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With best regards of
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"Experimental Researches on the Propagation of Heat by Conduction in Bone, Brain-tissue, and Skin." By J. S. LOMBARD, M.D., formerly Assistant Professor of Physiology in Harvard University. Communicated by Dr. BROWN-SÉQUARD, F.R.S. Received October 1. Read November 17, 1881.

Introduction.

The question of the precise degree of the conductivity for heat of the tissues lying between the surface of the brain and the outer surface of the integument is, of course, of the first importance in studying the possible effects on the exterior of the skin of changes of temperature occurring in the superficial layers of the cerebrum; and the question of the degree of conductivity of brain-tissue itself is of great importance with reference to the extent to which propagation through the cerebral mass of thermal changes occurring in a single point or tract of the brain may take place.

Many years ago the writer made a few (not, however, very exact) experiments on the conductibility of bone, which did not lead him to anticipate any serious obstacle in the skull to the outward transmission of heat from the brain. Moreover, the experiments of Professor Tyndall on conduction in elephant's tusk, whalebone, cow's horn, &c., pointed to tissues of this nature as being better conductors than sealing-wax and bees'-wax, on both of which substances the writer had made many experiments, and which he knew would conduct sufficiently well to enable one, with delicate apparatus, to appreciate a slight change of temperature through a thickness of them greater than the average thickness of the skull.

In order to make the theoretical conditions of transmission to the outer surface as unfavourable as could, with any justice, be warranted, the writer selected the conductivity of paraffine as the representative of the conductivity of bone and skin combined, and founded on this basis his line of reasoning respecting the effect of slight variations of the temperature of the surface of the brain on the temperature of the exterior of the skin. But in June, 1880, M. François Franck, in a communication made to the Société de Biologie, gave the results of experiments made by him on the conductivity of bone, skin, and brain-tissue, which placed the whole subject in a new light.* M. Franck stated that a difference of temperature of 1° C. failed to make itself felt at the end of fifteen minutes through 3 millims. of bone, using a thermometer detecting 0°·05 C. With 2° C. difference of temperature a doubtful change of 0°·05 C. was obtained; indeed, it required a difference of 4° C. to effect a change of 0·2°. Using thermo-electric apparatus detecting 0°·01333 C. ($\frac{1}{75}$), M. Franck failed to find any indication of a transmission of heat with a difference of temperature of 1° C. Skin he found to conduct about the same as bone, while on the contrary, through 30 millims. of brain-tissue transmission readily took place.

As it is difficult to conceive of rises of temperature in the brain, due to changes of mental activity, measured by whole degrees Centigrade, M. Franck's experiments on bone and skin, if correct, would peremptorily end all question of the possibility of changes of temperature in the superficial layers of the brain, arising from psychical processes, affecting *directly* the outer surface of the scalp.

So able an experimenter as M. Franck making the above statements, the writer felt himself obliged to go over the whole ground thoroughly, although convinced at the outset that, as regards bone at least, M. Franck was in error. Accordingly, the writer devoted himself for the space of nearly six months entirely to the experimental examination of the conduction of heat in the tissues in question, drawing his

* "Gazette Médicale," July 3, 1880.

results from over 700 experiments picked out from a still larger number. It will be seen that M. Franck is quite correct as regards the comparatively good conductivity of brain-tissue, but in error as concerns the conductivity of bone and skin.*

In approaching this subject, we have at the start, to take into consideration what rises of temperature are likely to occur in the brain as the result of increased mental action of different kinds.

The only *direct* information in our possession concerning the production of heat in the brain during increased cerebral activity is furnished by the well-known admirable experiments of M. Moritz Schiff.† As M. Schiff did not reduce his results to a thermometric standard, we are left wholly in the dark as to the *degree* of the rises of temperature noted by him. It has been rather gratuitously assumed, because M. Schiff did not calculate the thermometric values of the deflections of his galvanometer, that, therefore, these values must have been exceedingly small—too small, in fact, to be easily estimated—and, consequently, that the rises of temperature in the brain were proportionally feeble. But a knowledge of the general nature of the galvanometer and thermo-piles employed by M. Schiff, together with a careful study of the experiments themselves, have failed to prove to the writer that M. Schiff was experimenting with any extraordinary degree of delicacy. To begin with, the electromotive force of the piles employed was not great. Although M. Schiff mentions certain alloys of Rollman, all the results of his experiments on the brain appear to have been obtained with single pairs of either the antimony-bismuth, copper-bismuth, or platinum-German silver combinations. Now the electromotive forces of these combinations may be expressed by 35, 24, and 4·5 respectively, while the electromotive forces of the combinations principally used by the writer are represented by 119·5 and 210. The galvanometer used by M. Schiff was a combination of the principles of the Meyerstein and Wiedemann instruments. These instruments are certainly not superior, even if they are equal, in sensitiveness to the Thomson galvanometer, which the writer has usually employed. The perturbations, arising from external causes, mentioned by M. Schiff, may occur when instruments of the kind are not adjusted to any very great degree of delicacy, and therefore are not necessarily proofs of high sensitiveness. But the principal proof that the galvanometric deflections did not represent very minute values of temperature is to be found in the account of the experiments themselves. It is there stated that with single pairs of German silver and platinum, implanted in

* The question of the *specific heat* of the tissues has been purposely omitted, as nothing definite is known on this important point. Yet the writer is strongly inclined to believe that the differences in the rate of thermal transmission in these tissues are in part owing to differences in their specific heats.

† "Archives de Physiologie," t. III, 1870, p. 6.

corresponding points of the two hemispheres of large dogs, the permanent galvanometric deflections, showing the difference of temperature between the two points, were about 15° of the scale, which was divided into millimetres.* Now it is very unlikely that the temperatures of two points of opposite sides of the brain would, *on an average*, approximate each other nearer than by 0°·03 C.,—this after making full allowance for the good conductivity of brain-tissue. In practice it is difficult to find in the different tissues, unless the points examined are within a centimetre of each other, a nearer approach to equality than the difference just given. Of course, still smaller differences may be met with by accident, but one cannot count upon finding them at a venture. The dogs are specified as *large*, and, indeed, in one place,† M. Schiff gives the distance between the two points examined. In this case each pile was 15 millims. from the longitudinal median line; the two points examined were consequently at least 30 millims. apart. We may assume then that the 15° of the galvanometer did not represent less than 0°·03 C.; therefore 1° of the galvanometer was equal to 0°·002 C. Now the simple odour of food with these animals caused deflections of 6° or 7°, equal to 0°·012 C. to 0°·014 C.,‡ and the mastication of food increased these figures to 12° and 14° of the galvanometer, equal to 0°·024 C. and 0°·028 C. It must, however, be borne in mind that these deflections *did not by any means represent the total rise of temperature, but only the difference of rise between the two points examined.* All M. Schiff's results are in fact *relative*, based on the assumption that one of the two points examined would rise in temperature more than the other. The use of the second pile with him was, in fact, principally for the purpose of keeping the primary deflection of the galvanometer within the field of division on the scale, this pile thus serving as a compensating element. Now if a *difference of rise of temperature* of from 0°·012 C. to 0°·028 C. can be produced in the two hemispheres of the dog by the feeble cerebral action excited by the means given, it is certain that the thermal effects of the active exercise of the intellectual and emotional faculties of man may be estimated in, at least, *tenths* of a degree Centigrade.

In the case of the experiments on fowls, we have further and still stronger proof, both that the apparatus was not excessively delicate, and also that the alterations of temperature were not so very small. In these experiments the thermo-electric arrangement was a small bar of bismuth 4 to 5 millims. long, in the two ends of which copper wires were buried to a depth of 1 millim., thus forming a thermo-electric junction at each end. As the copper wires were embedded in the bismuth to a depth of 1 millim., the two junctions were only from 2 to

* *Loc. cit.*, pp. 205, 207.

† *Loc. cit.*, p. 211.

‡ *Loc. cit.*, p. 210.

3 millims. asunder. This close proximity of the two junctions must have very greatly diminished the delicacy of the arrangement, as a change of temperature at one junction would speedily be propagated to the other, setting up a reverse current in the latter.* Moreover, considering how good a conductor the brain-tissue is, a slight change of temperature in the point of brain in contact with one junction would very quickly be felt in the point in contact with the other junction, only 4 or 5 millims. of tissue intervening. Again, the galvanometer appears to have been less sensitive in these experiments than in those first cited. Yet M. Schiff obtained deflections of 12° to 14° from the insignificant psychical processes awakened in these animals by the exhibition of coloured papers, &c. It is very evident that, under such adverse circumstances as those specified, the *absolute rise* of temperature must have been considerable to have given any sort of a balance to one point over the other.

Weighing all the evidence, then, there does not appear to the writer, to be the slightest reason why rises of temperature as high as 0°·3 C. should not occur in the brain of man during mental activity; and elevations of 0°·2 C. are certainly admissible; but the results which will be given in this paper are based on values of only 0°·1 C.

In the present experiments, instead of making use of differences of temperature of 1° C., or more, *fractions* of a degree have been employed, as furnishing more conclusive proof of the possibility of the transmission of small differences of temperature, than could be afforded by the mere reasoning from larger to smaller values. We will consider first the apparatus employed, and then the methods of experimenting.

Apparatus Employed.

The instruments employed in testing the conductivity of the tissues under consideration, were as follows:—

First.—Thermo-electric piles of from one to four pairs, composed of the antimony-zinc-cadmium alloy of Professor Moses G. Farmer, joined to bismuth as the other metal. The general construction of these piles has been fully described elsewhere,† and the only point of difference to which special attention need be called here, is, that whereas, in the description referred to, the conducting wires are represented as composed of copper strands, in the present instance they consisted of single fine copper wires 0·011 inch in diameter,—con-

* See the writer's remarks on reverse currents in piles, in "Regional Temperature of the Head," p. 6. It would have been almost *utterly impossible* to have tested the thermometric values of a pile so constructed,—at least such is the writer's experience.

† See the writer's work "Regional Temperature of the Head," p. 19. The particular alloy referred to above is the one designated "No. 1."

ductors of this size and character being more manageable in packing the pile in paraffine in the manner to be described further on.*

Second.—The writer's rheostat and keys.†

Third.—Sir William Thomson's galvanometer and scale.

The greatest precaution must be taken to guard against the development, in any part of the apparatus, of accidental currents due to external thermal influences. For this reason, not only should every exposed junction of dissimilar—or even *similar*—metals be thoroughly protected with cotton-wool, but also the whole rheostat and the keys should be covered over with several layers of flannel, the plugs and keys being manipulated through a single thickness of the cloth, the other layers being momentarily raised for this purpose, *and only at the very point concerned.* Moreover, besides covering thickly with wool the binding screws of the Thomson galvanometer, the whole brass back of the instrument should be covered with flannel extending over the top and sides of the box containing the coil, and leaving only the glass front exposed.

Methods of Experimenting.

In earlier experiments (1867–68), in the case of bad conductors generally, provided the substances were of sufficient density, a form of apparatus similar to that used by Professor Tyndall in like investigations was employed;‡ but in later, including the present, experiments, the methods adopted were different, and in the present instance were of two kinds, both, however, the same in principle, and differing only in detail.

The fundamental principle of both methods was the determination by means of a thermo-pile applied to one surface of the substance under examination,—say, for example, a piece of bone,—of the rapidity and extent of the change of temperature induced by conduction in this surface by the contact of the opposite surface with a mass of water of a temperature differing in a slight but definite degree from that of the air in the immediate neighbourhood. At the outset, the whole of the piece of bone and the pile, if properly protected, will be at the temperature of the surrounding air; and when contact of one surface of the bone with the water takes place, this surface, assuming the temperature of the water gives rise to a thermal movement across the bone proportional to the difference of temperature between its two surfaces, and as these two surfaces are now respectively at the temperatures of the air and of the water, the movement is proportional to the difference between the latter two temperatures.

* All possibility of currents caused by vibration of the conducting wires must be guarded against, hence larger wires than those specified, unless flexible like strands, are unsafe.

† *Op. cit.*, p. 22.

‡ "Heat considered as a Mode of Motion," American ed., p. 233.

The first important points of the methods, are, therefore, the determination and regulation of the differences between the temperatures of the air and the water. These differences were determined by thermometers and thermo-piles (the latter being included in a circuit distinct from that of the pile used in testing for conductivity, and having their own galvanometer) placed in and near the water, the thermo-piles giving differences of 0°·02 C. In practice it was found that, with care and patience, a difference of about 0°·125 C. between the air and water could be pretty steadily maintained long enough for the purposes of the experiments. It is, however, as a rule, better to reverse the ordinary order of things, and *to take heat from the bone instead of furnishing heat to it*, that is to say, it is better to have the temperature of the water *lower* by the desired amount than that of the air, than to have it *higher*, for the temperature of the water is more easily maintained at a point differing slightly from the temperature of the air when the former is the lower of the two. If the temperature of the room in which the experiment is made be carefully watched, we may be certain that the temperature of the water will not exceed that of the air; the principal difficulty will be to keep the temperature of the water from falling too much below that of the air, and this end is best attained by withdrawing by suction, through a long tube held in the mouth, a small quantity of the liquid, and then returning it after a longer or shorter stay in the mouth.* A little practice will enable one to graduate, in this simple manner, with great nicety, the temperature of a small mass of water. The amount of water usually employed was about one quart contained in an earthen vessel, exposing no more surface of water to the air than was necessary for the introduction of the different appliances used in the experiments.

We have next to attend to the manner of applying the thermopile to the surface of the substance examined, and the precautions necessary in so doing; and here the two methods diverge, the one being applicable to the case of bone, and the other to that of brain and skin. We will consider each method in turn, taking first that which concerns bone.

Bone.

To begin with, the closest possible contact between the face of the pile and the bone must be aimed at. To this end, the surface of the bone is filed smooth, and the face of the pile having been accurately fitted to it, the two are closely and permanently attached to each other by means of a thin layer of shellac varnish applied to the face of the pile and to the surrounding ebonite casing. Firm and steady pressure must be maintained until the shellac is quite dry, as the interposition

* Care must be taken not to alter sensibly the *level* of the water by withdrawing too large an amount, for reasons to be seen further on.

of minute bubbles of air will be fatal to successful experimenting. The pile and bone thus constitute a single piece.

The next step is to isolate, as far as possible, the whole pile from all external thermal influences, except such as act through the piece of bone, or through the conducting wires of the pile. To effect this, the pile is enveloped in its whole length, and beyond to a distance along its conducting wires of several times its length, in layers of fine cotton-wool, which latter are afterwards steeped in melted paraffine. The casing thus formed extends laterally beyond the edges of the surface of the bone to which the face of the pile is attached. The first layer of cotton-wool is applied loosely, and the paraffine is comparatively cool when poured upon the wool. The result of this is that the paraffine does not penetrate very deeply into this first layer, thus leaving a mass of loose wool, next the pile, entangling a certain amount of *air*, and this latter furnishes a strong safeguard against external influences. Of course, care must be taken that the attachment of the face of the pile to the bone be not broken by the heat of the paraffine. When all is complete the whole arrangement consists of a mass of paraffine-soaked cotton-wool some 60 millims. in length, one end of which is terminated by the piece of bone which protrudes from the centre of this end,* while from the other end emerge the conducting wires of the pile, the pile thus forming the core of the mass, and being shut off laterally and at its upper end from the exterior by from 20 to 40 millims. of envelope.

Two narrow strips of pasteboard, bound tightly by means of strips of flannel, on opposite sides of the mass, near its upper end, and brought together and tied so as to form a sort of arch above this end, furnish a *handle* by which the mass can be held vertically, with the exposed bone downwards, by the claw of a horizontal arm working up and down a perpendicular metallic rod fitted into a small but steady stand placed on the table, which supports the vessels containing the water, and the thermometers and thermo-electric appliances used in testing the differences of temperature between the air and the liquid.

Brain and Skin.

The fundamental principle was—as has been said—the same here as in the case of bone, but, as the substances could not with safety be brought into immediate contact with the water, the following special arrangements were adopted: A box of thin pasteboard 50 millims. deep by 85 millims. square was used as a mould, and was filled with melted paraffine. After solidification had taken place, a space was cut

* One must be sure that the paraffine does not extend down the sides of the piece of bone so as to touch the water when the under surface of the bone is brought in contact with the liquid,—as paraffine will conduct sufficiently well to introduce errors into the results if the above precaution be not taken.

out in the centre of the mass, extending from the upper surface to the pasteboard bottom; at and near this latter point the area of the space was just large enough to accommodate the piece of tissue to be tested. The pasteboard bottom under the space was next cut out, and its place supplied by a copper plate less than 0·5 millim. in thickness, which was closely and exactly fitted in, melted paraffine being used on the inside to secure it. The substance to be tested, when in position, therefore rested on the thin copper plate, and was surrounded by paraffine walls.* The pile (enveloped at the end near its face in only a thin layer of paraffine-soaked wool, so as not to touch the surrounding walls of paraffine) was pressed down firmly upon the substance lying on the copper plate, and was kept in position by wedging with cotton-wool the space between its envelope, near the upper end of the latter, and the paraffine walls. The reason for preventing the envelope of the pile near its face from touching the surrounding paraffine walls, is that the latter are, at the bottom of the box, in almost *direct contact with the water;* and as paraffine conducts about as well as the substances tested, a thermal movement might *possibly* take place *directly*, between the face of the pile and the water, through the paraffine walls. The intervention of an *air-space* between the envelopes of the pile and the paraffine wall, not only in the neighbourhood of the face of the pile, but extending to a point far beyond the entire length of the latter, rendered any such thermal movement impossible. Two strips of pasteboard were fitted to the sides of the box, in the same way as in the case of bone. These strips, moreover, served as supports for a mass of cotton-wool, which covered the top of the box, in order to cut off communication between the air imprisoned in the box and the external atmosphere through any chance crevice in the cotton-wool wedges holding the pile in place.

The prepared bone, or the paraffine box containing the piece of brain or skin, having been attached to the claw of the sliding arm mentioned on page 180, by means of the pasteboard strips, is brought over the surface of the water, and then carefully lowered until the under surface of the bone or the copper plate in the bottom of the box is *just immersed, and no more*, in the liquid.† When this is effected the sliding arm is made fast, and the bone or box removed by raising the whole arrangement, as one piece, by means of the perpendicular rod

* In comparing bone with brain and skin, it was found that the interposition of the copper plate had no effect on either the rapidity or the extent of the thermal transmission. This was proved by covering the under surface of a piece of bone, previously tested, with a copper plate of the thickness of that used in the experiments on brain and skin, when it was found that the conductivity remained unchanged.

† The necessity of the caution contained in the note at the bottom of page 180 will now be obvious.

of the stand. The wet surface of the bone or box is next carefully dried with cotton-wool, and protected from external disturbing influences by an enclosure of thick pasteboard placed near the vessel containing the water.

If now, at a given moment, we wish to commence an experiment, we have merely to raise the whole arrangement, as was done when we removed the bone or box, bring the latter over the water, and then *set the stand down again.* As the distance between the water and the substances to be brought in contact with it was previously accurately determined, and the necessary adjustment made with the sliding arm, we may be certain that the proper degree of immersion is ensured. Moreover, as in experiments of this kind a second's time is of importance, and as the above procedure can be timed so as to bring the surface of the bone or box in contact with the water at a given second (and that, too, without the necessity of the observer taking, for a moment, his eyes off the scale of the galvanometer or the timepiece, as the movements necessary can be performed without looking when once their direction and extent are appreciated), it fulfils another important requisite in this portion of the work.* Before adopting this simple procedure the writer made many experiments with more or less complicated apparatus; but all these appliances were, one after another, thrown aside as introducing troublesome, and often dangerous, complications. It must be remembered that the exposed surface of bone, or copper bottom of the box, must be protected, when not immersed, from radiation, possible currents of air, &c., otherwise, thermal exchanges will take place through the exposed surfaces, and —using such delicate means of investigation as we are now treating of —the index of the galvanometer will not be steady for a moment; this being the case, the bone or box cannot be simply suspended, in free air, over the water, to be lowered upon the latter when the appointed time comes; and all attempts to protect them properly, while thus suspended, have led to difficulties, bringing with them, among other evils, delays in the removal of the protections, and, therefore, *errors of time.*

It remains now to describe the manner in which the observations were made.

In the first place, the deflections of the galvanometer were noted regularly every fifteen seconds, commencing from the second at which contact between the bone or copper plate and the water took place, up to six minutes. If, however, as sometimes happened, the first sign of the thermal movement showed itself before the first fifteen seconds had elapsed, of course that particular movement was also noted. After the sixth minute the deflections were noted every half minute or every

* It is hardly necessary to say that the possibility of currents caused by vibration of the conducting wires of the pile in the movements in question, was fully appreciated, and negatived by direct experiment.

minute according to the rate of movement of the index of the galvanometer, which was usually much diminished by this time, the permanent thermal condition, or state of thermal equilibrium, being now, as a rule, not very far off. The readings of the thermometers and of the thermo-electric apparatus used in testing the differences of temperature between the air and the water, were noted every half minute. As it was not the rule—even when the greatest care was used—to find the index of the galvanometer at 0° of the scale at the start, it was almost always necessary to add to or subtract from the readings of the thermometers the thermometrical value of the deflection at the moment when the instrument began to show the first sign of the thermal transmission. Thus, suppose the thermometers to show a difference between the air and the water of 0°·125 C. in favour of the former, and the index of the galvanometer to be 5° of its scale on the *cold* side of 0°. If the galvanometer be set to show 1° deflection as equal to 0°·0006742 C., we must deduct 0°·003371 C. (5 × 0·0006742) from the 0°·125 C. difference between the air and the water, since the surface of bone or brain or skin in contact with the thermo-pile is already cooler than the air by 0°·003371 C. The *true* thermometric difference between the two surfaces of the substance under examination is, therefore, 0°·121629 C.

Experiments on Bone.

The bones examined were the skull and long bones of sheep, and the ribs of oxen.

In the experiments on the skull, pieces of various thicknesses and areas were taken from different parts, but the results to be given here were obtained with fresh pieces of the parietal and occipital bones 7·5 millims. in thickness, and 21·5 millims. by 15 millims. in area.

We have three principal points for consideration, namely, as follows:—

(*a.*) The time required for the *first sign* of the change of temperature to show itself through the bone.

(*b.*) The degree of change of temperature produced at certain measured intervals of time.

(*c.*) The maximum of the change of temperature produced, when the *permanent thermal condition* is attained.

Taking the above in the order in which they are set down, we have first to consider the question indicated under the heading "*a.*"

To begin with, the degree of difference of temperature to which the bone was subjected must be taken into account. The average degree of difference of temperature was 0°·129 C., the maximum being 0°·147 C., and the minimum 0°·1136 C. Under these conditions, the average time required for the first appearance through the bone of the thermal change, with the apparatus set to detect 0°·0006742 C., was 28·4 seconds. In 53·333 per cent. of the cases it was 23 seconds; in 26·667 per cent. it was 38 seconds; and in the remaining 20 per cent. it was 30 seconds.

If the results of the different experiments are calculated for 0°·1 C. difference of temperature, on the basis that the time required would be inversely proportional to the degree of difference of temperature, the average time is found to be 37·3 seconds, the maximum and the minimum being respectively 55·86 and 26·29 seconds. The average *rate* of the thermal transmission is, therefore, 1 millim. per 4·9733 seconds, the maximum and the minimum times being, respectively, 7·448 and 3·5053 seconds.

(*b*.) Degree of change of temperature produced at certain measured intervals of time.

We will examine the changes produced at the end of 1 minute and 15 seconds, 2 minutes, 4 minutes, and 6 minutes, respectively, measured from the moment when the bone touched the water. We will take simply the averages and extremes of the changes due to the differences of temperature given under the preceding heading, having first, however, reduced all the results to values representing the effects of 0°·1 C. difference. Table I gives these averages and extremes in both galvanometric and thermometric figures. The galvanometric deflections, it will be seen, indicate the steps towards equalisation of the temperatures of the two surfaces of the bone at the several periods: thus, as 0°·1 C. is equal to 148·316° of the galvanometer,* and as 0°·1 C. represents the difference of temperature between these two surfaces at the start, the steps towards equalisation are measured by the approximation of the figures of the galvanometric degrees to 148·316.

Table I.—Effects of 0°·1 C. difference of temperature through 7·5 millims. of sheep's skull. 1° of galvanometer is equal to 0°·0006742 C.; and 0°·1 C. is equal to 148°·316 of galvanometer.

Time from the moment of contact of bone and water.	Averages.		Maxima.		Minima.	
	Degrees of galvanometer.	Thermometric values.	Degrees of galvanometer.	Thermometric values.	Degrees of galvanometer.	Thermometric values.
At the end of—						
1 min. 15 sec.	23·864°	0·01609° C.	34·916°	0·02354° C.	13·058°	0·00845° C.
2 „ 0 „	54·170	0·03652	74·720	0·05038	30·470	0·02054
4 „ 0 „	88·804	0·05987	115·485	0·07786	40·000	0·02696
6 „ 0 „	116·476	0·07853	135·384	0·09127	68·504	0·04618

* 1° C. is equal to 1483°·16 of the galvanometer; hence 1° of the galvanometer is equal to 0°·0006742 C.

Percentages of heat transmitted, deduced from the above values.

Times.	Averages.	Maxima.	Minima.
1 min. 15 sec.....	16·090 per cent.	23·541 per cent.	8·804 per cent.
2 „ 0 „	36·523 „	50·378 „	20·543 „
4 „ 0 „	59·874 „	77·864 „	26·969 „
6 „ 0 „	78·532 „	91·287 „	46·187 „

This table shows that already by the end of one minute and a quarter the thermal transmission was, on an average, very marked, and that at the end of the sixth minute, $78\frac{1}{2}$ per cent. of the initial difference of temperature had been made up. It will further be seen that these results are widely at variance with those of M. Franck, the latter having failed to obtain, at the end of fifteen minutes, using thermometers detecting 0°·05 C., any indication of conduction through only 3 millims. of bone, with a difference of temperature of 1° C.; while, according to the table, a change of nearly 0°·06 C. was found, at the end of *four* minutes, through 7·5 millims. of bone, with a difference of only 0°·1 C.

(*c.*) The maximum change of temperature produced when the *permanent thermal condition* is attained.

We have under this heading to consider the thermal condition of the bone at the time when the flow of heat through it has settled into a regular and steady movement, in which each cross section of the conductor receives and transmits equal quantities.

We have first to inquire how long a time is usually occupied in the attainment of this condition.

With the differences of temperature specified under the heading (*a*) the time ranged from 9 minutes to 11 minutes 30 seconds, the average of all the times being 9 minutes 53 seconds. In 42·857 per cent. of the cases it was 9 minutes, in 28·572 per cent. it was 10 minutes, in 14·285 per cent. it was 11 minutes 30 seconds, while the remaining 14·286 per cent. was divided equally between 11 minutes and 10 minutes 30 seconds respectively.

Table II gives the effects of the transmission at this period, reduced to values representing 0°·1 C. difference of temperature.

Table II.—*Permanent thermal condition* effected by 0°·1 C. through 7·5 millims. of sheep's skull. 1° of galvanometer is equal to 0°·0006742 C., and 0°·1 C. is equal to 148°·316 of galvanometer.

	Degrees of galvanometer.	Thermometric values.	Percentages of heat transmitted.
Averages	127·431°	0·08591° C.	85·918 per cent.
Maxima.........	138·333	0·09326	93·269 ,,
Minima.........	104·800	0·07065	70·659 ,,

We find from the above table that in the permanent thermal state—reached in the majority of cases, as we have just seen, by the tenth minute—the initial difference of temperature of 0°·1 C. between the two surfaces of the bone is, on the average, reduced to 0°·01409 C., nearly 86 per cent. of the excess of heat on the warmer of the two surfaces being now transmitted to the cooler surface.

Experiments on Brain-Tissue.

The brain-tissue used was that of the sheep, and was in a fresh condition. Pretty much the whole of the brain was examined, and blocks of different thicknesses and areas were employed, but the experiments with which we are at present concerned were made on pieces cut from the upper surface of the cerebrum, 7·5 millims. in thickness and of an area of 21·5 millims. by 15 millims., being thus identical in dimensions with the pieces of skull already treated of. A preliminary series of experiments had, however, to be made to determine whether the dura mater opposed any noteworthy barrier to thermal transmission. This question was decided in the negative, it being found that the resistance of the membrane in question was so slight that it could safely be disregarded.

We will examine the results obtained on the pieces of brain in the same manner as was adopted in the case of the skull.

(*a*.) The time required for the *first sign* of the change of temperature to show itself through the piece of brain.

The average degree of difference of temperature to which the brain-tissue was subjected was 0°·13116 C., the maximum being 0°·1513 C. and the minimum being 0°·1202 C. With these differences, the average time elapsing before the first appearance on the upper surface of the piece of tissue of the thermal change (the apparatus having the same delicacy as in the experiments on the skull) was 30·88 seconds. In 44·444 per cent. of the cases it was 23 seconds, in 27·777 per cent.

it was 38 seconds, in 22·223 per cent. it was 30 seconds, and in the remaining 5·556 per cent. it was 53 seconds.

If all the individual results are reduced to values representing 0°·1 C. difference of temperature, the average time becomes 40·49 seconds, the maximum and the minimum being respectively 63·706 and 27·646 seconds. The average *rate* of the thermal movement is, therefore, 1 millim. per 5·3986 seconds, the maximum and the minimum times being respectively 8·4941 and 3·6853 seconds. There appears indeed from these figures to be but little difference at this period between brain and skull.

(*b.*) The degree of change of temperature produced at certain measured intervals of time.

Proceeding in precisely the same manner as in the case of the skull, we arrive at the results set forth in Table III. These results are evidence of the accuracy of M. Franck in attributing a high conducting power (comparatively speaking) to brain-tissue; for the values given in the table approximate closely, especially in the earlier periods, to those contained in Table I for the skull. If we take the differences between the thermometric values at the same periods in the averages of the two tables, we find that the superiority of bone over brain-tissue is represented, even at its greatest, by only a little more than the one-hundredth of a degree Centigrade. The average degree of superiority of the bone over the cerebral tissue in point of conductivity at the different periods will be seen below :—

Table III.—Effects of 0°·1 C. difference of temperature through 7·5 millims. of upper surface of cerebrum of sheep. 1° of galvanometer is equal to 0°·0006742 C.; and 0°·1 C. is equal to 148°·316 of galvanometer.

Time from the moment of contact of copper plate, on which the piece of brain rested, with the water.	Averages.		Maxima.		Minima.	
	Degrees of galvanometer.	Thermometric values.	Degrees of galvanometer.	Thermometric values.	Degrees of galvanometer.	Thermometric values.
At the end of—						
1 min. 15 sec.	21·036°	0·01418° C.	32·445°	0·02187° C.	6·370°	0·00429° C.
2 „ 0 „	42·721	0·02880	59·068	0·03982	19·379	0·01306
4 „ 0 „	74·840	0·05045	103·200	0·06957	32 558	0·02195
6 „ 0 „	99·075	0·06679	136·000	0·09169	49·612	0·03344

Percentages of heat transmitted, deduced from the above values.

Times.	Averages.	Maxima.	Minima.
1 min. 15 sec. ..	14·176 per cent.	21·875 per cent.	4·294 per cent.
2 „ 0 „ ..	28·803 „	39·825 „	13·066 „
4 „ 0 „ ..	50·459 „	69·581 „	21·951 „
6 „ 0 „	66·799 „	91·696 „	33·450 „

Times.	Thermometric degree of average superiority of skull over brain.	Percentages of degree of average superiority of skull over brain.
1 min. 15 sec.......	0·00191° C.	1·914 per cent.
2 „ 0 „	0·00772	7·720 „
4 „ 0 „	0·00942	9·415 „
6 „ 0 „	0·01174	11·733 „

Comparing the maximum values of the two tables (I and III), it will be noticed that at the end of the sixth minute the brain-tissue *exceeds* the skull by 0°·00042 C.

(*c.*) The maximum change of temperature produced when the *permanent thermal condition* is attained.

First, as to the time required to reach this condition, with the differences of temperature set down under the heading (*a*), the range was from 9 to 11 minutes, the average of all the times being 9 minutes 52·5 seconds. In 50 per cent. of the cases it was 9 minutes, in 37·5 per cent. it was 11 minutes, and in the remaining 12·5 per cent. it was 10 minutes.

In Table IV we have the results of the transmission at this period, reduced, as in the case of the skull, to values representing 0°·1 C. difference of temperature.

Table IV.—*Permanent thermal condition* effected by 0°·1 C., through 7·5 millims. of cerebrum of sheep. 1° of galvanometer is equal to 0°·0006742 C., and 0°·1 C. is equal to 148°·316 of galvanometer.

	Degrees of galvanometer.	Thermometric values.	Percentages of heat transmitted.
Averages..........	113·029°	0·07620 C.	76·208 per cent.
Maxima..........	138·888	0·09364	93·638 „
Minima	72·000	0·04854	48·545 „

Comparing the above table with Table II, we find that the average difference in the conducting powers of skull and brain-tissue is now reduced to 0°·00971 C., in favour of the bone; but if we take the maximum values, the conductivity of brain-tissue slightly exceeds that of skull, namely, by 0°·00038 C.

Experiments on Skin.

The skin experimented on was fresh sheep's skin; and, in the particular experiments with which we have now to deal, pieces of the shaven scalp 3 millims. in thickness, and of the same area as the pieces of skull and cerebrum already described, were employed.

Following the course adopted with skull and brain-tissue, we have the same points as before to consider.

(*a.*) The time required for the *first sign* of the change of temperature to show itself through the piece of scalp.

The average degree of difference of temperature to which the scalp was subjected was 0°·12957 C., the maximum and the minimum being, respectively, 0°·1645 C. and 0°·125 C. With these differences the time required for the first sign of the change of temperature to manifest itself, on the upper surface of the piece of skin—with the apparatus set, as before, to detect 0°·0006742 C.—was 17·6 seconds. In 60 per cent. of the cases the time was 19 seconds; while the other 40 per cent. was divided equally among 23, 16, 15, and 8 seconds.

Reducing all the results to values representing 0°·1 C. difference of temperature, the average time is found to be 22·88 seconds, the extremes being 29·417 and 10 seconds. The average *rate* of the thermal movement is consequently 1 millim. per 7·6267 seconds, the maximum and the minimum times being, respectively, 9·8057 and 3·3333 seconds. The average rate of the thermal transmission per millimetre for 0°·1 C. difference of temperature appears, therefore, to be lower, at this period, in scalp than in bone or brain-tissue; and the lowest rate in scalp is below the corresponding rates in bone and brain-tissue; but on the other hand, the highest rate is found in scalp, although the degree of superiority is insignificant. In Table V the results obtained on the three tissues, at this period, are brought together for comparison.

(*b.*) The degree of change of temperature produced at certain measured intervals of time.

Table V.—Comparison of times required for the *first sign* of the thermal change to show itself through 7·5 millims. of sheep's skull, 7·5 millims. of sheep's brain, and 3 millims. of sheep's scalp, respectively, with apparatus detecting 0°·0006742 C.

Degrees of difference of temperature to which the several tissues were subjected.

	Bone.	Brain.	Skin.
Averages............	0·1290° C.	0·13116° C.	0·12957° C.
Maxima	0·1470	0·15130	0·16450
Minima.............	0·1136	0·12020	0·12500

With the above differences of temperature the times required for the first appearance through the tissues of the thermal change were as follows:—

	Bone.	Brain.	Skin.
Averages	28·4 seconds.	30·88 seconds.	17·6 seconds.
Maxima	38·0 „	53·00 „	23·0 „
Minima	23·0 „	23·00 „	8·0 „

Percentages of the frequency of occurrence of the different times noted.

Bone.		Brain.		Skin.	
Times.	Percentages.	Times.	Percentages.	Times.	Percentages.
23 seconds	53·333	23 seconds	44·444	19 seconds	60·000
38 „	26·667	38 „	27·777	23 „	10·000
30 „	20·000	30 „	22·223	16 „	10·000
		53 „	5·556	15 „	10·000
				8 „	10·000

Times calculated for 0°·1 C. on the basis that the time required would be inversely proportional to the degree of difference of temperature.

	Bone.	Brain.	Skin.
Averages	37·30 seconds.	40·490 seconds.	22·880 seconds.
Maxima	55·86 „	63·706 „	29·417 „
Minima	26·29 „	27·646 „	10·000 „

Times required to traverse 1 millim. of each of the tissues, calculated for a difference of 0°·1 C.

	Bone.	Brain.	Skin.
Averages	4·9733 seconds.	5·3986 seconds.	7·6267 seconds.
Maxima	7·4480 „	8·4941 „	9·8057 „
Minima	3·5053 „	3·6853 „	3·3333 „

Table VI gives the results obtained at the end on the several times adopted in the preceding tables as bone and brain.

Table VI.—Effects of 0°·1 C. difference of temperature through 3 millims. of sheep's scalp. 1° of galvanometer is equal to 0°·0006742 C.; and 0°·1 C. is equal to 148°·316 of galvanometer.

Time from the moment of contact of copper plate, on which the piece of skin rested, and water.	Averages.		Maxima.		Minima.	
	Degrees of galvanometer.	Thermometric values.	Degrees o galvanometer.	Thermometric values.	Degrees of galvanometer.	Thermometric values.
At the end of—						
1 min. 15 sec.	17·191°	0·01159° C.	21·120°	0·01424° C.	10·576°	0·00713° C.
2 „ 0 „	31·241	0·02106	38·808	0·02616	20·898	0·01409
4 „ 0 „	59·208	0·03992	83·952	0·05660	35·861	0·02417
6 „ 0 „	80·766	0·05445	96·492	0·06505	63·884	0·04307

Percentages of heat transmitted, deduced from the above values.

Times.	Averages.	Maxima.	Minima.
1 min. 15 sec.	11·597 per cent.	14·239 per cent.	7·137 per cent.
2 „ 0 „	21·063 „	26·165 „	14·090 „
4 „ 0 „	39·921 „	56·603 „	24·179 „
6 „ 0 „	54·452 „	65·058 „	43·070 „

It will, at once, be evident, that, although the pieces of skull and of cerebrum are two and a-half times thicker than the pieces of skin, yet the amount of heat transmitted by the latter is considerably less than the amount transmitted by the former, with the exception, that the minimum values of scalp are higher than the corresponding values of brain-tissue, and approach somewhat closely to those of skull.

If we should apply the well-known physical calculations of Fourier and others, and through them seek to determine the changes of temperature which would exist if the piece of skin were increased in thickness to 7·5 millims., the inferiority of the tissue in conducting power compared with bone and brain-tissue, would become much more striking ;* but unfortunately, not only theory—based upon the lack of homogeneity in these structures—but also a large number of direct experiments made by the writer, show that such calculations are not to be relied upon. In the case alone of the hard tissue of bone, it has sometimes happened that the results of the mathematical calculations and those of the experiment have partially agreed. We cannot, then, with any certainty, reason from one thickness of bone, brain, or skin to another. To have reduced the bone to 3 millims. in thickness to correspond with the skin, would have entailed serious risks of error in the method of experimenting adopted.† The thickness of bone chosen was a natural thickness of the skull often found in the animal experimented on, and the same is true of the thickness of the scalp.

(*c*.) The maximum change of temperature produced, when the *permanent thermal condition* is attained.

With the differences of temperature given under the heading (*a*), the permanent thermal condition was reached in a time ranging from 11 to 15 minutes, the average being 12 minutes 15 seconds. In 50 per cent. of the cases the time was 11 minutes, and the other 50 per cent. was divided equally between 12 and 15 minutes.

In Table VII we see the effects of the thermal movement at this stage, reduced as before to the basis of 0°·1 C. difference of temperature.

Table VII.—*Permanent thermal condition* effected by 0°·1 C. through 3 millims. of sheep's scalp. 1° of galvanometer is equal to 0°·0006742 C.; and 0°·1 C. is equal to 148°·316 of galvonometer.

	Degrees of galvanometer.	Thermometric values.	Percentages of heat transmitted.
Averages	100·155°	0·06751° C.	67·514 per cent.
Maxima	117·480	0·07920	79·209 „
Minima	82·104	0·05535	55·354 „

* The application of these formulæ *sweeps away the whole of Table VI*, as according to them, even at the end of the sixth minute no sign of the transmission would be found through 7·5 millims. of scalp.

† By exchanges between the face of the pile and the water through the paraffine envelope (see note, p. 181), which latter would, with the above thickness of bone, be in dangerous proximity to the liquid.

Placing the above beside Tables II and IV, even leaving out the question of relative thickness, the inferior conducting power of skin, compared with bone and cerebral tissue, is again manifest, although the degree of this inferiority is diminished. Thus, taking the averages at the end of the sixth minute, the skin falls below bone by 24·08 per cent., and below brain-tissue by 12·347 per cent.; while now these differences are reduced, respectively, to 18·404 per cent., and 8·694 per cent. If we take the maximum values, the skin is inferior to bone (the maximum value of the latter being a trifle lower than that of brain-tissue) by 26·229 per cent. at the end of the sixth minute, and by 14·06 per cent. in the permanent thermal condition. With regard to the minimum values, they are now, as at former periods, higher in skin than in brain-tissue.

Conduction in Bone and Skin combined.

Let us now suppose the 3 millims. of scalp to be lying upon the 7·5 millims. of bone, as in life, and a rise of temperature of 0°·1 C. to occur on the cerebral surface beneath. We have seen that the dura mater offers no appreciable resistance, and have, therefore, simply to deal with the compound conductor of bone and skin. We will first estimate how long a time would elapse after the rise of temperature in the brain before 0°·0006742 C. difference would be found on the outer surface. Now it has been shown that the average time required for 0°·1 C. to traverse the bone is 37·3 seconds, while the average time required for the same difference of temperature to traverse the skin is 22·88 seconds; the total time would therefore, be 60·18 seconds, the shortest time would be 36·39 seconds, and the longest time 85·277 seconds.

Next, with regard to the amount of heat which would be transmitted through the compound conductor. Looking at Table I we see that the bone has transmitted, at the end of 1 minute 15 seconds, 16·09 per cent. of the heat received, and from Table VI we learn that, during the same time the skin has transmitted 11·597 per cent.;* therefore, the skin receiving from the bone 16·09 per cent. of the original amount of heat would transmit 11·597 per cent. of these receipts, or 1·86395 per cent. of the original amount; hence the change of temperature observed on the outer surface of the scalp, at this period, would be 0°·001866 C. Table VIII gives the results, for the several periods of time, deduced in the above manner from Tables I and VI. These results show that, in spite of the decided resistance introduced by the skin, there would not be the slightest difficulty in detecting, with delicate apparatus, at an early period, on

* Averages.

the outer surface of the scalp, a change of 0°·1 C. on the surface of the brain, in the animal in question.

Table VIII.—Effects of 0°·1 C. difference of temperature through 7·5 millims. of sheep's skull and 3 millims. of sheep's scalp, *taken together*. 1° of galvanometer is equal to 0°·0006742 C.; and 0°·1 C. is equal to 148°·316 of galvanometer.

Times.	Averages.		Maxima.		Minima.	
	Degrees of galvanometer.	Thermometric values.	Degrees of galvanometer.	Thermometric values.	Degrees of galvanometer.	Thermometric values.
At the end of—						
1 min. 15 sec.	2·767°	·001866° C.	4·971°	·003352° C.	0·931°	·000628° C.
2 „ 0 „	11·409	·007692	19·550	·013181	4·293	·002894
4 „ 0 „	35·450	·023902	65·367	·044073	9·671	·006520
6 „ 0 „	63·424	·042762	88·083	·059389	29·504	·019892

Percentages of heat transmitted.

Times.	Averages.	Maxima.	Minima.
1 min. 15 sec.	1·866 per cent.	3·352 per cent.	0·628 per cent.
2 „ 0 „	7·692 „	13·181 „	2·894 „
4 „ 0 „	23·902 „	44·073 „	6·520 „
6 „ 0 „	42·762 „	59·389 „	19·892 „

Coming to the permanent thermal condition of the compound conductor, we can estimate, in the same manner as we have just done, from the separate tables for bone and skin, the amount of heat which would be transmitted when this condition is reached. Table IX gives the results of these estimates. Here, again, we have evidence that—although diminished—the external manifestations of 0°·1 C. change at the cerebral surface would still be amply great to admit of detection by much coarser instruments than those we are employing. Supposing the rise of temperature at the cerebral surface to be only 0°·01 C., instead of 0°·1 C., it would still be plainly visible at the exterior at the end of the fourth minute; for the percentage of transmission at this period would give a galvanometric deflection of 3°·545, equal to 0°·00239 C., while when the permanent thermal condition was attained, the deflection would be 8°·603, equal to 0°·0058 C. But, as was stated in the introduction, there is no reason whatever why rises of temperature of 0°·2 C., and even 0°·3 C. may not occur in the brain of man, and perhaps in the brains of other of the higher animals, during intellectual and emotional activity, with, consequently, decidedly greater external manifestations than those given in our calculations.

Table IX.—*Permanent thermal condition* effected by 0°·1 C. through 7·5 millims. of sheep's skull and 3 millims. of sheep's scalp, *taken together*. 1° of galvanometer is equal to 0°·0006742 C.; and 0°·1 is equal to 148°·316 of galvanometer.

	Degrees of galvanometer.	Thermometric values.	Percentages of heat transmitted.
Averages	86·033°	0·058006° C.	58·006 per cent.
Maxima	119·572	0·073877	73·877 ,,
Minima...........	58·010	0·039112	39·112 ,,

With regard to the effect of the blood circulating between the surface of the brain and the outer surface of the skin, the only way in which this liquid could check the outward thermal propagation would be by virtue of its specific heat. The writer has considered this question at some length in the work already cited,* and he sees no reason now to depart from the line of argument there followed. If, as was there done, we allow a loss of 50 per cent. of the initial rise of temperature to satisfy the capacity for heat of the blood (and we are really not warranted in granting such a loss) our 0°·1 C.—now reduced to 0°·05 C.—would still show itself at the outer surface, at the end of the second minute, by a galvanometric deflection of 5°·704, equal to 0°·003846 C.

We have next to see how far the good conductivity of brain-tissue would act to prevent localisation at the outer surface of the scalp of changes of temperature in a narrowly circumscribed area of the cerebral surface.

Imagine, as before, a point of the cerebral surface to have its temperature raised 0°·1 C. Now, setting out from this point, the excess of heat would be transmitted to points in the surrounding cerebral mass situated at a distance of 7·5 millims., in the proportions shown in Tables III and IV. What the transmission to a point of the external surface situated directly over the focus of heat would be we have just seen. We have, then, merely to take the temperatures contained in Tables III and IV, and using the percentages of transmission through

* *Op. cit.*, pp. 115, 118.

skull and scalp combined, given in Tables VIII and IX, to calculate the temperatures which would be found at a point of the outer surface lying over the point of cerebral surface situated 7·5 millims. from the focus of heat. For example, Table III shows us that, at the end of the sixth minute, a point of the brain, situated 7·5 millims. from another point heated 0°·1 C., would have its own temperature raised, by conduction, 0°·06679 C., and Table VIII shows us that the transmission through skull and scalp combined (which would, of course, be proceeding coincidently) is, at this time, 42·762 per cent.; hence the temperature of the outer surface would be 0°·02856 C. Tables X and XI show the effects of this indirect transmission to the outer surface.

Table X.—Effects produced through 7·5 millims. of sheep's skull and 3 millims. of sheep's scalp, taken together, lying over a point of cerebral surface 7·5 millims. distant from another point of this same surface, the temperature of which latter point is raised 0°·1 C. The results are calculated from Tables III and VIII. This table is for comparison with Table VIII where the effects of the *direct* transmission from the heated point are given. 1° of galvanometer is equal to 0°·0006742 C.; and 0°·1 C. is equal to 148°·316 of galvanometer.

Times.	Averages.		Maxima.		Minima.	
	Degrees of galvanometer.	Thermometric values.	Degrees of galvanometer.	Thermometric values.	Degrees of galvanometer.	Thermometric values.
At the end of—						
1 min. 15 sec.	0·392°	·000264° C.	1·087°	·000733° C.	0·040°	·000027° C.
2 ,, 0 ,,	4·873	·003286	7·786	·005249	0·560	·000378
4 ,, 0 ,,	17·888	·012060	45·483	·030664	2·122	·001430
6 ,, 0 ,,	42·360	·028560	70·769	·047712	9·868	·006633

Percentage of heat transmitted.

Times.	Averages.	Maxima.	Minima.
1 min. 15 sec.	0·264 per cent.	0·733 per cent.	0·027 per cent.
2 ,, 0 ,, ...	3·286 ,,	5·249 ,,	0·378 ,,
4 ,, 0 ,, ...	12·060 ,,	30·664 ,,	1·430 ,,
6 ,, 0 ,, ...	28·560 ,,	47·712 ,,	6·633 ,,

Table XI.—Permanent thermal condition effected through 7·5 millims. of sheep's skull and 3 millims. of sheep's scalp, taken together, lying over a point of cerebral surface 7·5 millims. distant from another point of this same surface, the temperature of which latter point is raised 0°·1 C. The results are calculated from Tables IV and IX. This Table is for comparison with Table IX, where the effects of the *direct* transmission from the heated point are given. 1° of galvanometer is equal to 0°·0006742 C.; and 0°·1 C. is equal to 148°·316 of galvanometer.

	Degrees of galvanometer.	Thermometric values.	Percentages of heat transmitted.
Averages	65·563°	0·044202° C.	44·202 per cent.
Maxima	102·606	0·070176	70·176 „
Minima...........	28·160	0·018985	18·985 „

Plainly, if it were a question of mere conduction alone, and if the skull and skin at the several points were of equal thickness, and possessed of the same conductivity, it would be easy to locate on the outer surface, within a radius of 7·5 millims., a change of 0°·1 C. occurring on the cerebral surface.

The following are the differences of temperature in favour of the point of surface lying directly over the focus of heat, which would be found under the circumstances we are considering:—

Times.	Average differences of temperature.	Permanent thermal condition.	
			Differences of temperature.
1 min. 15 sec....	0·001602° C.	Average	0·013804° C.
2 „ 0 „ ...	0·004406	Maximum	0·003701
4 „ 0 „ ...	0·011842	Minimum*......	0·020127
6 „ 0 „ ...	0·014202		

But, in truth, in the case of the tissues concerned, we are not, in the first place, dealing with simple homogeneous conductors of uniform thicknesses. Even within the narrow area specified, the bone or skin may exhibit decided differences of conductivity, due to slight variations of structure or composition. That this may be the case, the writer has over and over again proved by direct experiment. As the

* It will be noticed that the *least* difference is found with the *maximum* of transmission, and the *greatest* difference with the *minimum* of transmission.

propagation of heat by conduction is not *rectilinear*, a slight alteration of texture or composition might easily deflect the path of transmission in such a way as to wholly change the relative temperatures of the outer surface which we have given. Differences of thickness, also small, but sufficient to overthrow our calculations—may exist. Lastly, the circulation of the blood, already alluded to, although incapable of checking the outward transmission, might yet, within such narrow limits, bring about a confusion in the external manifestations of the interior change of temperature. It is only when areas of much greater dimensions—for instance, of 50 or 60 millims. square—are taken, that we can look with any degree of confidence to the relative external temperatures as furnishing a key to the relative temperatures of the underlying tracts of cerebral surface.* Moreover, in increased mental activity—whatever may be its kind—the change of temperature on the outer surface of the head is of widespread extent, and not confined to such limited areas as those on which our calculations are based.

* See the writer's "Regional Temperature of the Head," pp. 119 and 209.

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