SKIN TEMPERATURE IN RELATION TO THE WARMTH OF THE ENVIRONMENT

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(With 2 Figures in the Text.)

CONTENTS

I. Introduction

From time to time various workers have made observations of skin temperature (usually that of the forehead) in relation to air temperature, and several equations relating forehead temperature to air temperature have been recorded.

The published results show considerable differences in the forehead temperatures observed at a given air temperature. These results have been summarised by Phelps and Vold (1934), who show that with an air temperature of 20° C. different observers record mean temperatures of the forehead, or of the forehead and cheeks, ranging from 31·8 to 34·9° C. in clothed subjects. Some of this variation is probably due to differences in the methods by which the skin temperatures were measured, but other factors, such as the amount of clothing worn by the subjects, are likely to have affected the results.

These earlier investigations relate to individuals or to small groups of subjects, and the results are not of general application. If one is to be able to predict the forehead temperature from a knowledge of the air temperature, and to be able to estimate the error to which such prediction is liable, the estimate must be based on observations made on a large number of subjects. Hitherto no such observations appear to have been recorded; and there does not seem to be available much information relating the temperatures of the extremities to air temperature.

In a recent study of comfort in relation to the thermal environment, systematic measurements were made of the temperatures of the foreheads, hands and feet of a large number of persons performing very light industrial work. These measurements have been related to the temperature conditions under which they were made, and the results are presented in this paper.

II. Method of investigation

At selected points in the various factories visited, observations of the temperature, velocity and humidity of the air, and of the intensity of radiation, were made. Further observations were made using instruments which give measures of combinations of these factors. These include the kata-thermometer, with which the dry kata cooling power was determined; and the eupatheoscope, which is calibrated in terms of "equivalent temperature". The data relating to the temperature, humidity and velocity of the air were also combined according to the "effective temperature" scale, which is widely used in America. The observed air temperatures ranged from about 12 to 24° C.

Immediately after these readings had been taken the skin temperatures of the group of operatives working within a few feet of the observation position were measured. Altogether 3085 sets of skin temperature observations were made. Of these observations 94 per cent. were made on women and girls, and 89 per cent. of all the subjects were seated at their work. Usually a subject was tested only once, but a number of persons were tested on two or three different occasions. It is estimated that observations were made on nearly 2000 different subjects. In this way the present study differs from previous investigations, in which the observations have been confined to small groups of subjects.

The temperatures of the forehead and of the palm of one or both hands were measured by means of a Moll radiation thermopile.

For the measurement of foot temperatures a thermo-junction was applied outside the stocking at a point on the inner aspect of the foot about an inch below the ankle. As nearly all the subjects were women or girls wearing thin silk or rayon stockings, the measured temperature was substantially that of the skin beneath the stocking. In calibrating the couple, the standard junction, carefully insulated, was immersed in a vacuum flask of water, and the testing junction was applied to the outer face of a thin-walled copper bath, which contained water at a known temperature. The calibration thus made allowance for the influence on the temperature of the thermo-junction of the cooler air surrounding it. In some trial observations made in the laboratory on two subjects wearing thin rayon socks, the foot temperature was measured with the thermo-junction applied outside the sock, and then the shoe and sock were quickly removed and the temperature again measured with the Moll thermopile. In sixty observations made on the two subjects the mean of the estimations made with the contact thermo-junction differed by only 0·01° C. from the mean of the measurements made with the thermopile on the naked skin, while the average error of individual observations, taking thermopile values as standard, was only $\pm 0{\cdot}44°$ C.

The observations have been divided into two groups. In the larger group (A) the 2571 subjects were not exposed to any marked radiant heat effects, and the temperature was fairly uniform as between head level and floor level. In the other group (B), with 514 subjects, the women and girls concerned were using gas-heated soldering irons which emitted a considerable amount of radiant heat, and the air temperature at head level was often considerably higher than that at floor level. It is obvious that the temperature of the air at 4 ft. above the floor (*i.e.* the head level of a seated person) does not adequately describe the warmth conditions to which the persons in group B were exposed.

III. The correlation of skin temperature with environmental conditions

(*a*) *Forehead temperature*

Table I shows the correlation coefficients, which throughout the paper are quoted with their probable errors, for forehead temperature and the various instrumental measurements.

Table I. *Correlation of forehead temperature with warmth conditions.*

Forehead temperature correlated with	Correlation coefficient (r) for Group A	Group B
Air temperature 4 ft. from floor	$+0{\cdot}330 \pm 0{\cdot}012$	$+0{\cdot}159 \pm 0{\cdot}029$
Equivalent temperature ...	$+0{\cdot}346 \pm 0{\cdot}012$	$+0{\cdot}181 \pm 0{\cdot}029$
Effective temperature	$+0{\cdot}328 \pm 0{\cdot}012$	$+0{\cdot}178 \pm 0{\cdot}029$
Dry kata cooling power ...	$-0{\cdot}327 \pm 0{\cdot}012$	$-0{\cdot}083 \pm 0{\cdot}029$

The correlation coefficients for group A are all of similar magnitude, and there is no statistically significant difference between any pair of them. Thus the forehead temperature appears to be as closely associated with air temperature as with any of the other three more complex measures. In group B, also, there is no significant difference between the coefficients quoted, but the coefficients for this group are all distinctly lower than in group A. The subjects in group B were exposed to localised radiation, particularly on their faces; and such directional radiation, which had a considerable effect on the forehead temperature, had a relatively small influence on the instrumental measurements referred to in the table.

Phelps and Vold (1934) made two series of observations on three female subjects. Correlating the face temperature (mean of forehead and both cheeks) with air temperature they obtained, for the individual subjects, coefficients ranging from 0·48 to 0·61 in the first series, and from 0·70 to 0·75 in the second series. The present observations yield distinctly lower correlations owing, no doubt, to the influence of individual differences among the large population examined.

(*b*) *Hand temperature*

In Table II the correlation coefficients of hand temperature with measurements of room temperature, etc., are given.

The coefficients for both groups are similar in size. In group A there is no significant difference between the coefficients shown. In group B the correlation of hand temperature with dry kata cooling power is lower than the other coefficients, but the difference is not significant.

Table II. *Correlation of hand temperature with warmth conditions.*

Hand temperature correlated with	Correlation coefficient (r) for Group A	Group B
Air temperature 4 ft. from floor	$+0\cdot353 \pm 0\cdot012$	$+0\cdot339 \pm 0\cdot030$
Equivalent temperature ...	$+0\cdot364 \pm 0\cdot012$	$+0\cdot367 \pm 0\cdot029$
Effective temperature	$+0\cdot374 \pm 0\cdot012$	$+0\cdot346 \pm 0\cdot030$
Dry kata cooling power ...	$-0\cdot353 \pm 0\cdot012$	$-0\cdot263 \pm 0\cdot032$

(*c*) *Foot temperature*

It is to be expected that the temperature of the feet will be influenced not only by the air temperature usually measured, that at about head level, but also by the temperature of the air surrounding the feet. In Table III, therefore, the correlations of foot temperature with air temperature and dry kata cooling power measured at a height of 6 in. from the floor are given, as well as those with temperature, etc., measured at or about head level.

Table III. *Correlation of foot temperature with warmth conditions.*

Foot temperature correlated with	Correlation coefficient (r) for Group A	Group B
Dry bulb temperature, 6 in. from floor	$+0\cdot536 \pm 0\cdot010$	$+0\cdot667 \pm 0\cdot017$
Dry kata cooling power, 6 in. from floor	$-0\cdot221 \pm 0\cdot013$	$-0\cdot552 \pm 0\cdot021$
Dry bulb temperature, 4 ft. from floor	$+0\cdot504 \pm 0\cdot010$	$+0\cdot532 \pm 0\cdot022$
Dry kata cooling power, 4 ft. from floor	$-0\cdot249 \pm 0\cdot013$	$-0\cdot541 \pm 0\cdot022$
Equivalent temperature	$+0\cdot464 \pm 0\cdot011$	$+0\cdot504 \pm 0\cdot023$
Effective temperature	$+0\cdot487 \pm 0\cdot010$	$+0\cdot533 \pm 0\cdot022$

There is, of course, a high correlation between the air temperatures at heights of 6 in. and 4 ft. from the floor, for when the temperature at one level is high that at the other level also tends to be high. This association is particularly marked in the observations of group A ($r = +0\cdot892 \pm 0\cdot003$), and the temperature 4 ft. from the floor is therefore a substantially accurate index of the temperature 6 in. from the floor. In the group B observations the association between the two air temperatures is less pronounced ($r = +0\cdot732 \pm 0\cdot014$), and with similar air temperatures at head level there were variations in the temperature near the floor. The influence of this difference in the degree of association between the two air-temperature measurements is reflected in the coefficients shown in Table III, for in group B the correlation of foot temperature with 6-in.-level air temperature is significantly higher than that with the air temperature at a height of 4 ft., while in group A the correlations of foot temperature with the two air temperatures are not significantly different. In group B the coefficient for 6-in.-level air temperature is definitely higher than the remaining coefficients which do not differ significantly from each other. In group A the coefficient for 6-in.-level air temperature is significantly higher than the others with the exception of that for head-level air temperature, and the correlations for dry kata cooling power are significantly the lowest for the group.

The influence of the floor-level air temperature on the temperature of the feet is made clear when partial correlation coefficients are calculated.

In Table IV it is shown that with a constant temperature near the floor, changes in temperature at head level have but little effect on foot temperature, but with a constant temperature at head level change in the temperature near the floor has a notable effect on the temperature of the feet.

Table IV. *Partial correlations of foot temperature with air temperature.*

Foot temperature correlated with	Constant	Partial correlation coefficient for Group A	Group B
Air temperature, 6 in. from floor	Air temperature, 4 ft. from floor	$+0{\cdot}222 \pm 0{\cdot}014$	$+0{\cdot}481 \pm 0{\cdot}030$
Air temperature, 4 ft. from floor	Air temperature, 6 in. from floor	$+0{\cdot}067 \pm 0{\cdot}014$	$+0{\cdot}087 \pm 0{\cdot}030$

In both groups the correlation coefficients of dry kata cooling power with foot temperature are significantly less than those of foot temperature with floor-level air temperature. It was shown in Tables I and II that in group B the correlations of skin temperature with cooling power tended to be lower than the other coefficients for the groups, although in each case the differences from the remaining coefficients were not statistically significant. Considering these results together with those in Table III, however, it seems possible that skin temperature may be less closely associated with kata-thermometer readings than with the other measures of environmental conditions mentioned. It appears also that, under conditions such as those encountered in this investigation, where there was no strong air movement (air velocity, 10–100 ft. per min.), the simple dry-bulb air temperature was, on the whole, as good an index of skin temperature as either equivalent temperature or effective temperature.

If, however, we consider only forehead temperature and hand temperature, both of which are influenced more by warmth conditions at head level than by those near the floor, there is in each of the four series of data in Tables I and II a slight but constant superiority of equivalent temperature over air temperature (measured at 4 ft. from the floor) as an index of skin temperature. In each instance the difference is insignificant, but the four series taken together suggest that the apparent superiority of equivalent temperature is a real one, and it is probable that if, in the environmental conditions studied, there had been a greater range of air movement this superiority would have shown itself more definitely.

IV. Skin temperature in relation to air temperature

In the factories in which the observations in group A were made the air was fairly uniform in temperature and with but moderate velocity, and the temperature of the surroundings was much the same as that of the air. These

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observations therefore show the extent to which the average skin temperature of a large number of persons wearing ordinary clothing varies with change in air temperature. The average values are plotted in Fig. 1. The points plotted in the diagram represent the average skin temperatures observed at different

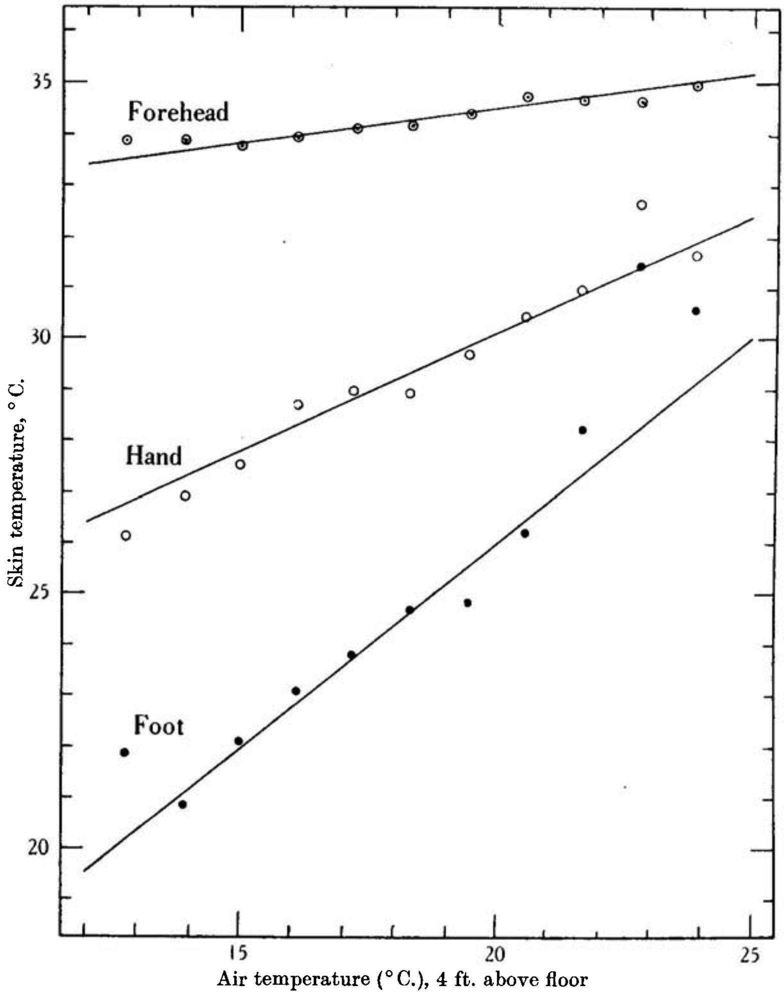

Fig. 1. Average skin temperature in relation to air temperature.

intervals of air temperature, and through each set of points the regression straight line has been drawn. The equations to these lines are

Forehead temperature: $t_s = 0{\cdot}139t_a + 31{\cdot}74$ ......(i),

Hand temperature: $t_s = 0{\cdot}465t_a + 20{\cdot}81$ ......(ii),

Foot temperature: $t_s = 0{\cdot}806t_a + 9{\cdot}86$ ......(iii),

where t_s and t_a represent skin temperature and air temperature respectively, both temperatures being given in ° C.

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The equation for forehead temperatures fits the mean observed values very closely, and the regression coefficient shows that, on the average, the temperature of the forehead rises by 0·139° C. for a rise of 1° C. in air temperature. This coefficient is distinctly lower than any of those quoted by Phelps and Vold (1934), including the value given by C. G. Warner and the writer (Bedford and Warner, 1934) in an earlier paper which was based on a much smaller number of observations.

The mean values for the temperature of the palmar surface of the hand also lie closely about the regression line. The average hand temperature rises by 0·465° C. for a rise of 1° C. in air temperature.

Over the greater part of the curve, the regression line for foot temperature fits the observed values very well. The only points which lie appreciably away from the curve are those for the highest two air temperatures and that for the lowest air temperature. Altogether these three points represent less than 1·7 per cent. of the total observations, so it seems probable that the relation between foot temperature and air temperature is sufficiently described by a straight line. According to the regression equation a rise of 1° C. in air temperature is accompanied on the average by a rise of 0·806° C. in the temperature of the foot.

The mean skin temperatures associated with certain air temperatures have been calculated from the regression equations and are given in Table V.

Table V. *Skin temperature in relation to air temperature.*

Air temperature ° C.	Average temperature (° C.) of skin of: Forehead	Hand (palmar surface)	Foot
15	33·83	27·8	22·0
16	33·96	28·3	22·8
17	34·10	28·7	23·6
18	34·24	29·2	24·4
19	34·38	29·7	25·2
20	34·52	30·1	26·0

V. Correlation of the temperatures of different areas of skin

It is to be expected that there will be a relation between the temperatures of the skin of different parts of the body; that a person with a cool forehead will tend to have cool hands and feet, and that one with cold hands will have cold feet. This proves to be the case, but the association is not very close. The intercorrelations of skin-temperature measurements on the subjects of group A are given below.

Table VI. *Intercorrelations of skin temperatures.*

Skin temperatures correlated	Coefficient of correlation (r)
Forehead temperature and hand temperature	$+0{\cdot}297 \pm 0{\cdot}012$
Forehead temperature and foot temperature	$+0{\cdot}121 \pm 0{\cdot}013$
Hand temperature and foot temperature	$+0{\cdot}313 \pm 0{\cdot}012$

Each of the coefficients is less than those recorded earlier for the correlation of skin temperature with air temperature.

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VI. Discussion

The curves of Fig. 1 show the variation with air temperature of the average skin temperatures of the forehead, hands and feet of a large number of subjects; and it is thought that they may be of some use as standards with which observations on individual subjects may be compared. It is to be expected, however, that single observations may differ considerably from the values indicated by the curves. In the data under discussion there is much variation in the skin temperatures recorded at any particular air temperature. The root-mean-square errors of estimation of skin temperature from air temperature ($\sigma_{s \cdot a}$) are

Forehead temperature	...	$\sigma_{s \cdot a} = 0{\cdot}81^\circ$ C.
Hand temperature ...	...	$\sigma_{s \cdot a} = 2{\cdot}51^\circ$ C.
Foot temperature ...	...	$\sigma_{s \cdot a} = 2{\cdot}80^\circ$ C.

The correlations between the temperatures of different areas of skin are lower than those between skin temperatures and air temperature. Consequently, estimates of skin temperature calculated from the air temperature by means of equations (i) to (iii) will, on the whole, be more accurate than estimates made from a knowledge of the temperatures of other areas of skin. The temperature of a person's foot, for example, can be estimated with somewhat greater accuracy from a knowledge of the air temperature than from a knowledge of that person's hand temperature or of his forehead temperature.

In a study of the thermal exchanges between men and the environment, Houghten and others (1929) found that, with still air at a relative humidity of 20 per cent., the heat loss by radiation and convection was zero at an air temperature of 37° C. That is to say, the mean temperature of the body surface was then equal to the air temperature, and the only channel of heat loss was by evaporation.

Phelps and Vold (1934) noted that if they extrapolated beyond the range of conditions covered by their investigation, and calculated the face temperature for a room temperature of 37° C., they obtained a face temperature of 37° C. Their average absolute humidity corresponds to a relative humidity of about 17 per cent. at 37° C.

If from the equations (i) and (ii), given in the present paper for forehead and hand temperatures, we calculate the point at which air temperature and skin temperature coincide, we obtain values of 36·9° C. for forehead temperature, and 38·9° C. for hand temperature, which are in close agreement with the findings of the other observers quoted. Equation (iii), however, does not give a close agreement, for the calculated temperature at which air and foot temperatures would coincide is 50·8° C.

These regression equations were fitted by the method of least squares, and the slope of the curve of foot temperature is distinctly influenced by the observations (about 7 per cent. of the total) made at air temperatures above

21° C. It seemed of interest to find how the observation points would be fitted by straight lines meeting at a point and passing through the points representing the mean observed values. Such lines are shown in Fig. 2, where the regression lines of Fig. 1 are drawn in broken lines for comparison. The curves are made to meet in the point representing air and skin temperatures of 37·25° C. —a reasonable value for internal body temperature. The curves for forehead and hand temperatures are almost coincident with the regression lines. The curve drawn through the points representing the foot temperature observations

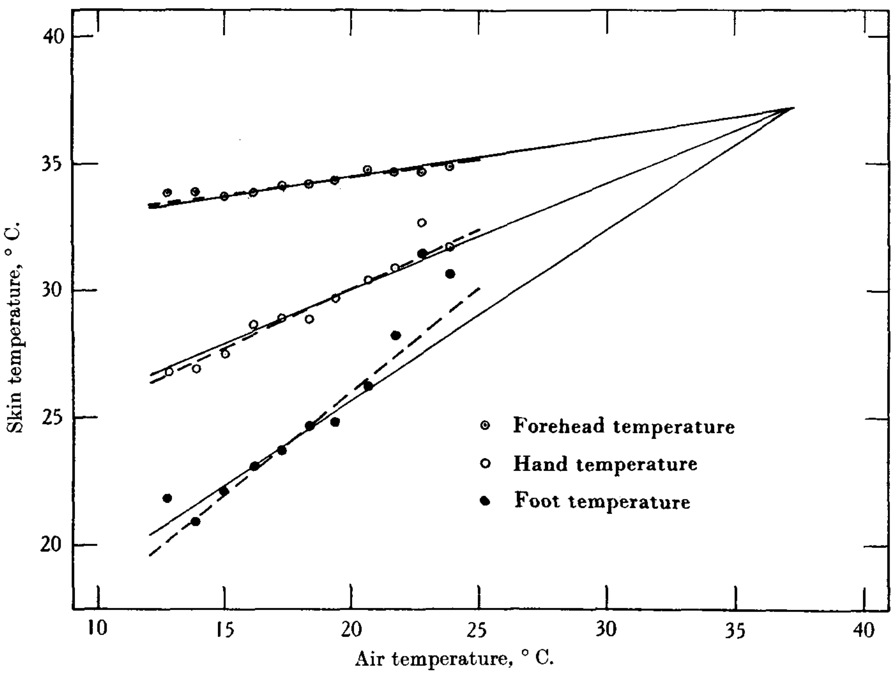

Fig. 2. Relation of skin temperature to air temperature, subjects normally clothed and doing very light work.

does not slope as steeply as the regression line, but for air temperatures of 15–21° C., a range covering the bulk of the observations, it fits the points very well. The mean vapour pressure in these observations was 7·17 mm. Hg, which corresponds to a relative humidity of 15 per cent. at a temperature of 37·25° C.

As an index of changes in the peripheral circulation, Burton (1934) proposes the use of a "thermal circulation index". This index (r) is given by

$$r = \frac{\text{External drop of temperature}}{\text{Internal drop of temperature}} = \frac{T_s - T_e}{T_i - T_s} \qquad \text{......(iv)},$$

where T_s is the surface temperature of a particular area of skin, T_e is the temperature of the environment (humidity, ventilation and clothing being

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controlled), and T_i is the internal body temperature at some specified point. Equation (iv) may be arranged to read

$$T_s = \left(\frac{1}{1+r}\right) T_e + \left(\frac{r}{1+r}\right) T_i \qquad \ldots\ldots(\text{v}).$$

The equations from which the firm lines in Fig. 2 have been drawn are of this form, T_s and T_e being the mean observed skin and air temperatures respectively, and T_i being taken as 37·25° C. The values of r calculated for the mean observed skin temperatures, with an average air temperature of 18° C., are:

Skin area	Thermal circulation index (Burton)
Forehead	5·4
Palm of hand	1·39
Foot	0·50

VII. Summary

The skin temperatures of industrial workers, mainly women and girls, engaged in very light occupations, have been correlated with environmental conditions. The temperatures of the forehead and of the palm of the hand were measured with a Moll radiation thermopile, and for the temperature of the foot a thermo-junction was used. Altogether 3085 sets of observations were made.

Various measures of environmental warmth (dry-bulb air temperature, equivalent temperature, effective temperature, and dry kata cooling power) were correlated with skin temperature. The dry-bulb air temperature is about as good an index of skin temperature as any of the other measures used, while it appears that skin temperature may be slightly less closely associated with dry kata cooling power than with the other measures of warmth conditions.

At an average air temperature of 18° C., the average skin temperatures observed were: on the forehead 34·25° C.; on the palm of the hand 29·2° C.; and on the foot 24·4° C. The average increases in skin temperature for a rise of 1° in air temperature were: on the forehead 0·139°; on the hand 0·465°; and on the foot 0·806° C.

There was much variation in the skin temperatures recorded at any particular air temperature. The root-mean-square errors of estimation of skin temperature from air temperature were 0·81, 2·51, and 2·80° C., for the forehead, hands and feet respectively.

Correlations between the temperatures of different areas of skin were rather lower than those between air and skin temperature.

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