RADIATION OF HEAT FROM THE HUMAN BODY. V. THE TRANSMISSION OF INFRA-RED RADIATION THROUGH SKIN

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In 1934 the authors (1) reported the results of spectroscopic observations on the emission, reflection and transmission of infra-red radiation by the human skin. The experiments were undertaken with the primary purpose of determining whether the emissive and absorptive properties of the skin were those of black-body radiator within the spectral range in which the human body radiates heat. The results of the experiments, carried out by the use of a reflecting infra-red spectrometer equipped with a rock salt prism, confirmed previously accumulated evidence (2, 3, 4) as to the truth of this assumption, and thus seemed to establish beyond all doubt the validity of the radiometric method of skin temperature measurement. Recently published results of Christiansen and Larsen (11), using questionable technique, would lead one to the dubious conclusions that the white human skin has a radiating power only about 78 per cent that of a black body and that the skin is quite transparent to the infra-red radiation in the region of the radiation emission from the human body. This new evidence is in direct contradiction to that of the combined work of nearly all other workers on this problem; it will be briefly discussed below. During the course of our previous transmission experiments it was noted that: (1) the penetrability of skin for the near infrared region of 0.75 μ to 3 μ, which is not included in the range of black-body emission above alluded to, was considerably lower as found by us than as reported by the majority of previous observers (5, 6, 7, 8, 9, 10) and (2) the transmission spectrum of the thinnest layers of skin showed an apparently characteristic fine structure which resembled that of the infra-red spectrum of many organic compounds, and its most prominent bands were thought to be due to the C–H, N–H and O–H linkages in the organic substances composing the skin.

The present report is of further experiments concerned principally with these two findings of the former investigation. Since nearly all observers agree that it is only within the near infrared range than any appreciable penetration of the skin occurs, it is this portion of the spectrum, if any, which is effective in the deep penetration of radiant heat. As the present use of infra-red therapy is based partially on the supposition that the infra-red radiation penetrates in effective amounts, it was thought desirable to repeat the observations on living skin as well as on dead skin, on which alone our previous observations had been made. To determine more exactly the amount of scattered transmitted radiation, thus determining accurately the total amount of transmitted radiation, is also of importance. This range of wave lengths also includes those effective in infra-red photography, and the question of how far and in what quantities the radiation penetrates is of importance in determining the limitations of this method of photographing subcutaneous structures.

As regards the second of the findings, i.e. the presence of characteristic absorption bands in the transmission spectrum of very thin (epidermal) samples of skin, it seemed desirable to repeat these observations also, using an instrument with greater dispersion, and thus to resolve the absorption bands more exactly and possibly identify them.

METHOD

The present set of observations were made by means of a rock-salt prism spectrometer designed by one of us and built in our laboratory by Mr. G. F. Soderstrom; its design and construction will be reported later. The chief differences between it and the instrument used in the former investigations are that a larger prism was used and that the light beam was made to traverse the prism twice. Both of these modifications produced a far greater dispersion and consequent better resolving power. Calibration was carried out with great care using some 23 calibrating points, and is considered correct to .01 μ. As in the former experiments a Nernst glower was used as the energy source and a vacuum thermocouple as the receiving element. A Leeds and Northrup high sensitivity galvanometer was used in conjunction with the latter, and the deflections were read directly on a glass scale. A potentiometer was connected in series with the galvanometer, and was used whenever the deflections were very large, thus obviating the necessity of changing slit widths between measurements of the direct and transmitted beam when these differed greatly in energy. The slit widths used varied from 0.1 to 0.5 mm., and the data presented are without slit-width corrections.

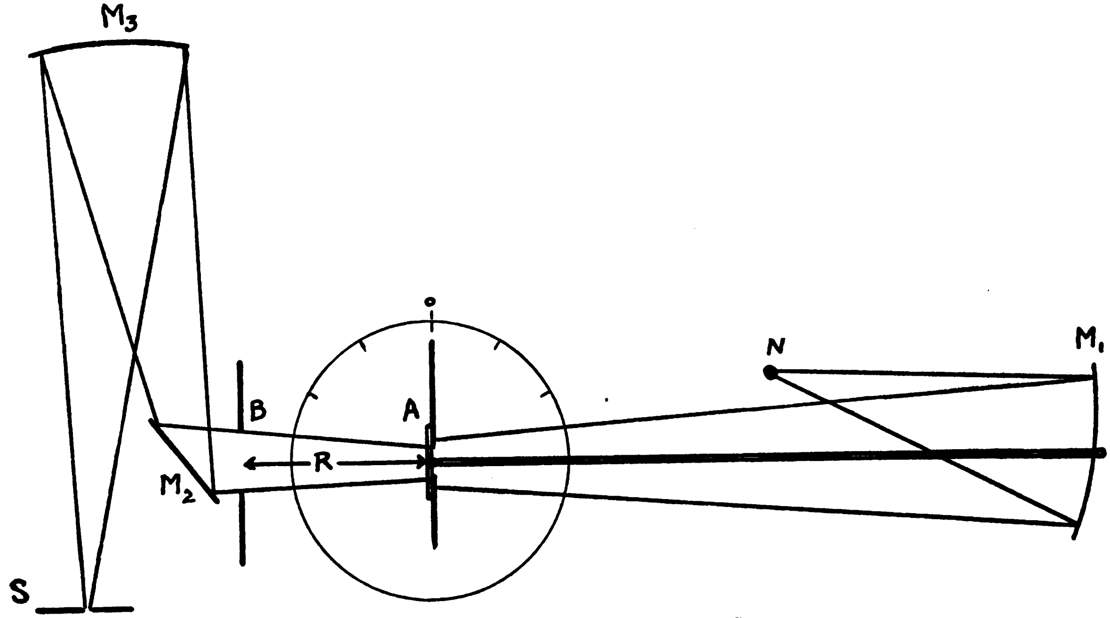

Fig. 1. Diagram of External Optical System.

The external optical system was essentially the same as used in the former investigation and was a modification of a method originally developed by Hutchins (12) for the measurement of scattering. The arrangement for this is shown in Figure 1. The specimen to be examined is mounted over a rectangular diaphragm at *A*, so placed as to be normal to the axis of the cone of incoming rays. The light from the Nernst glower is focussed upon the specimen so that at *A* we have a source of radiation which emits in all directions, depending upon how much scattering takes place. The light source *N* and the concave mirror M_1 together with *A* can be rotated about a vertical axis through *A* by any desired amount. A second rectangular diaphragm *B* is fixed with respect to the mirrors M_2, M_3 and the entrance slit of the spectrometer *S*. By rotating the specimen with the light source the distribution of the scattered light with the angle may be determined, as was done in the former experiments. By the interposition of the diaphragm *B*, however, it is possible to go further and integrate over the entire hemisphere the total amount of scattered radiation from *A*, the distance *R* and the dimensions of the glower image *A* and the diaphragm *B* being known The value thus calculated may then be applied as a correction factor for scattering to the direct transmission values.

Observations both of direct transmission and scattering were made on (1) relatively thick specimens of dead human skin obtained from surgical amputations, (2) the entire thickness of a rabbit's ear first alive and later amputated, and (3) thin epidermal pieces of human skin obtained by cantharides blister from the volar surfaces of the forearm of living subjects. As it was found in preliminary experiments that the method of sponging the dead specimens with saline to prevent excessive drying was not entirely effective in preventing drying and consequent change in penetrability of the tissue, this method was abandoned, and the entire specimen with aperture frame was kept immersed in the normal saline between readings. This was made possible by having the frame slide in a grooved holder which was accurately fitted so that the skin specimen always returned to the same position. As a result, the skin was exposed to the radiation only as long as it took the galvanometer to come to equilibrium—about 7 seconds—which was not long enough to cause any drying or change in penetrability. The living rabbit's ear could not be conveniently attached to the sliding frame so that the latter was left in place in the holder, and the ear held against it for each observation, the placement being oriented by means of the vascular markings of the ear. The living ear was not artificially moistened as was the dead tissue. It had been shaved of all hair before the experiment. The thin human skin obtained by cantharides blister was examined in the moist condition as above described and again after having been thoroughly dried. The reason for this will appear in the discussion of the results. The dried skin was placed between two rock salt plates to prevent overheating and scorching. The procedure in general was to determine the direct transmission by measuring the intensity of the incident beam and of directly transmitted beam at each spectrometer setting. For the total transmission the amount of energy scattered from the normal must be taken into account. Accordingly, with the spectrometer set for a given wave length, the specimen with its optical system described above, was rotated about a vertical axis by 5° steps. Observations were made with increasing angle until the deflection reached zero. In this manner the *form* of the distribution of scattering about the angle, $\theta = 0$, was determined. Measurements of scattering were made at 1 μ, 2 μ, 3 μ, 5 μ, and 7 μ, and as the scattering varies only gradually with wave length, becoming less with greater wave lengths, the corrections for intermediate wave lengths were interpolated for over a considerable range. The error thus introduced is negligible.

The correction for scattering

From a consideration of Figure 1 it is apparent that what is being measured, for any value of θ, is the energy emitted from the surface A and received by the surface B. By measuring this amount at various values of θ the angular distribution curve of the energy scattered over the hemisphere may be determined. The total energy can then be calculated by integrating the function of the distribution of scattering over the hemisphere, mathematically, if the function is easily determinate, or by graphical integration. Figure 2 shows such scattering curves for several materials measured at 1.7 μ, and it may be seen that while white bond paper follows the simple cosine function of Lambert's Law very well the other materials, including those with which we are concerned, do not. Ängstrom's modification of Lambert's Law was found to fit the data for ground glass and skin so that the integrations, whether graphic or mathematical, were in complete agreement if this function were used.

When the total scattering is thus determined by integration of the distribution curves, the total energy transmitted, I, is given by the equation

$$I = \frac{2\pi SR^2F}{B},$$

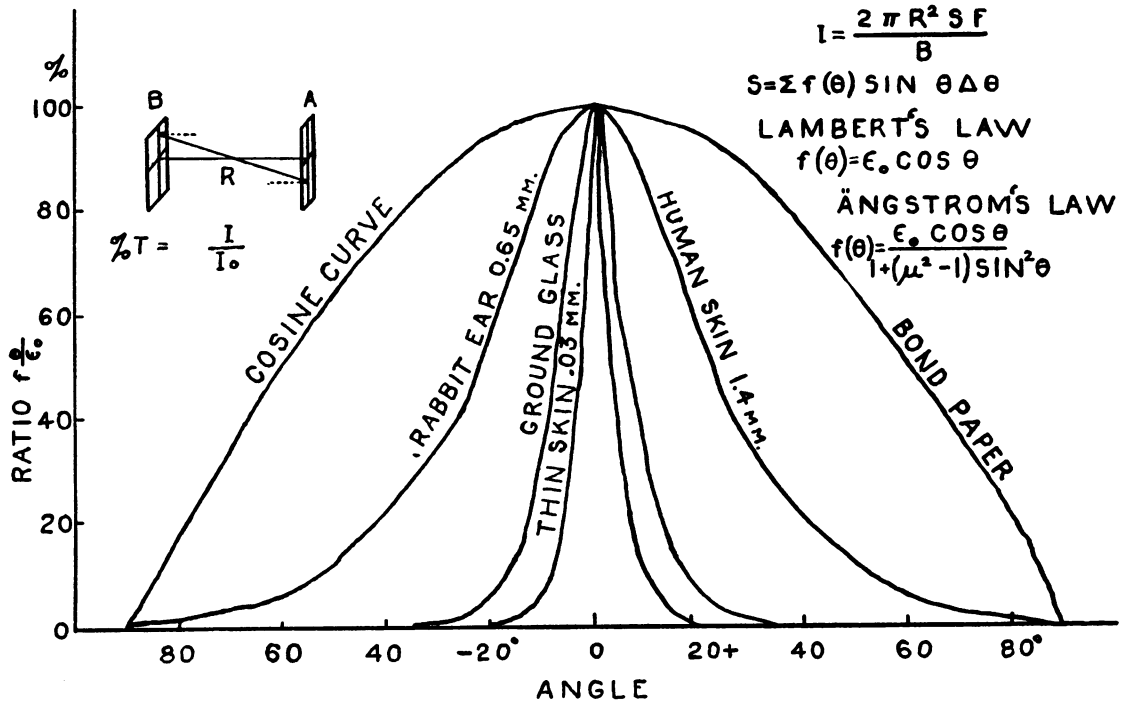

FIG. 2. DISTRIBUTION CURVES OF SCATTERED TRANSMITTED ENERGY FOR VARIOUS MATERIALS.

in which S = total scattering = $\sum_0^{\pi/2} f(\theta)$ sin $\theta\Delta\theta$.

For Angstrom's law

$$f(\theta) = \frac{\epsilon_0 \cos\theta}{1 = (\mu^2 - 1)\sin^2\theta},$$

where θ = angle from the normal,

ϵ_0 = intensity of the scattering for $\theta = 0$,

$f(\theta)$ = intensity of the scattering for any angle θ,

μ = constant.

All of these quantities except μ are measurable and therefore μ can be determined.

R, *F*, and *B* are all determined from the experimental set up:

R = distance between diaphragms,

F = obliquity factor

$$= \frac{1}{1 - \frac{1}{4R^2}(a^2 + \alpha^2 + b^2 + \beta^2)},$$

B = area of receiving aperture whose dimensions are a, b,

α, β = dimensions of emitting aperture A.

The percentage of the total incident energy transmitted, T, is determined by the ratio of the total amount of energy transmitted to the amount of incident energy I_0, or

$$T = \frac{I}{I_0}.$$

Observations were made on ground glass as a means of checking the method. The total transmission through a plate of ground glass was determined and compared with the direct transmission through a plate of polished glass cut from the same piece. It was found that the polished glass transmitted 68 per cent and the ground glass 61 per cent. A discrepancy of about this magnitude is to be expected because of internal reflection at the ground surface so that the ground glass should transmit somewhat less than the clear specimen and the agreement must be considered very good.

In our earlier communication (1) on infra-red transmission of skin it was pointed out that the attempts of other investigators (9, 10) at correcting for scattering by the use of methods which involve placing the specimen in close proximity to the receiving thermo-element introduce the error of reradiation. In this way they were led to suppose that the scattering of the transmitted light followed Lambert's Law, but as is shown here, such is far from the case with skin or even ground glass.

RESULTS

In Figure 3 are shown graphically the results of the experiments on transmission through a rabbit's ear and through two relatively thick specimens of human skin. The thicknesses were determined by measurement of sections mounted on microscopic slides after routine fixation, sectioning, and staining following the termination of the experiments. All of the curves are corrected for scattering except Curve 3a which corresponds to Curve 3 uncorrected.

Curve 1 represents the transmission of the living rabbit ear. Curve 2 represents the transmission of the same ear a few minutes after being severed from the rabbit. Curve 3 represents the transmission of the ear after it has been dead for two days. The thickness of the ear was 0.65 mm.

The two pieces of human skin were of 1.4 mm. and 2.0 mm. maximum thickness respectively. Both of these were obtained from an amputated leg. The thinner piece was filed down to quite uniform thickness after freezing. The thicker piece was neither frozen nor filed but merely trimmed down with a razor blade as well as possible to a fairly even thickness. The filing and trimming, of course, was done on the inner surface, and the material removed was merely subcutaneous fat and connective tissue. Both specimens were actually composed of skin plus some subcutaneous connective tissue, the skin itself forming less than half of the total thickness. They were kept in normal saline solution in the icebox until examined, the thinner piece one day after amputation, the thicker not until two days after amputation.

Examination of the curves for the rabbit ear reveals that the living tissue allows considerably less penetration than the dead and that, moreover, the longer the tissue has been dead the greater the transmission. Comparison of the uncorrected curve (3*a*) and the corrected curve (3) shows that a large proportion of the energy is scattered. This accounts for the much greater transmission through human skin shown here than we reported for comparable thicknesses in our former investigation, since in the latter only the direct transmission was measured. Thus we find a maximum total transmission of direct plus scattered radiation of 10 per cent for a thickness of about 1 mm.

while the direct transmission alone amounts to only about 1 per cent. Even the corrected value, however, is very much less than the 21 per cent maximum transmission through 5 mm. reported

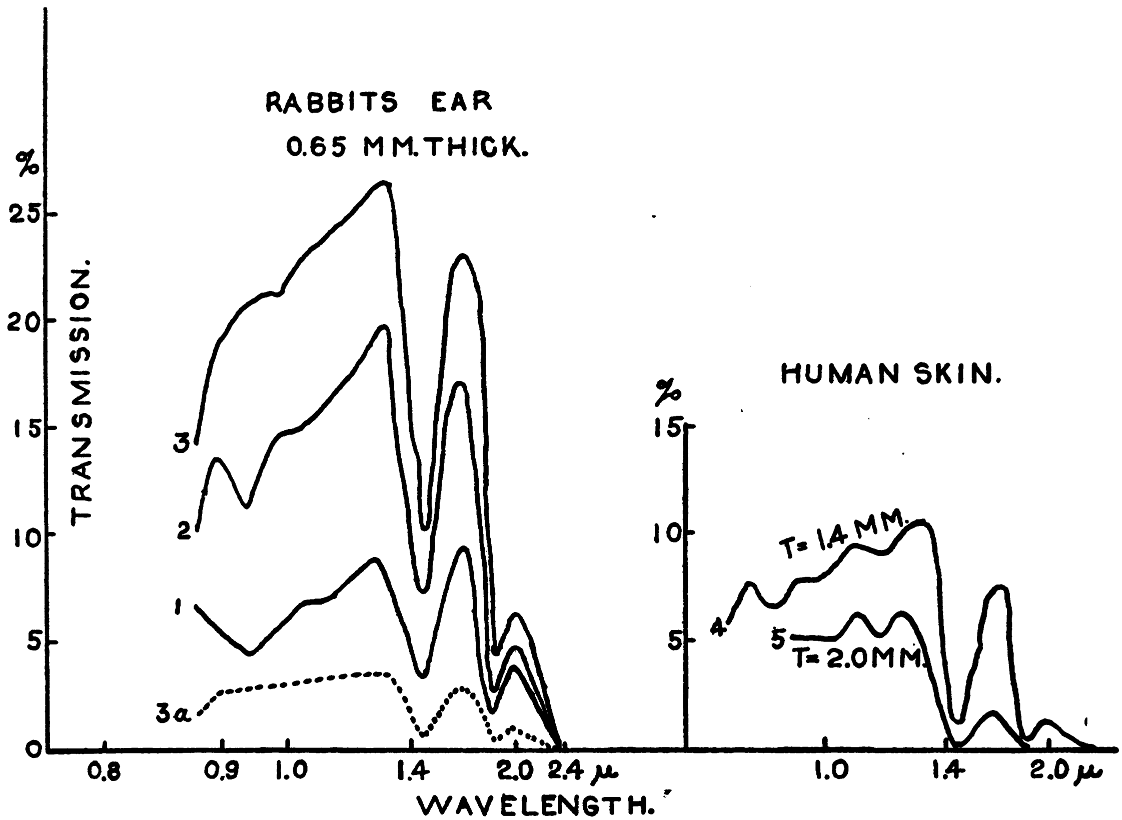

FIG. 3. TRANSMISSION CURVES OF RABBIT'S EAR AND OF THICK SPECIMENS OF HUMAN SKIN. CORRECTED FOR SCATTERING EXCEPT CURVE 3a WHICH REPRESENTS CURVE 3 UNCORRECTED.

Curve 1—living rabbit ear.
Curve 2—rabbit ear dead one day.
Curve 3—rabbit ear dead two days.
Curve 4—human skin, thickness 1.4 mm.
Curve 5—human skin, thickness 1.5 to 2.0 mm.

by Danforth (7) and Cartwright (8). From our results, the estimated maximum transmission through such a thickness would be less than 1 per cent. If living skin were used the transmission would be even less as the rabbit ear experiment shows. The absorption bands found in the curves may be identified as due to water, as also is the cut off at 2.4 μ. It will be noticed that they are present in the curve for the living rabbit ear which was not moistened with saline, as well as in the other curve.

In Figure 4 is given the transmission curve of a thin piece of skin consisting of the horny layer of the epidermis alone, .03 mm. in thickness. The absorption bands in the curve for the wet skin are all identified as being due to water, in fact the curve is an exceptionally good example of the water spectrum. The curve is corrected for scattering but no correction is needed beyond 7.6 μ. From Figure 2 it is obvious that the magnitude of the scattering factor is very much less for such thin epidermal pieces than it is for the thick specimens. The intense water spectrum of the wet skin has evidently obscured the bands due to other components of the skin. On drying, however, bands due to other radicals appear while the water bands become less prominent or even disappear entirely. Thus in the curve for dry skin we find that a band has appeared at 3.45 μ which is due to the C–H bond and that the 4.7 μ band is no longer recognizable. Shifts have also occurred in the double band at 3 μ and the double band at 6 μ in which the N–H and C–H bonds are both concerned.

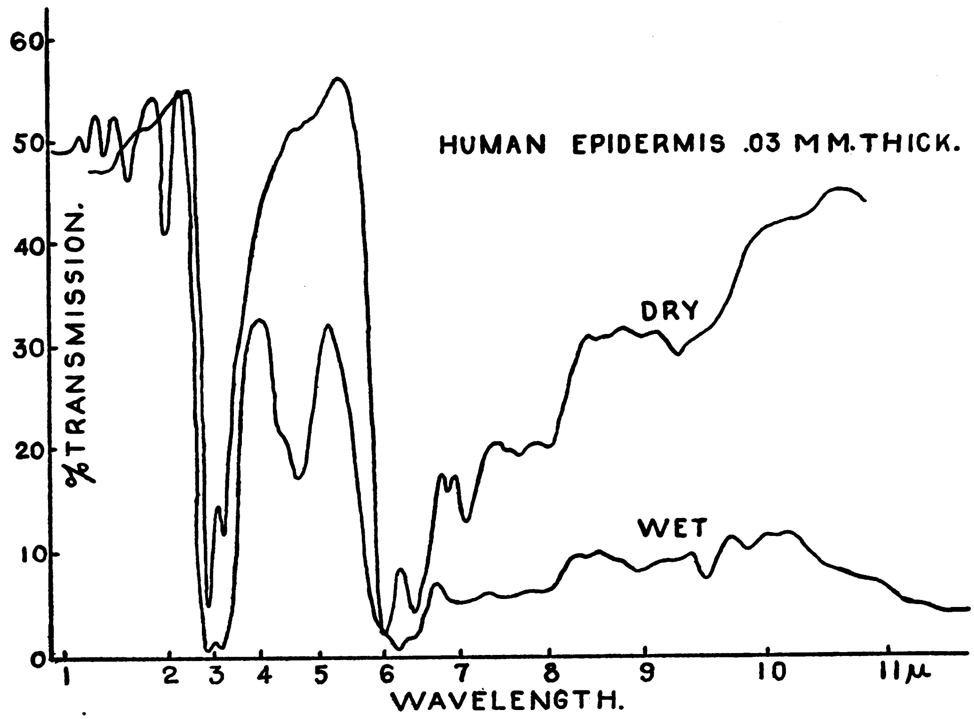

Fig. 4. Transmission Spectrum of Human Epidermis, Wet and Dry.

Observations on the infra-red spectrum of other biological materials are being made since it seems possible that infra-red spectroscopy may be a powerful potential tool for biochemical analysis.

DISCUSSION

The results of the present investigation confirm the conclusions drawn earlier as to the radiating capacity of the skin. That is, the skin in appreciable thickness is quite opaque to radiation of wave lengths greater than 3 μ whether the tissue be living or dead. This is in contradiction to the findings of Christiansen and Larsen. These authors, using the Cobet radiometer and a surface thermocouple, concluded that the radiating capacity is 78 per cent that found by us, and that the radiation beyond 4 μ penetrates the skin in appreciable amounts. The technique of using a thermocouple to measure the *absolute* skin temperature has been criticized before and any conclusions drawn from data thus secured have been shown to be untrustworthy. Further, these authors have not explained the low reflecting power and transmission of the skin to the long infra-red as was found by us. Also the whole of the evidence, with this exception, radiometric and spectroscopic, seems to be in complete agreement in placing the radiating capacity of the skin at about 99 per cent that of a perfect radiator.

The quantitative method of integrating the scattered light transmitted through the several layers of skin permits the estimation of the total amount of energy penetrating one layer and incident on the next. The striae of the tissue act as refracting, reflecting and scattering areas: thus the light which comes through a layer may possibly have traversed a thickness greater than that of the actual layer. There is no way of determining the exact path of a given ray and it is not possible, therefore, to compute the absorption coefficient of skin in the true optical sense. One can, however, compute what may be termed the " effective " absorption coefficient which has been found to be 5.5 for the corneum and 1.54 for the lower layers and subcutaneous tissue for $\lambda = 1.2\ \mu$.

cutaneous tissue; 99 per cent of the total radiation is absorbed within 3 mm. of the surface. It is evident from Figure 3 that for good penetration

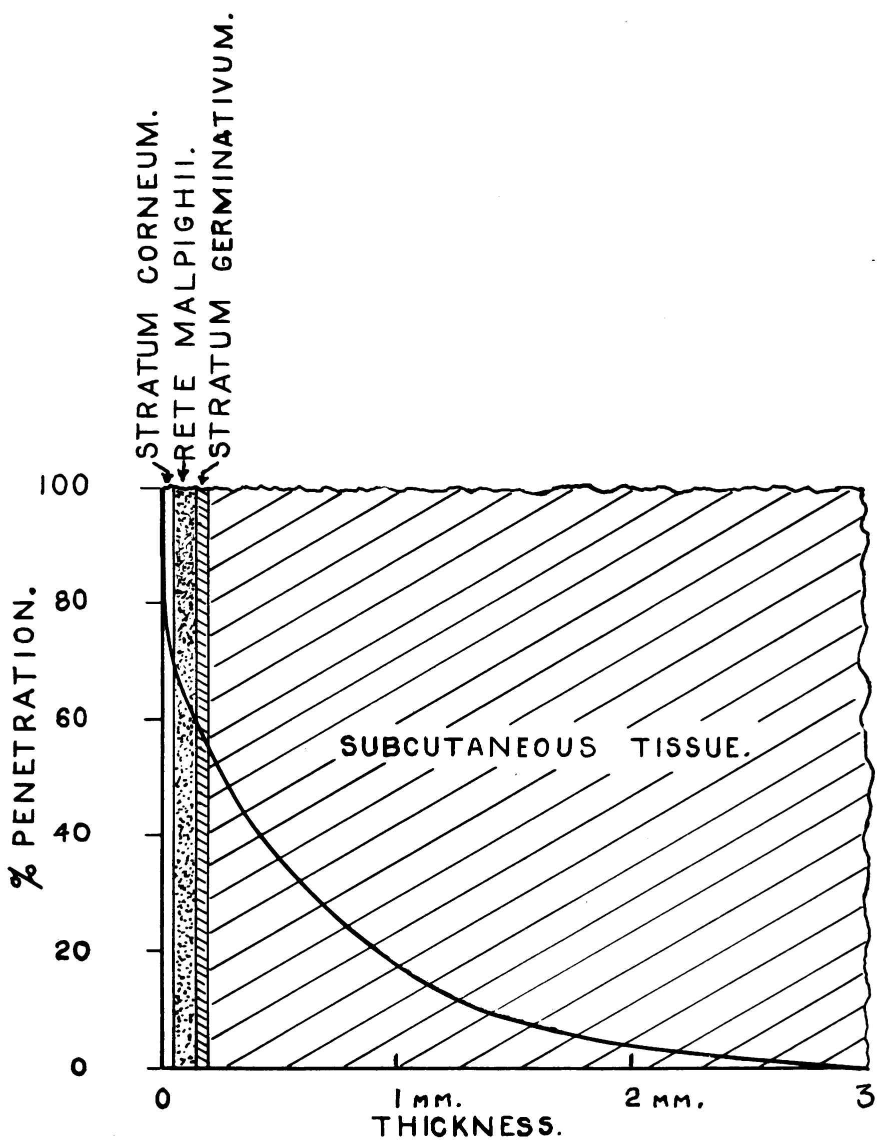

FIG. 5. SCHEMATIC DIAGRAM SHOWING EXTINCTION OF INFRA-RED RAYS OF THE MOST PENETRATING WAVE LENGTH ($\lambda = 1.2\ \mu$) BY DEAD TISSUE.
The blood in living skin would cause a much more rapid extinction.

If one chooses the most penetrating of all the infra-red radiations, wave length $= 1.2\ \mu$, a curve of maximum penetration can be drawn as is shown in Figure 5.

Of the total incident energy, 21 per cent is reflected by the surface; 66 per cent penetrates the corneum; 50 per cent penetrates to the subcutaneous tissue; 99 per cent of the total radiation is absorbed within 3 mm. of the surface. It is evident from Figure 3 that for good penetration of the infra-red rays, a lamp of very high temperature should be used so that the maximum of radiation shall fall at $\lambda = 1.2\ \mu$. The temperature of such a lamp is easily calculated from Wien's Law.

$$\lambda_{max}\, T = 2940,$$

where T = absolute temperature of the lamp and λ_{max} = wave length of maximum radiation in μ.

Thus for $\lambda_{max} = 1.2\ \mu$,

$T = 2100°$ C. as the optimal lamp temperature, a temperature easily reached by a *bright* tungsten filament.

As the infra-red radiation is wholly absorbed near the surface by both living and dead tissue, the therapeutic benefits from such rays must be provided by some peripheral mechanism. The thermal effect of these rays is well known, but inasmuch as 50 per cent of the radiation passes

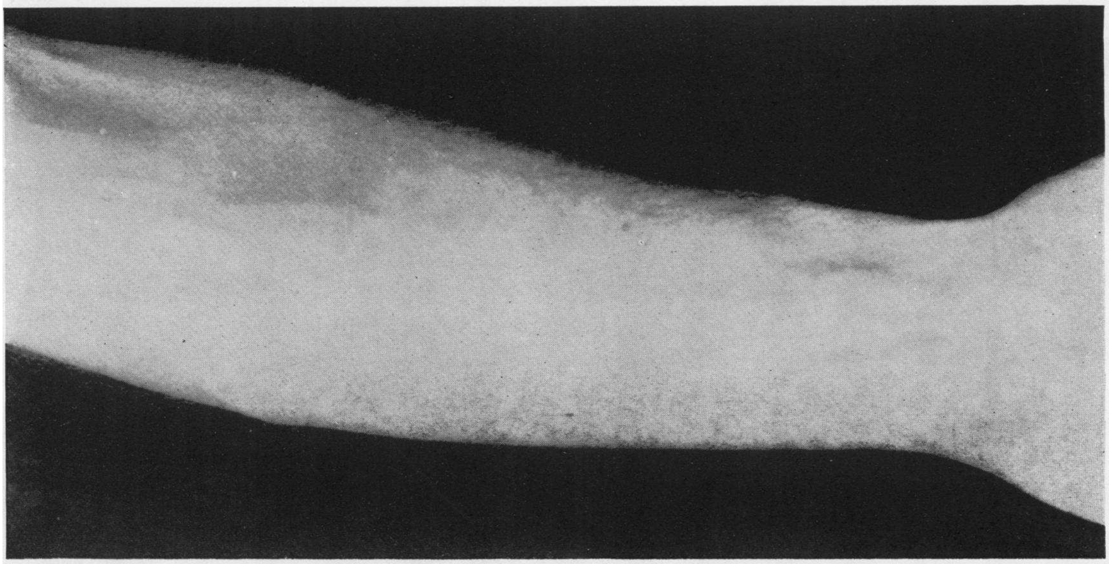

PLATE I

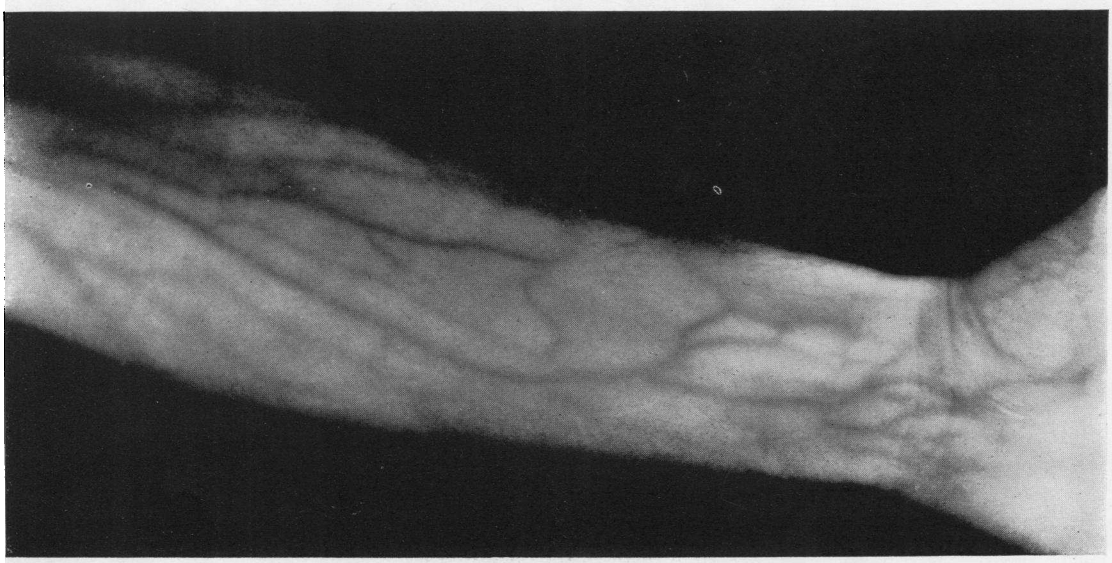

PLATE II

FIG. 6.

PLATE I. PHOTOGRAPH OF VOLAR SURFACE OF ARM WITH EASTMAN PANCHROMATIC PLATE; NO FILTER.

PLATE II. PHOTOGRAPH OF SAME SURFACE WITH EASTMAN PLATE I-R USING INFRA-RED FILTER WHICH WAS COMPLETELY OPAQUE TO VISIBLE LIGHT.

through the stratum germinativum it is possible that some chemical action may be stimulated by these rays in these very important lower skin layers. In any case the hope of reaching deep tissue with these rays is rather a vain one.

From Figure 2 it is quite apparent that the scattering of the light increases greatly with thickness of the tissue. This explains the haziness obtained with infra-red photography as shown in Figure 6. Here are shown two photographs of the same surface, one (Plate I) made with the Eastman panchromatic plate with no filter; the other (Plate II) made with the Eastman plate using a filter transmitted only infra-red radiation between 0.8 μ and 1.5 μ. The high reflectivity of the skin for visible light has completely masked any subcutaneous detail in the first photograph, but in the second plate the lower reflecting power for the infra-red permits the photographing of the peripheral veins. The haziness is entirely due to scattering so that very fine detail could never be expected of structures as far under the skin as ½ mm., also due to the great absorption of the tissue for the infra-red no pictures of structures deeper than 2 mm. can be expected. It might be pointed out that all of the detail in Plate II can be easily seen with the naked eye.

SUMMARY

Evidence has been presented in the foregoing that infra-red transmission through skin, even of the most penetrating rays, is of small proportion, about 95 per cent of these being absorbed within 2 mm. of the surface and 99 per cent within 3 mm. of the surface. The use of dead skin in experiments on infra-red transmission has been shown to lead to too high rather than too low transmission values so that the disagreement of the above findings with those of other investigators cannot be ascribed to this cause. A method has been devised for the accurate measurement of scattered transmitted radiation. The absorption bands of the infra-red spectrum of skin have been identified.

We believe that the evidence justifies the following conclusions:

1. The heating effect of infra-red radiation is exerted principally on the body surface, and whatever therapeutic effect is obtained by such radiation is due to this local effect and not to deep penetration of the rays which is negligible in amount.

2. Photography of the human body in infra-red light, while yielding detail not obtainable by ordinary photography, will not yield pictures of structures more than a few millimeters under the surface and, due to scattering, will not give sharp detail.

3. The absorption spectrum of normally wet skin is essentially that of liquid water. Upon drying, other absorption bands not due to water become evident.

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