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REPORT NO. 373

**OPTICAL PROPERTIES OF EXCISED PORCINE SKIN
I. SURFACE REFLECTION FACTORS***

by

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ABSTRACT

OPTICAL PROPERTIES OF EXCISED PORCINE SKIN I. SURFACE REFLECTION FACTORS

OBJECT

This investigation was undertaken to discuss and evaluate the errors caused by surface reflections in measurements of the internal reflectance and transmittance values of excised skin specimens.

RESULTS AND CONCLUSIONS

A method for determining the approximate values of the internal surface reflection factors is given and applied to excised skin specimens of the Chester White pig for two wavelengths (514 and 731 m μ). The factors contributing to the errors and to their magnitude are discussed.

The excised skin of the Chester White pig, 20 to 30 pounds, is for practical purposes optically homogenous at the wavelengths 514 and 731 m μ .

RECOMMENDATIONS

It is recommended that these studies be continued to cover the wavelength region of interest in the thermal burn problem, namely ultraviolet, visible and near infrared.

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OPTICAL PROPERTIES OF EXCISED PORCINE SKIN

I. SURFACE REFLECTION FACTORS

I. INTRODUCTION

Only that part of the radiant energy which is absorbed by any substance can exert a primary effect on it. In order to evaluate the magnitude of the primary effect, it is necessary to know not only the total amount but also the spatial distribution of the absorbed energy. Accurate values of the absorption of visible and infrared radiant energy by skin are essential for the determination of its heating power. Numerous data relevant to the spectral absorption of such energy have been published (1-8), yet there is considerable disagreement among them. Some causes for the discrepancies will be dealt with in the following paragraphs.

Two factors can contribute significantly to the error in the measurement of the reflectance and transmittance of a substance such as skin.

Skin is a diffusing medium, that is, light passing through a sheet or layer of this material may be repeatedly scattered. Thus, the direction of the emergent radiation may have no relation to its incident direction. Failure to measure the emergent radiation in all directions can introduce a serious error in the measured value of the absorbed energy.

reflected. Knowing the angular distribution of light and the relative index of refraction at a plane boundary, the surface reflection factors can be calculated by Fresnel's equations. Judd (9) has calculated that about 60 per cent of completely diffused light incident internally on a plane boundary of $n_2/n_1 = 1.5$ is reflected, whereas only about four per cent of normally incident light is reflected. Ryde (10) and Duntley (11) point out that internal total reflection occurs at large angles of incidence; therefore, any slight deviation of the diffuse light from perfect uniformity at these angles has a considerable effect on the value of this reflection factor. Consequently, this factor must be determined experimentally.

II. THEORY

The symbols used in this paper are defined in Table I.

TABLE I

Definition of Symbols	
τ	measured transmittance
ρ	measured reflectance
ρ_b	measured reflectance with black backing in optical contact
T	internal transmittance
R_o	internal reflectance
r_1	external or incident surface reflection factor
r_2	internal surface reflection factor
S	scattering coefficient
K	absorption coefficient
X	thickness of sample

Additional subscripts I and II indicate the orientation of the other symbols as to the respective sides of the sample.

The following assumptions are made: 1) the sample is of constant finite thickness, and is extended infinitely in the direction parallel to its surfaces; 2) the optical inhomogeneities are small compared to the thickness of the sample; and 3) both the incident and internal flux of light are completely diffused.

A homogeneous specimen is defined as one in which the absorption and scattering phases, or optical inhomogeneities, are uniformly distributed throughout the sample and the two surfaces are equivalent. In a nonhomogeneous sample the optical inhomogeneities vary vertically to the surfaces and/or the surfaces are not equivalent.

A. General Case

By taking into account all successive multiple internal reflections, it can be shown that the measured transmittance τ and reflectance ρ are related to the internal transmittance T and reflectance R_0 by the following equations:

$$\tau = \frac{(1-r_{1I})(1-r_{2II}) T}{(1-r_{2I}R_{0I})(1-r_{2II}R_{0II}) - r_{2I}r_{2II}T^2} \quad (1)$$

$$\rho = r_{1I} + (1-r_{1I})(1-r_{2I}) \frac{R_{0I}(1-r_{2II}R_{0II}) + r_{2II}T^2}{(1-r_{2I}R_{0I})(1-r_{2II}R_{0II}) - r_{2I}r_{2II}T^2} \quad (2)$$

The internal transmittance is considered to be apolar; that is, it is invariant with regard to direction of illumination. Zocker and Török (12) have theoretically proven the apolarity of internal transmittance in a nonhomogeneous specimen. Kubelka (13) has demonstrated theoretically and experimentally that, in addition to the apolarity of internal transmittance, the internal reflectance of a nonhomogeneous sample depends upon the direction of illumination. However, Kubelka pointed out two cases of nonhomogeneous layers in which the internal reflectance is independent of the direction of illumination. These two cases of pseudohomogeneous layers are (a) where the optical inhomogeneities are symmetrically distributed around a central plane parallel to the surface of the layer, and (b) where the spatial distribution of the scattering and absorbing phases varies vertically to the surfaces of the layer but the ratio of the absorption coefficient to scattering coefficient (K/S) is constant.

B. Homogeneous Specimens

In a homogeneous sample $r_{1I} = r_{1II}$, $r_{2I} = r_{2II}$, $R_{0I} = R_{0II}$ according to definition. In this case Equations (1) and (2) reduce to

$$\tau = \frac{(1-r_1)(1-r_2) T}{(1-r_2 R_0)^2 - r_2^2 T^2} \quad (3)$$

$$\rho = r_1 + (1-r_1)(1-r_2) \frac{R_0(1-r_2 R_0) + r_2 T^2}{(1-r_2 R_0)^2 - r_2^2 T^2} \quad (4)$$

These equations are identical to those derived by Ryde (10) for the limited conditions of homogeneous samples and completely diffused light.

C. Determination of Surface Reflection Factors

The method discussed here for determining the surface reflectance factors follows that suggested by Stenius (14). Equations (3) and (4) give the measured transmittance and reflectance of homogeneous samples. As the thickness of the specimen approaches zero, it follows that T approaches one and R_0 approaches zero. Substituting $T = 1$, $R_0 = 0$ in Equations (3) and (4) gives

$$\lim_{X \rightarrow 0} \tau = \tau_0 = \frac{1-r_1}{1+r_2} \quad (5)$$

$$\lim_{X \rightarrow 0} \rho = \rho_0 = r_1 + \frac{r_2(1-r_1)}{1+r_2} \quad (6)$$

Solving for r_2

$$r_2 = \frac{1-r_1}{\tau_0} - 1 \quad (7)$$

$$r_2 = \frac{\rho_0 - r_1}{1 - \rho_0} \quad (8)$$

By measuring τ and ρ as a function of the thickness and extrapolating to $X = 0$, the approximate values of the internal surface reflection factor r_2 can be determined. Empirically, it has been found for excised pig skin of young animals that the transmittance data can be readily fitted to the type equation $\tau = \tau_0 e^{-bX}$, thereby simplifying the

extrapolation to zero. The marked change in slope of the reflectance curves of excised pig skin at small values of X , as shown in Figure 5, makes this extrapolation impractical.

Neither r_1 nor r_2 can be eliminated from the dependent Equations (5) and (6); therefore, a value of r_1 must be assumed in order to calculate r_2 . If it is assumed that the maximum value of r_1 is that of the internal reflection at a plane interface with a relative index of refraction of 1.35 (water = 1.33), then for light of normal incidence according to Judd (9) r_1 is less than .02, and for completely diffused incident light r_1 is less than .07. It will be shown that the calculated value of r_2 is not markedly dependent on the assumed value of r_1 . In any case the uncertainty for r_2 introduced by the assumed value of r_1 is in most cases smaller than that due to the uncertainty of the extrapolated value of τ .

It is of interest to examine the differences between the theoretical values i. e., the internal transmittance and reflectance, and the corresponding measured values as affected by the surface reflection factors in an ideal sample. Figures 2 and 3 show the per cent errors in the measured values as a function of r_2 for selected values of T and R_0 as calculated according to Equations (3) and (4). A value of 0.04 is assumed for r_1 .

Several important relations are evident in these graphs. The relative error is strongly dependent upon the values of T , R_0 and r_2 . By choosing the proper thickness of the sample, that is the best relative values of T and R_0 , the dependence of the error on r_2 is minimized, or the magnitude of the relative error may be minimized. Another important feature to be noted is that the error may be either positive or negative; that is the measured values of transmittance or reflectance may be either larger or smaller than the corresponding internal values. Note the large relative error in both T and R_0 for thin samples or samples with low scattering and absorbing powers ($T = .80$, $R = .10$), especially as r_2 increases.

III. EXPERIMENTAL METHODS

A. Biological

The skin samples were obtained from Chester White pigs ranging in weight from 20 to 30 pounds. This animal was selected because of the close structural similarity of its skin to that of humans (15); it has been used extensively in the study of injuries resulting from

exposure to radiant energy (16), and the spectral reflectance of its skin closely resembles that of a fair complexioned human (8).

Prior to the excision of the samples, the animals were anesthetized with Dial in urea - urethane, 75 mg/kg. Their hair was removed with clippers and an electric razor. Then they were washed with mild soap and rinsed thoroughly with water. After being suspended by their rear legs, the animals were sacrificed by severing the carotid arteries so as to provide relatively bloodless skin for samples.

One hour later skin samples were removed from the hips and dorsal aspects of the side with a Brown electrodermatome. The specimens ranged from .2 to 1.5 mm in thickness. It was difficult to obtain samples thinner than .3 mm or thicker than 1.5 mm using this technique. The thickness of each specimen was measured between glass plates of known dimensions with a micrometer caliper. Immediately after excision the samples were mounted on aluminum rings 38 mm in diameter and 6 mm high. The samples were kept in a moist chamber at refrigerator temperature except when being measured. All measurements were made as rapidly as possible to prevent the effects of dehydration. Hansen (17) demonstrated that the transmittance of skin changes with its state of hydration.

B. Physical

The transmittance and reflectance were measured with a reflectometer designed by Derksen and Monahan (18) and modified by Jacques (19) to include an integrating sphere. The specimen holder set up before the integrating sphere for reflectance measurements is shown schematically in Figure 4. The upper part of the positioning base consists of a tube in which a solid or drilled aluminum rod can be moved axially. The sample ring with specimen slides over the end of the rod in such a way that the distance between the front surface of the rod and the back surface of the sample can be adjusted from direct contact to 5 mm distance. For the measurements of ρ the skin specimens were backed with an aluminum rod drilled and shaped to a cavity 2.5 cm deep with a 2 mm wall thickness and a taper of 30° at the bottom. The surface of the cavity was covered with camphor black; its reflectance was 0.4 per cent.

For the measurement ρ_b the dermal side of the samples was in optical contact with a black backing. The reflectance of the black backing was 4.5 per cent. Optical contact was obtained by wetting the black surface with distilled water, pressing the sample against it, and

then squeezing out the air bubbles at this interface. The light beam incident on the samples was a parallel beam with an angle of incidence of 15° .

The reflectance standards were freshly prepared magnesium carbonate blocks. In the basic Equations (2) and (4) all reflectance terms are defined as the ratio of reflected light to incident light, i. e., as absolute reflectances. To convert the values measured relative to magnesium carbonate to absolute values the values were corrected to magnesium oxide by the data of Jacques (20) and then to absolute values according to Middleton and Saunders (21).

For the transmittance measurements the integrating sphere was used as a source of diffused light. The specimens were placed over the photocell aperture of the integrating sphere so that they were between the light source and the photocell (see Fig. 4). A spacer provided a $5 \times 5 \times .7$ cm chamber for the specimens between the aperture and the photocell. The chamber was blackened to reduce scattered light. The distance between the sample and the photocell was such (5.5-7.0 mm) that no correction for light multiply reflected between sample and photocell was deemed necessary; the maximum error is estimated to be of the same order of magnitude as the error inherent in the instrument. For these measurements the light beam was directed onto the sphere surface between the sample and standard parts.

All samples were measured with the epidermal side toward the incident light unless otherwise specified. Initially, the measurements were made within two to five hours after excision and then repeated daily for four days. It was noted, however, that there was a steady significant decrease in the transmittance values of all samples over this period of time. In fourteen samples, ranging from .2 to 1.3 mm thickness, the daily rate of decrease in transmittance relative to the original value was 4 per cent for wavelength 514 m μ and 2 per cent for wavelength 731 m μ . Therefore, the data reported in the following sections are confined to the first measurements (two to five hours after excision) unless otherwise stated. The nominal band width at the exit slit for both wavelengths was 6 m μ .

IV. RESULTS

A. Homogeneity of Specimens

By measuring the reflectance of a sample from both surfaces, it can be determined whether or not the sample is optically homogeneous or pseudohomogeneous as defined above. As mentioned above, the

Table 2 gives the reflectance values of thirteen skin samples from two animals when the light is incident on the epidermal side and dermal side of the sample. $\Delta\rho$ indicates the difference between the two values. The two reflectances for each sample are average values obtained from daily measurements made on 4 to 5 consecutive days. Over the period of five days the average daily decrease in reflectance values was less than one-half per cent. It is felt that this method best averages out the variations due to differences in sample thicknesses when the specimens are inverted on the sample rings and to small variations in the moisture content of the specimens. The magnitude of the differences $\Delta\rho$, the somewhat random distribution of positive and negative values and the absence of influence of sample thickness on the difference strongly suggests that excised skin of pigs in this age range and of thicknesses up to about 1.5 mm is optically homogeneous to light of wavelengths 514 and 731 m μ .

TABLE 2
REFLECTANCE OF X-RAY SPECIMENS MEASURED
FROM THE EPIDERMAL (σ_1) AND THE DERMAL SITE (σ_2)

ANIMAL	SAMPLE	THICKNESS (mm)	513 mμ			731 mμ		
			ρ_I	ρ_{II}	$\Delta \rho$	ρ_I	ρ_{II}	$\Delta \rho$
S1	1	.64	.321	.259	.062	.226	.228	.002
	2	.77	.311	.316	-.005	.309	.309	-.002
	3	.83	.323	.333	-.010	.317	.317	.000
	4	1.04	.354	.334	.020	.344	.261	.083
	5	1.42	.360	.373	-.003	.343	.303	.040
	6	1.34	.375	.388	-.003	.438	.604	.166
			$\Delta \rho$.001			$\Delta \rho$.000		
S2	1	.20	.208	.310	-.102	.177	.109	.068
	2	.56	.208	.303	-.095	.231	.238	-.007
	3	.64	.355	.363	-.008	.316	.330	-.014
	4	1.13	.371	.367	.004	.304	.304	.000
	5	1.30	.424	.407	.017	.420	.404	.016
	6	1.49	.400	.388	.012	.387	.361	.026
	7	1.27	.403	.407	-.004	.418	.400	.018
			-.010			.003		

B. Determination of Internal Reflection Factors

A simple method for demonstrating the effect of the internal reflectance factor on the measured reflectance values is to eliminate one surface of the sample. If $r_{2\pi}$ is set equal to zero in Equation (2), the equation is reduced to the following form for a homogeneous sample:

$$\rho_b = r_1 + \frac{(1-r_1)(1-r_2)R_0}{(1-r_2R_0)} \quad (9)$$

This transformation reduces the measured value of reflectance. The difference between ρ and ρ_b decreases with increasing thickness, and as the optical thickness approaches infinity, ρ_b approaches ρ . Experimentally, the situation represented by Equation (9) can be approximated by placing a black surface in optical contact with one surface. In these experiments the black surface used had a reflectance value of about 4 per cent.

Figure 5 demonstrates the differences between ρ and ρ_b as a function of a sample thickness for the two wavelengths 514 and 731 m μ . It is noted that the optical surfaces can materially alter the measured reflectance. Also note that the difference between the two measurements decreases as sample thickness increases.

The data presented in Figure 5 are based on the measurements of seven samples of skin from one animal. They are representative of the data from four animals. The reflectance curves were visually fitted to the experimental points.

The curves for the transmittance values τ for the two wavelengths are based on the measurements as described earlier. Table 3 gives the transmittance values, corrected to absolute values, of twenty-one samples taken from four pigs. Figure 5 shows the values obtained from samples from one animal. These values are representative for the four animals. On a logarithmic scale, the transmittance values are represented by straight lines over the thickness range of the samples. Thus, the attenuating power of the tissue is related to the thickness of the sample (in the tested range) through a simple function of the form $\ln \tau = f(X)$ which can be expressed within the margin of the experimental error by the equation.

$$\tau = \tau_0 e^{-bX} \quad (10)$$

where τ_0 is the limit of τ as X approaches zero, b is the attenuation coefficient and X is the thickness of the sample. The constants for the transmittance curves were determined by the method of least squares. The values of τ_0 were then used to calculate r_2 from Equation (7) with an assumed value of .04 for r_1 . The constants τ_0 and b of Equation (10) and the calculated values of r_2 are given for four animals in Table 4.

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TABLE 3
MEASURED TRANSMITTANCE OF EXCISED PORCINE SKIN

514 mμ											
Pig 49			Pig 50			Pig 51			Pig 52		
Sample	Thick- ness (mm)	τ	Sample	Thick- ness (mm)	τ	Sample	Thick- ness (mm)	τ	Sample	Thick- ness (mm)	τ
1	.33	.644	1	.17	.711	1	.44	.558	1	.28	.633
2	.38	.633	2	.23	.722	2	.77	.478	2	.53	.536
3	.40	.656	3	.38	.622	3	.85	.411	3	.86	.444
4	.59	.556	4	.63	.511	4	1.04	.378	4	1.13	.367
5	.85	.478	5	.74	.508	5	1.42	.500	5	1.30	.300
6	1.13	.433	6	1.08	.378	6	1.34	.344	6	1.46	.278
7	1.33	.378	7	1.34	.333				7	1.27	.311

731 mμ											
Sample	Thick- ness (mm)	τ	Sample	Thick- ness (mm)	τ	Sample	Thick- ness (mm)	τ	Sample	Thick- ness (mm)	τ
1	.33	.744	1	.17	.860	1	.44	.722	1	.28	.744
2	.38	.787	2	.23	.778	2	.77	.669	2	.56	.700
3	.40	.758	3	.38	.722	3	.85	.633	3	.86	.608
4	.59	.700	4	.63	.678	4	1.04	.558	4	1.13	.589
5	.85	.644	5	.74	.633	5	1.42	.522	5	1.30	.533
6	1.13	.611	6	1.08	.578	6	1.30	.553	6	1.46	.487
7	1.33	.544	7	1.34	.500				7	1.27	.532

TABLE 4
CONSTANTS OF TRANSMITTANCE EQUATIONS AND CALCULATED INTERNAL REFLECTION
COEFFICIENTS OF EXCISED PIG SKIN

WAVELENGTH (mμ)	ANIMAL	$\hat{\rho}$ (cm^{-1})	ϕ_c	r_s
514	49	.54	.770	.232
	50	.66	.910	.189
	51	.80	.716	.346
	52	.79	$\frac{.803}{.777}$	.182
731	49	.32	.659	.120
	50	.38	.689	.129
	51	.34	.649	.130
	52	.37	$\frac{.685}{.639}$	.162

7
.633
.556
.444
.367
.300
.278
.311
.744
.700
.600
.589
.533
.467
.522

The accuracy of r_2 is influenced by the value assumed for r_1 . It was pointed out above that the value for r_1 may reasonably be assumed to be less than .07. The error caused by different assumed values of r_1 is probably less than that introduced by the uncertainty in the extrapolated value of τ_0 . Figure 6 shows that the internal surface reflection factor r_2 ranges from .20 to .27 for the 514 $m\mu$ wavelength and from .11 to .18 for 731 $m\mu$ when the assumed external surface reflection factor r_1 varies from .01 to .07. The average values of τ_0 for the two wavelengths from Table 3 were used in the calculations. The dotted line in Figure 6 shows the variation of r_2 as a function of τ_0 for an assumed value of .04 for r_1 . Reference to Table 3 shows that r_2 ranges from .19 to .34 for 514 $m\mu$ and .13 to .19 for 731 $m\mu$. Values of r_2 of the order of .20 for 514 $m\mu$ and .13 for 731 $m\mu$ may be assumed to be reasonable estimates.

Stenius (14) reports r_2 values between .11 and .16 for visible light for white paper dried between a mirror and a pad of blotting paper. Ryde and Cooper (23) give r_2 value in the same wavelength region for opal glass ranging between .35 and .45. The values reported here for excised porcine skin are seen to lie between those of paper with a fibrous surface, and opal glass, having a polished surface.

V. DISCUSSION

Two basic conditions for the above equations are (1) the incident light is diffuse and (2) the angular distribution of the light is not changed by the sample. It must be said that diffuse incident light does not give the assurance of diffuse internal light. For example at a plane interface of two regions of different indexes of refraction, the maximum angle a light ray penetrating the interface may have is that of the critical angle of internal reflection. Such a surface then tends to reduce the angular distribution of an incident beam. The presence of scattering sites in the second layer tends to increase the angular distribution in that layer. As the scattering power of this layer increases, the angular distribution of the light flux approaches that of a diffuse beam. Because of the high scattering power for the wavelengths used in this study and the rough surface of the skin, the error introduced by the second condition is assumed to be negligible, except for very thin samples.

The first condition was realized only in the transmittance measurements. In the reflectance measurements a parallel beam, incident on the sample surface at an angle of 15° , was used. The effect of this modification is considered slight on the basis of the following arguments

According to McNicholas (24) the reflectance values obtained with diffuse incidence and direct viewing are identical to those of diffuse viewing of direct incidence at the same angle used for viewing in the former case (Helmholtz reciprocity law) and if the sample follows Lambert's law of diffuse reflectance. Therefore, it is assumed that viewing such a sample with an integrating sphere (diffusing viewing) and illuminated with nearly normal incident light is essentially the same as normal viewing of diffuse incident light. The reflection of excised human skin, when corrected for external surface reflection, follows closely Lambert's law in the spectral range .55 to 2.20μ , as Hardy (5) has shown. Therefore it can reasonably be assumed that these two conditions are closely approximated for the internal reflectance, R_0 .

When a collimated beam of light enters a turbid medium its identity is lost to some extent by scattering within the sample. The scattering results in a change in the average path length of the beam within the sample as well as a change in the angular distribution of the light reaching the internal surfaces. As the average path length of the beam within the sample increases the absorption of radiant energy increases. As the angular distribution of light incident on the surface of emergence increases, the reflection of light back into the sample increases. According to Judd (9) in the case of a plane glass air interface of relative index of refraction of .67, the internal surface reflection factor varies from .04 for light of normal incidence to .60 for completely diffused incident light. Therefore the measured transmittance and reflectance of turbid media can vary markedly depending upon the angular distribution of the incident light. As the scattering power of a sample increases, either through increased thickness or an increase of the scattering coefficient, the angular distribution of light within a sample illuminated with a collimated beam, approaches that of diffuse light. Consequently, to avoid an apparent change in the fundamental scattering and absorption coefficients as a function of thickness of the sample either diffuse illumination is required or with a collimated beam the sample thicknesses must be restricted to optically thick samples. Hardy (5) reported that for thicknesses of excised human skin as great as 1 mm scattering was maximal for all wavelengths in the range from .55 to 2.20μ .

VI. SUMMARY

Neglecting the effect of surface reflections can introduce a significant error in the measured internal transmittance and reflectance values as shown here for excised pig skin at the wavelengths 514 and 731 m μ . The magnitude of the error depends upon the thickness, index of refraction,

and the scattering and absorption coefficients of the sample, also upon the geometrical design of the measuring instrument. Methods for correcting or minimizing the effect of surface reflections are given.

The bloodless skin of the Chester White pig, 20 to 30 pounds, is for practical purposes optically homogeneous at the wavelengths 514 and 731 m μ .

VII. RECOMMENDATIONS

It is recommended that these studies be continued to cover the wavelength region of interest in the thermal burn problem, namely ultraviolet, visible and near infrared.

VIII. REFERENCES

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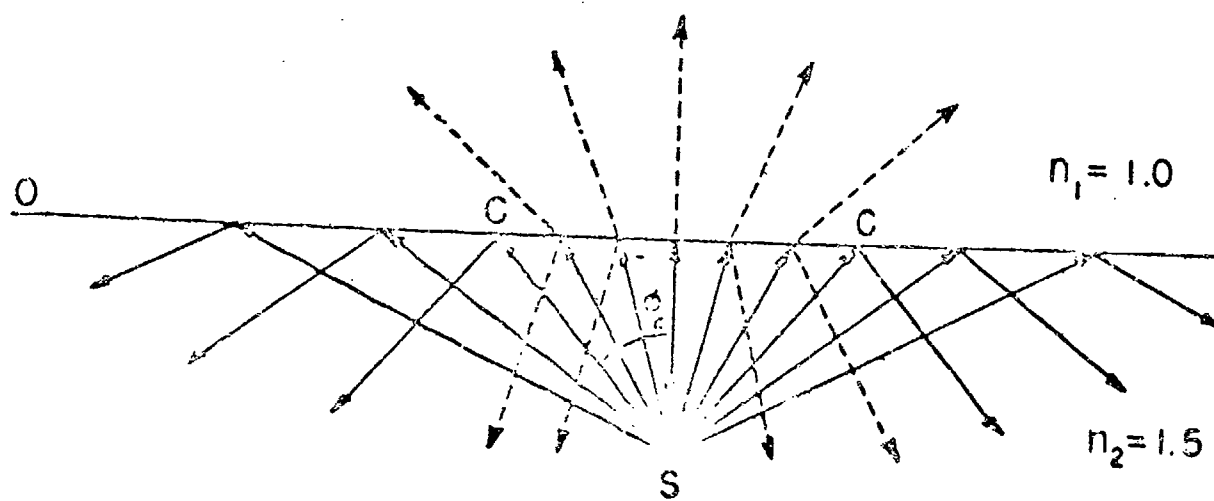


Fig. 1. Diagram of internal reflection of diffuse light.

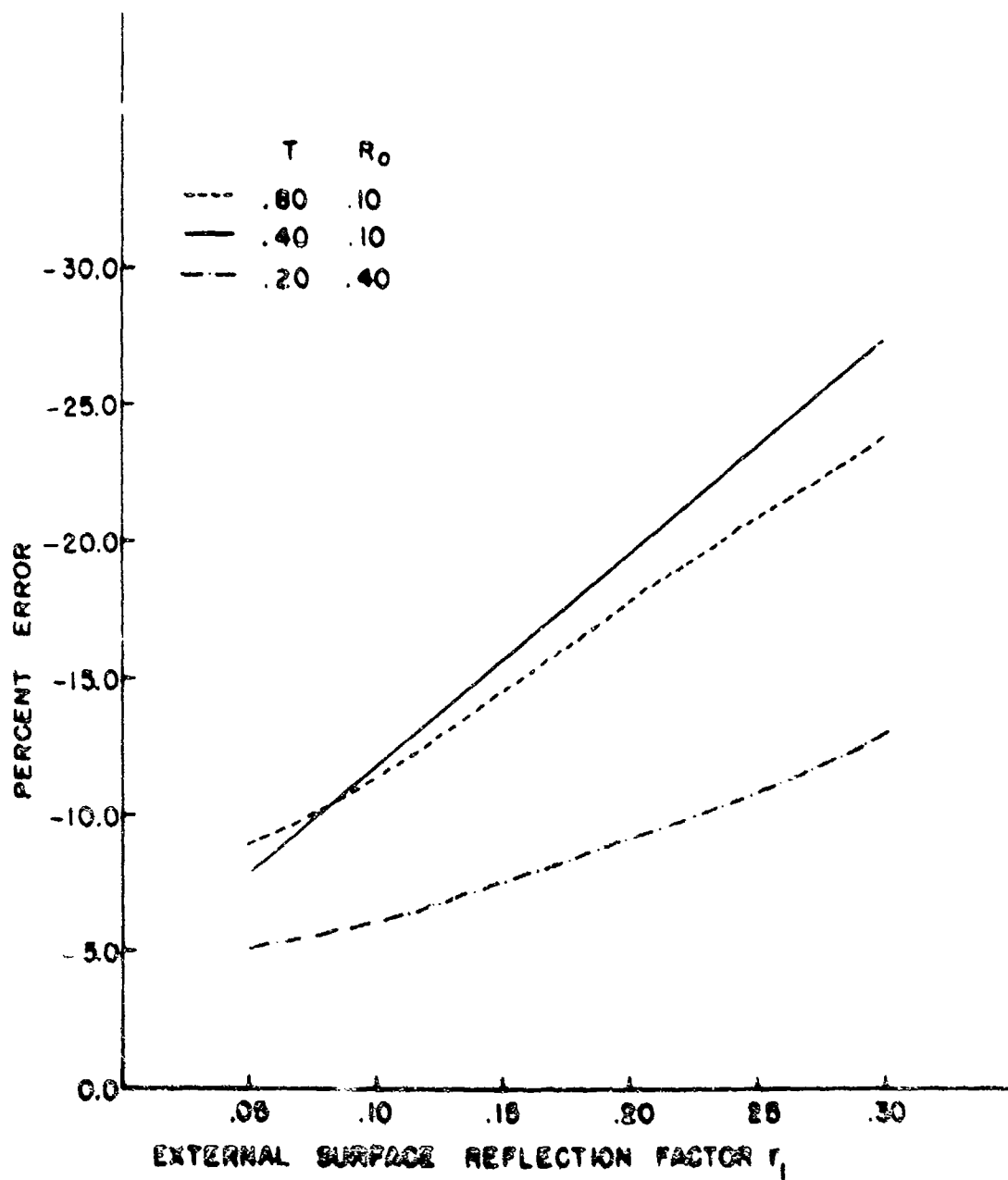


Fig. 2. Error in measured internal transmittance (τ) due to surface reflection factor. $r_1 = .04$.

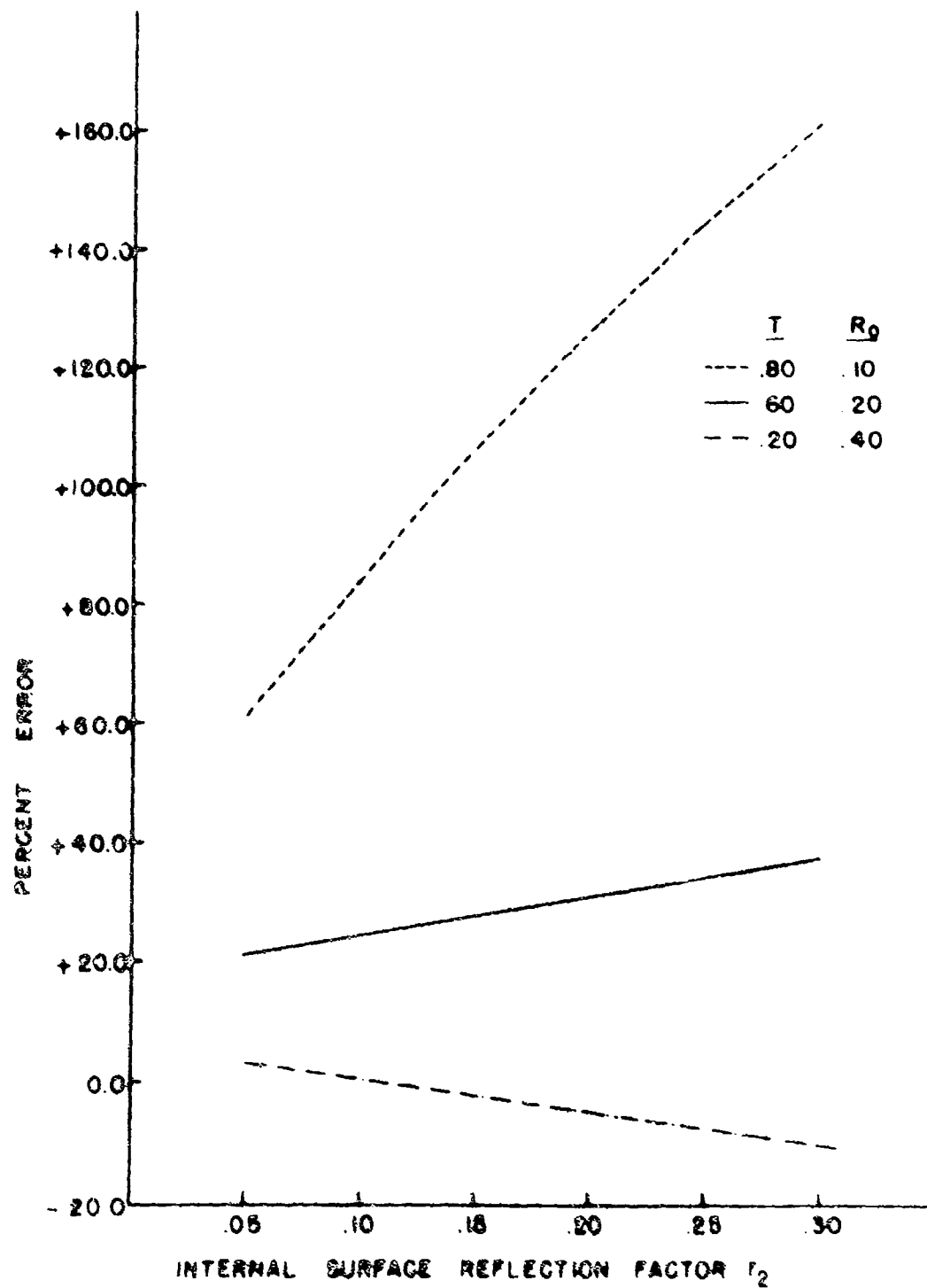


Fig. 3. Error in measured internal reflectance (%) due to surface reflection factor. $r_1 = .04$.

- A _ POSITIONING BASE
- B _ SPECIMEN HOLDER
- C _ SPECIMEN RING
- D _ SPECIMEN
- E _ SPHERE
- F _ PHOTOCELL APERTURE
- G _ PHOTOCELL

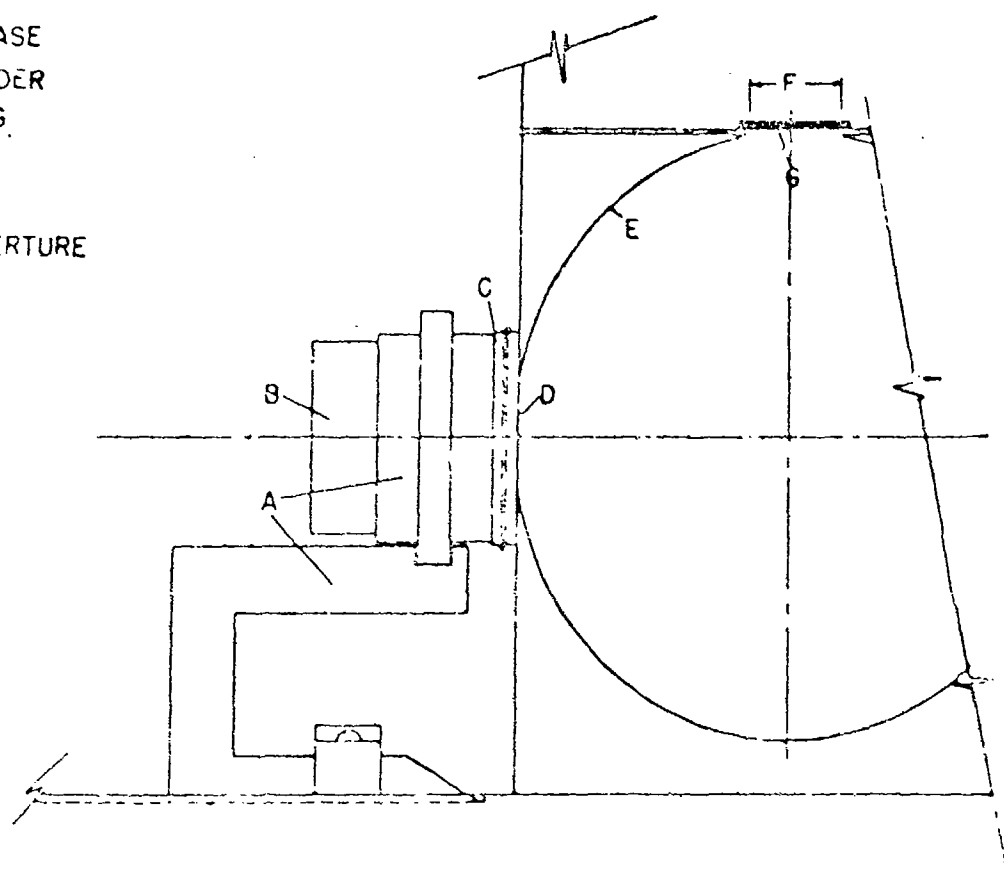


Fig. 4 Diagram of sample holder for reflectance measurements positioned in front of sample aperture of integrating sphere.

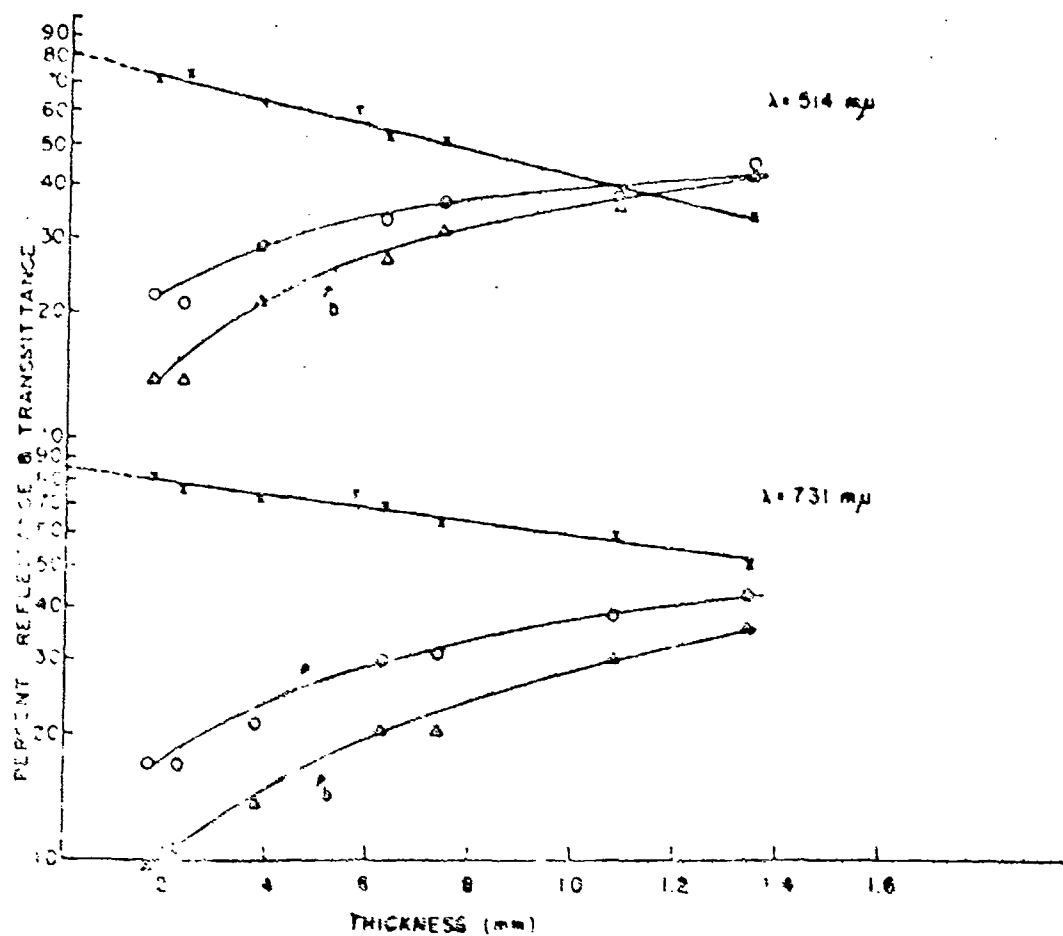


Fig. 5. Measured transmittance (---) and reflectance (—) of excised pig skin.

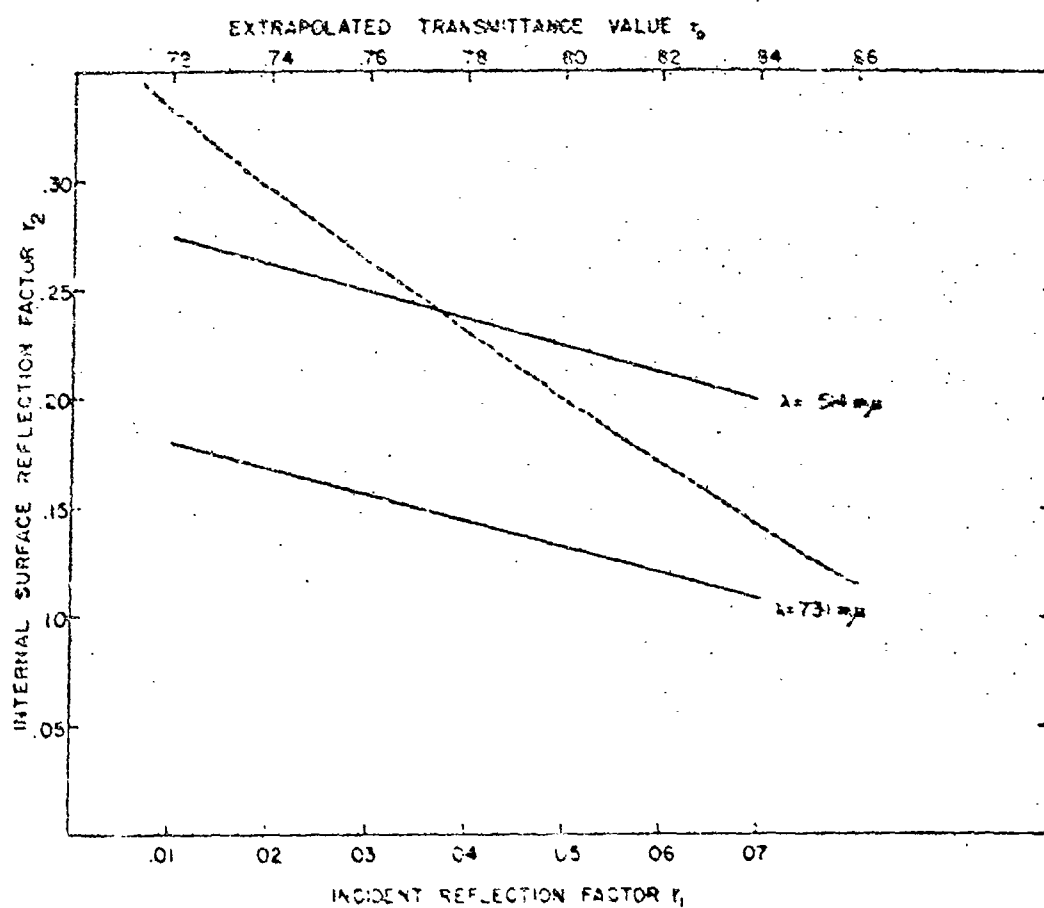


Fig. 6. The internal surface reflection factor (r_2) as a function of the incident reflection factor (r_1) and the extrapolated value of measured transmittance (τ_0).