and generally 5 min., to reach its maximum. Stewart points out that even the smallest mercury thermometer will have too much lag to be able to detect rapid changes of skin temperature.

VI. A COMPARISON OF RECORDED FOREHEAD TEMPERATURES.

It has been shown earlier in this paper that estimates of skin temperature made with different forms of apparatus are subject to considerable variation, and it is of interest to compare the results of some earlier observers. Since these results were obtained under varying environmental conditions it is desirable that they should be compared with some standard. The most consistent data for such a comparison are probably those relating to forehead temperatures, and as a standard for comparison we have used observations made recently by us on women and girls of various ages, normally clad, and doing light, sedentary work. In all 415 observations were made of the forehead temperatures of as many different subjects. The measurements were made by means of the Moll radiation thermopile, which was used without the rock-salt window. The air temperature ranged from 15 to 23° C., and the air velocity from less than 10–50 ft. per min., averaging 28 ft. per min. The coefficient of correlation of forehead temperature (y) with air temperature (x) is $+0{\cdot}44$, and the regression equation of forehead temperature on air temperature over the range of temperature covered is

$$y = 0{\cdot}348x + 27{\cdot}9 \qquad \text{......(i)},$$

where y and x are both in ° C. Owing, probably, to the variations in air velocity, differences in clothing, and individual differences in the subjects themselves, there is considerable scatter amongst the observations and the root-mean-square error of estimation of single forehead temperatures by means of the regression equation is 1·7° C.

Table III shows a comparison of the results of other observers with values calculated from the above equation. Where air temperatures less than 15 or over 23° C. have been used, values for forehead temperature have been calculated, although our observations did not go above that value.

Table III. *Comparison of forehead temperatures recorded by various observers with mean values given by thermopile measurements.*

Observer	Method of measurement	Air temperature ° C.	Forehead temperature ° C.	Corresponding temperature by equation (i) ° C.	Remarks
Oehler (1904)	Mercury thermometer	19–20	35·0	34·5–34·9	—
Vernon, Bedford and Warner (1930)	Thermopile	16	34·0	33·5	—
Kunkel (1889)	Thermo-junction	20	34·1–34·4	34·9	Apparatus previously warmed
		10–12	33·2–33·4	31·4–32·1	—
Benedict (1925)	,,	19·0–20·4	31·0–33·3	34·5–35·0	—
Ward (1930)	,,	20–22	32·6–33·9	34·9–35·6	Benedict-type junction
Miura (1931)	,,	20–21	34·4–35·2	34·9–35·2	,,
Reichenbach and Heymann (1907)	,,	19·4	31·1	34·7	Constant pressure type
Lange (1921)	,,	19–22	30·6–32·8	34·5–35·6	—
Liese (1930)	,,	25	33·6	36·6	Strauss-type junction
Strauss and Schwarz (1932)	,,	17·5	29·4–31·3	34·0	,,
		21	30·3–31·7	35·2	—
		25	32·1–32·6	36·6	—
Bloomfield, Ives and Britten (1930)	,,	14·5	32·4	32·9	—
		24·5	36·3	36·4	—
Stewart (1891)	Electrical resistance thermometer	18·3–18·5	32·6–33·0	34·3	—

Using a mercury thermometer, Oehler (1904) observed a forehead temperature which is only a fraction of a degree different from the value given by our equation. Earlier in this paper we have confirmed that skin temperatures can be estimated with considerable accuracy by means of mercury thermometers.

Observations made by Vernon, Bedford and Warner (1930) by means of the Moll thermopile used in the present investigation agree to within half a degree with the regression equation (i).

Kunkel (1889) used a thermo-junction fixed to a special holder, and he warmed the apparatus approximately to skin temperature before use. His observed forehead temperatures in air at 20° C. agree closely with equation (i). Those observed at 10–12° C. are from 1 to 2° C. higher than those given by the equation, but the air temperatures were considerably lower than the range covered by it.

In Table III data are quoted from Benedict (1925), and from Ward (1930) and Miura (1931) who both used Benedict-type thermo-junctions. Benedict's and Ward's temperatures are about 2° C. below those calculated from our equation, while those of Miura are almost identical with our calculated values.

Reichenbach and Heymann (1907), using a thermo-junction mounted on a three-footed holder, observed temperatures which are much lower than

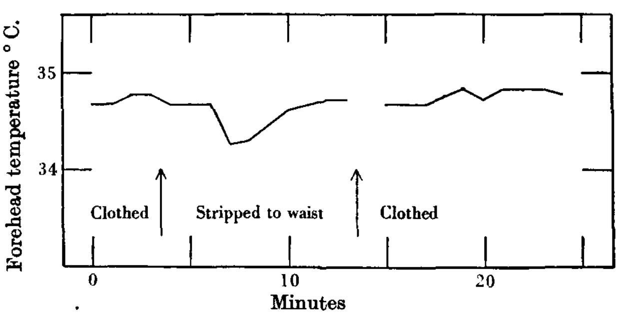

Fig. 10. Forehead temperature of subject (*a*) normally clad, and (*b*) stripped to the waist.

would be expected from our equation. The figure of 31·1° C. at an air temperature of 19·4° C. is 3·6° C. lower than our calculated value. Lange (1921) also gives temperatures which are 3–4° C. below those given by our equation. It seems probable that in these investigations the thermo-junctions were influenced by the temperature of the surrounding air.

Liese (1930) and Strauss and Schwarz (1932) used the Strauss thermo-junction device, but their subjects were not fully clad. The subjects of Strauss and Schwarz were stripped to the waist, and Liese's subject had his trunk covered only with an open shirt. The temperatures recorded by these observers are 2·7–4·9° C. below the values calculated from our equation for clothed subjects. These large discrepancies are doubtless due almost entirely to the cooling of the thermo-junction by the surroundings. The fact that the subjects had large areas of skin exposed probably does not account for more than a small fraction of the differences between the observed forehead temperatures and our calculated values, for we have found that stripping a subject to the waist has little influence on his forehead temperature.

Fig. 10 shows that when the subject was stripped to the waist there was a transitory fall in the temperature of the forehead, followed by an almost complete recovery. When the subject was again clothed there was scarcely any further rise in the forehead temperature. The air temperature during the experiment was 19° C., and the air was practically still. Skin temperatures were measured by means of the thermopile. Similar results were obtained in another experiment made when the air temperature was 21–21·5° C.

Bloomfield, Ives and Britten (1930) used a thermo-junction of the pattern shown in Fig. 3. Their main investigation concerned steel workers who were exposed to considerable radiation, but the figures quoted in Table III relate to persons who were not so exposed. Since the thermo-junction was not covered it might be expected that the forehead temperatures recorded would be somewhat below our calculated values, but in fact they agree very closely with these values. On the other hand, Aldrich (1928), using the same type of apparatus, obtained temperatures 1·1° C. below those arrived at by radiation measurements, and thermo-junction readings of skin temperature were always corrected by the addition of 1·1° C. to the observed temperature. In explanation of this discrepancy Aldrich offers a suggestion made by Dr Abbott, that since the skin is porous and the internal temperature of the body is higher than that of the surface, the melikeron (Aldrich's instrument for measuring radiation) sees into a deeper layer than that reached by the thermo-element. We would suggest that a more probable cause of the low thermo-junction temperatures is cooling of the junction by exposure to the air.

It was mentioned in an earlier section that Winslow and Greenburg (1932) used a thermo-junction which was exposed to the air. Their data of atmospheric conditions are given in terms of effective temperature, a scale which takes into account air temperature, humidity and air velocity, and it is therefore not possible to compare their results with the data already quoted.

The results obtained by Stewart (1891) with his resistance thermometer are about 1·5° C. below our calculated value.

VII. Summary and conclusions.

For the measurement of the temperature of exposed skin surfaces, we have reached the conclusion that the most accurate instrument is a radiation thermopile suitably screened from the effects of wind. As the thermopile does not actually touch the skin it does not interfere with the cutaneous circulation; neither does it hinder the heat-loss from the skin surface. Readings are simply and rapidly made; with the Moll thermopile and the Cambridge unipivot galvanometer used by us a reading can be taken in 4–6 sec. The readings are not influenced by wind if the thermopile is screened, and as the temperatures are measured as differences from that of a blackened surface of known temperature, change of air temperature does not upset the results. The apparatus is easily portable.

By rolling a mercury thermometer over a small area of skin the temperature can be estimated with but very slight error. This method is a reliable one for use where other apparatus is not available; but, it has the disadvantage that each observation takes from 1 to $1\frac{1}{2}$ min. Accurate estimates cannot be obtained by this method in the special cases when the skin temperature is subject to rapid variation.

Under steady conditions accurate estimates can also be made by means of a clinical thermometer protected by a cork wedge, but each observation takes from 4 to 5 min.

Of the types of thermo-junction tested by us the simple Lewis type of junction attached and protected by a strip of surgical tape appears to give the most accurate results. The average error, taking the thermopile values as standard, was only 0·5–0·8° C., and the thermo-junction temperatures were consistently higher than the thermopile values by about this amount.

The Benedict type of junction also gives results which compare reasonably well with those obtained from radiation measurements. In our observations the average error with this type of junction was 0·7–1·3° C., and the error usually had the effect of giving too high a value for the thermo-junction temperature. Other observers, however, have measured temperatures with this type of junction which appear to be somewhat low, and it appears possible that the temperature of the observer's hand may have influenced the readings obtained.

Forms of apparatus in which the thermo-junction and its leads are exposed to the effects of the air are liable to give very erroneous estimates of skin temperature. In our own comparisons the skin temperature was underestimated by 3–3·5° C. when the Strauss thermo-junction was used; and examples have been drawn from the literature which suggest that, with other apparatus in which the junction was exposed, the temperature was underestimated. If such forms of apparatus are used for measuring skin temperatures beneath the clothing, they may yield fairly reliable results, but in exposed positions considerable errors may arise. This liability to error is particularly serious where there is a wide range of air temperature and of air movement.

Skin temperatures can be measured with considerable accuracy by means of an electrical resistance thermometer.

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