CALORIMETRIC STUDIES OF THE EXTREMITIES

II. Experimental Apparatus and Procedures[1]

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The calorimeter used in these experiments is a modification of that devised and used by Stewart (1). The ensemble of apparatus is shown in figures 1 and 2. The details of construction of the calorimeter are sketched in figure 3. Preliminary tests showed that the water equivalent of the calorimeter under the conditions of use was 170 gram calories. In the chamber *b* there is a false bottom of wire of coarse mesh on which the foot of the subject is allowed to rest. This arrangement permits of better stirring of the water around the foot and also minimizes the tendency on the part of the person under test to move the foot. The temperature of the water in the calorimeter was measured and read to 0.01°C. by means of a certified Beckmann thermometer.

In order that the temperature may be kept as nearly uniform as possible throughout the calorimeter and therefore be correctly recorded by the thermometer, it is necessary that the water be stirred constantly and thoroughly during the period of the test. This stirring is accomplished by air currents in preference to any form of mechanical stirrer, not only because agitation by air is highly satisfactory, but also because of difficulties presented with any form of mechanical stirring.

The stream of air used for the agitation of the water in chamber *b* (fig. 3) must be at the same temperature as the water in this chamber and must enter it saturated with water vapor in order not to affect the temperature in the chamber. The apparatus used for this purpose was constructed and incorporated in the experimental ensemble as a

[1] This investigation was carried on while the writer was a member of the Section on Physics of The Mayo Clinic.

separate compartment *a* of the experimental calorimeter. It proved very reliable and easy to manipulate. Air drawn from the room is passed under pressure through a helical coil of copper tubing *X* immersed in water which is maintained as nearly as possible at the same

FIG. 1. APPARATUS USED IN MAKING CALORIMETRIC STUDIES ON THE EXTREMITIES

temperature as that of the bath used for the immersion of the foot. The temperature of chamber *a* is regulated by electric bulbs controlled by a series rheostat. The copper coil is wound around the heating lamp as indicated by *R* (fig. 3). A current of air passing through it keeps the "conditioning" bath, as it may be called, in chamber *a* thoroughly agitated. After passing through the coil *X* the air is allowed to bubble through the water in the container *Y;* this procedure saturates the air with water vapor and prevents loss of heat by evaporation in the foot bath. The chamber *Y* is immersed in the same auxiliary or "conditioning" bath as the coil *X*; hence the saturation of the air with water at the proper temperature is assured.

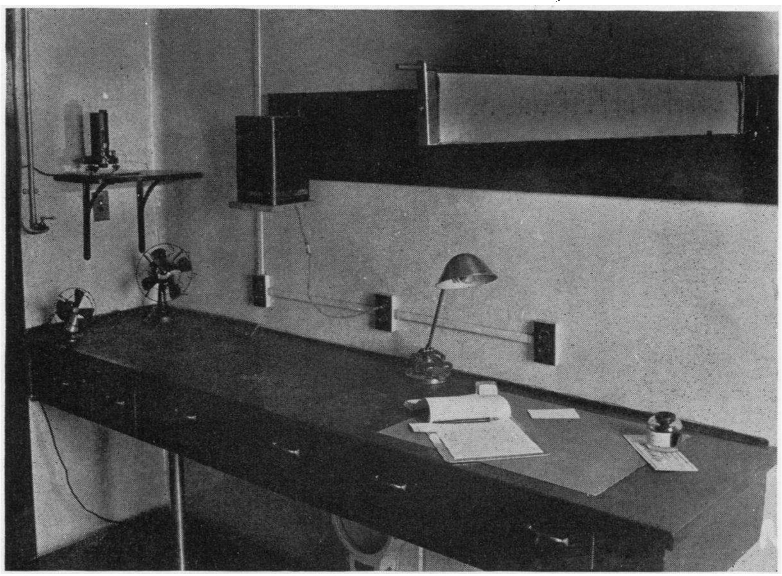

FIG. 2. ARRANGEMENT OF GALVANOMETER AND SCALE SO THAT EQUALITY OF TEMPERATURE OF WATER IN THE TWO COMPARTMENTS OF THE CALORIMETER MAY BE READILY OBTAINED WITH THERMOCOUPLES

A system of thermocouples inserted in the two chambers *a* and *b* connected to a sensitive galvanometer enables the operator to compare the temperatures of the water in the two compartments. The galvanometer, source of illumination and scale are shown in figure 2. The scale is made transparent so as to enable the operator to make the galvanometer reading from either side. When the temperatures are the same in both compartments there is no difference in electromotive force in the two sets of thermocouples, and hence no current flows through the galvanometer. Any difference in temperature of the thermocouples, however, causes the galvanometer reading to fall on one side or the other of the previously determined zero point, indicating the amount of regulation of the heating device which is probably required. This regulation is secured by means of a multiple-stepped rheostat.

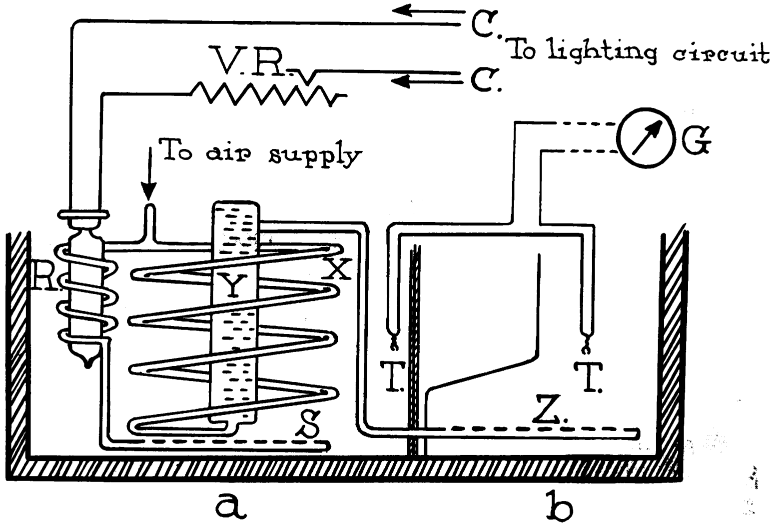

FIG. 3. DIAGRAMMATIC SKETCH OF CALORIMETER

a and *b* are the two compartments; *T*, *T*, thermocouples; *R* and *V. R.* variable resistance and heating circuit; *G*, galvanometer; *X*, *Y*, and *S*, apparatus for saturating air with water vapor; *Z*, device for stirring contents of chamber *b* with air from chamber *a*.

EXPERIMENTAL AND CLINICAL PROCEDURES

Figure 4 gives a typical curve showing the relationship between the temperature of the calorimeter and the time of the test. The portion *CD* represents the conditions during the time prior to the setting up of a fairly uniform rate of increase of temperature. The outer portions of the foot cool off during this period, and this cooling supplies a large part of the initial rise in temperature in the calorimetric bath. The portion *DE* of the curve represents the condition of fairly uniform or steady rate of transfer of heat; here the inherent heat, or heat capacity of the foot, has a negligible effect, while the surface circulation is responsible for the heat which is eliminated from the extremity after it has been immersed in the bath for some minutes. It is highly essential that the conditions of transfer of heat which are represented by the approximately straight line of the graph shall prevail if any fairly reliable clinical index of surface circulatory conditions is to be secured.

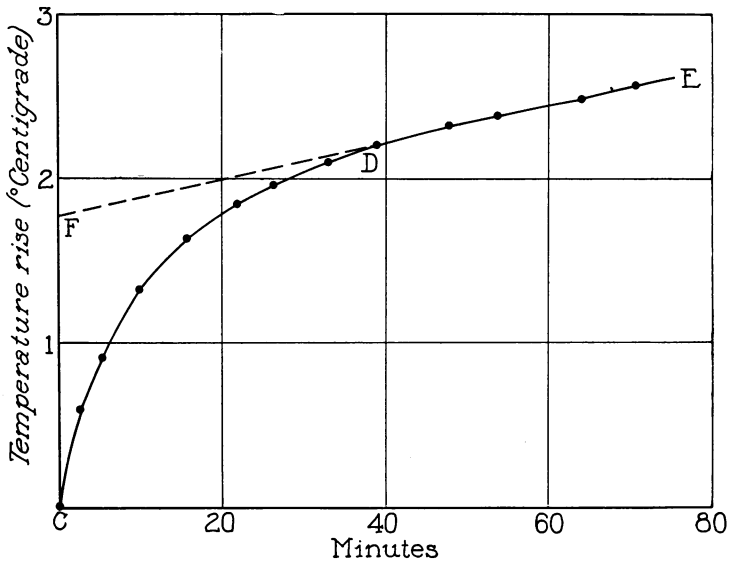

FIG. 4. A TYPICAL CURVE SHOWING THE RELATIONSHIP BETWEEN THE RISE OF TEMPERATURE OF THE CALORIMETER AND CONTENTS, AND THE TIME OF THE TEST

The portion of the curve *ED* represents the condition of a fairly uniform rate of transfer of heat.

A close approximation to the heat given out by the foot, other than by virtue of the superficial or peripheral circulation, may be obtained by extending the line *DE* back to the point *F* which intercepts the axis of temperature at the time at which the experimental test was started. The ordinate *CF* of this intercept indicates with fair accuracy the rise in temperature of the calorimeter due to the cooling of the tissues at or near the surface of the extremity. The approximation involves the supposition that the conditions of surface circulation have remained constant throughout the interval. All tests were continued until the graph, in each instance, had approximated a straight line, for at least twenty minutes.

The temperature of the calorimeter and its contents at the start of a test was always made the same as that of the room. This temperature was held, so far as possible, at about 22°C. It is, of course, necessary to correct for the cooling of the calorimeter as it warms up above the surrounding atmosphere. The cooling curve from which corrections have to be made very closely approximates a straight line for small differences of temperature. Twenty minutes was arbitrarily selected as the time interval to be considered in all tests. It is then necessary to know how much heat the calorimeter has lost during the same twenty minutes in order to make the proper correction, which may under certain circumstances be a considerable proportion of the heat transferred.

A gauge, shown in figure 5, was constructed to facilitate the rather laborious transfer of graphical data with the necessary correction into a numerical index. The gauge greatly facilitates the work and involves no added approximations. It was especially designed for the work in hand and consists of two parts. The upper part is made of transparent celluloid and slides up and down over the lower part which is heavy, lies flat and is covered with coördinate paper on which are plotted cooling curves for the metal boot of the calorimeter.

In use, the left edge of the lower part of the gauge is laid on the graph sheet vertically and opposite the time which marks the end of the twenty-minute interval in such a way that the temperature scales of the graph and gauge correspond. The transparent part is then moved up or down until the fiducial mark at the lower left-hand corner lies on the graph.

The amount that the graph is raised during a period of twenty minutes gives a direct measure of the heat transfer, but without any consideration of correction for the loss of heat to the surroundings. A cooling curve for the average differences of temperature during twenty minutes gives the necessary correction. The lower stationary part of the gauge has on it these correction curves for cooling for periods over twenty minutes.

The average temperature should be the basis for any cooling correction. A new setting is required to accomplish this; the lower part

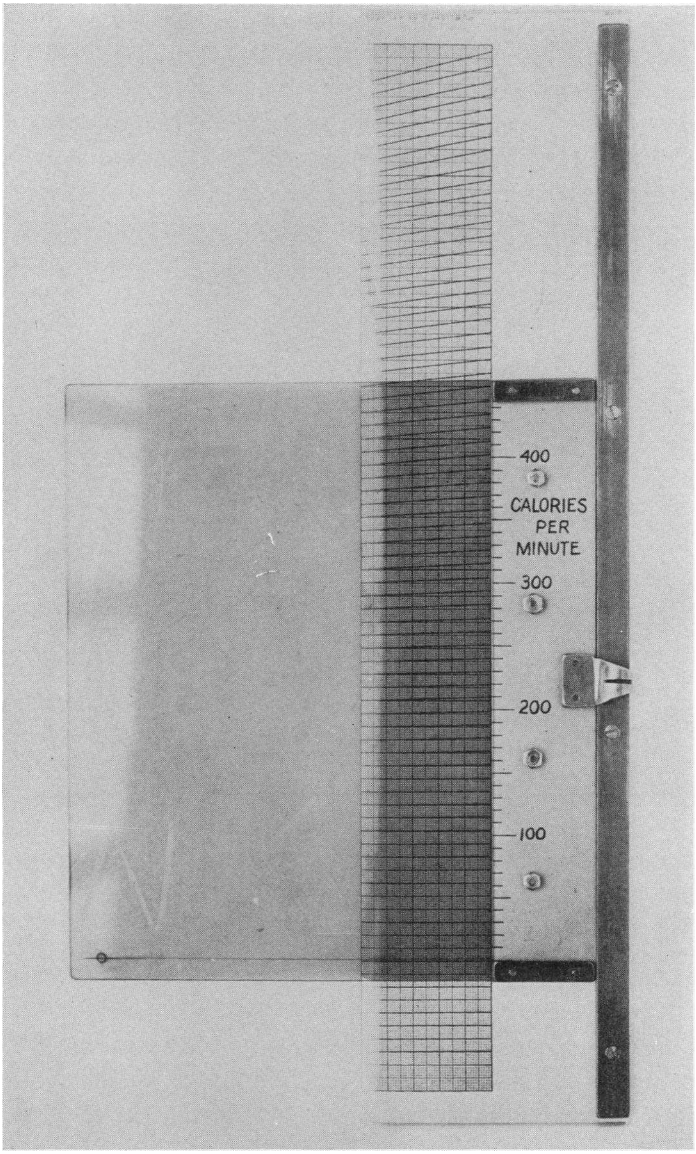

FIG. 5. A GAUGE TO FACILITATE THE TRANSFER OF GRAPHICAL DATA INTO CALORIES PER SQUARE INCH PER MINUTE

of the gauge is raised half the amount which the temperature has increased in the twenty minutes. The upper celluloid is then readjusted so that the fiducial mark rests in the time-temperature graph, and the correction curve then makes the necessary adjustment based on the average difference in temperature. An ordinary approximation to the average temperature will serve when the gauge is being set, since nearby correction curves are quite similar.

In description, the process is technical and appears laborious, but in practice it is simple and rapid, only a moment being required to secure

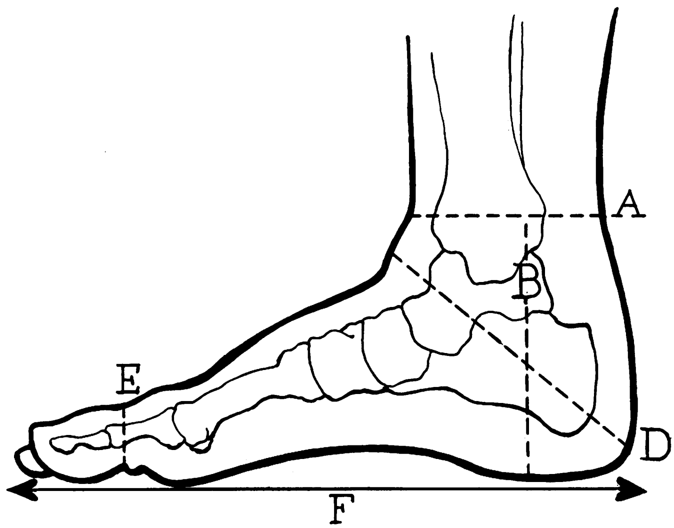

FIG. 6. DIAGRAMMATIC SKETCH OF THE MEASUREMENTS OF THE FOOT NECESSARY TO PERMIT THE CALCULATION OF THE AREA OF THE IMMERSED EXTREMITY BY A MATHEMATICAL FORMULA (E, D AND A ARE CIRCUMFERENCES

the reading with due correction for the loss of heat to the surroundings. The correction curve is followed to the right to the scale which gives the calories transferred during the twenty-minute period. The scale is so calibrated that the calories each minute are given and the necessity of dividing by twenty is also avoided. This, then, is the total amount of heat transferred, and when divided by the area of the foot gives the amount of heat transferred each minute for each square inch of skin on the foot. The heat transferred obviously depends on the area exposed.

There is such a variation in the size of feet, and consequently the depth of immersion, that it was decided to reduce all readings to unit area of skin exposed. Figure 6 shows the measurements which are taken on each foot. The area is computed by means of a formula

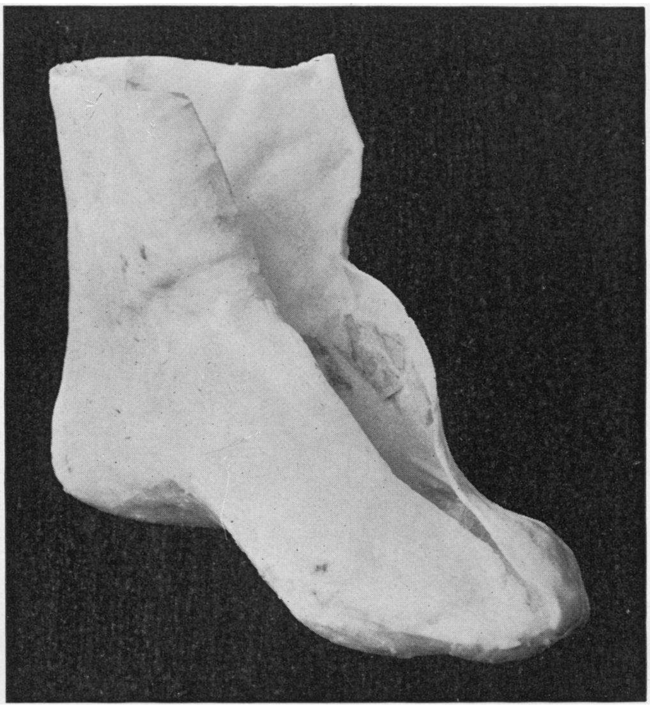

FIG. 7. PARAFFINED STOCKING USED TO MEASURE THE AREA OF THE FOOT

which was evolved from twenty-three actual determinations. The formula is:

$$\text{Foot area (in square inches)} = 0.31F\,(E + 3/4D) + 0.775B\,(A + 3/4D) - 0.124D^2$$

$$= 1.25\,(\text{Vol. in cc. of extremity}) + 2000\,(0.00147 - B)\,A$$

The actual areas were determined by drawing a tight-fitting lisle stocking over the foot after it had been covered with thin tissue paper. Paraffine, which was just above its melting point, was then slowly applied with a brush and allowed to cool. Figure 7 shows such a stocking after its removal, and figure 8 shows how it was cut in order to flatten or lay it out on a large sheet of photographic paper. The area of the paraffine stocking was secured by the method of weighing after a photographic print had been made.

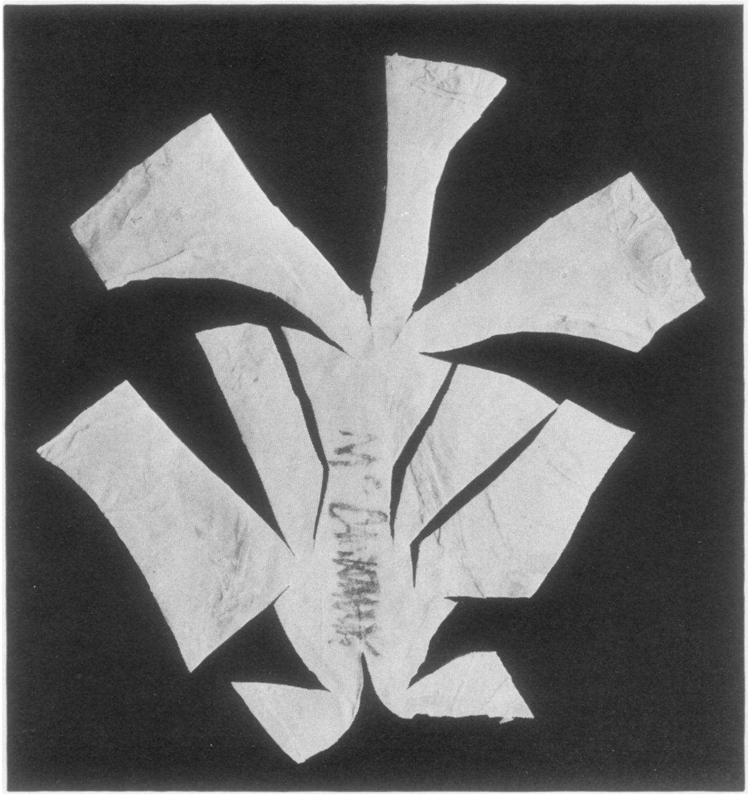

FIG. 8. THE PARAFFINED STOCKING LAID OUT FOR MEASUREMENT

DISCUSSION

Calculations on the volume of blood flow have not been made, since the conductivity of the skin, the number of functioning capillaries, and areas of exposed blood are also important and somewhat indeterminable factors which vary in different individuals. The number of calories transferred for each unit area of skin each minute is taken as the final index of heat transfer. These, I believe to be the only data which can be obtained and correctly interpreted, for one can obtain experimental data on rates of elimination of heat which are of value from both physiologic and pathologic viewpoints, and which do not involve any assumptions relative to the possibility that these rates of transfer of heat are direct measurements on the rates of flow of blood. The time required for a constant rate of transfer of heat to be reached varies much in individual cases, and this variation indicates quite clearly that one or more of the factors entering into these experimental studies are not the same in different individuals.

To the first order of approximation, it may be said that the change of temperature in the calorimeter represented by the ordinate *CF* (on the time-temperature graph of figure 4, for example) is due to the inherent heat in the tissues in the outer layers of the extremity immersed in the bath. The heat thus eliminated, when calculated and divided by the area of the extremity and the specific heat of the tissues, gives an approximate measure of the half-depth to which the superficial layers have been cooled. The determination of the half-depth to which the outer layers of an extremity have been cooled to the temperature of the calorimetric bath may be an index of the conditions of circulation of the blood in an extremity and may prove of value in future studies on these problems.

BIBLIOGRAPHY

1. Stewart, G. N.: Heart, 1911–1912, iii, 33. Studies on the Circulation in Man. Also Harvey Lectures, 1912–1913, 33.