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Spectral Radiative Properties of a Living Human Body

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Spectral radiative properties of the human body were studied experimentally in the region from the ultraviolet to the far-infrared to know the thermal response of the human body exposed to solar radiation and infrared radiation. The measuring equipment for reflectance and transmittance of a semitransparent scattering medium was developed and measurement on a living human skin was performed in vivo. The measured parts are forearm, cheek, dorsum hand, hip, and hair. The values obtained by the present study are much different from those of previous in vitro measurements. Fairly large values for hemispherical reflectances are observed in the visible and near-infrared regions but very small values for hemispherical reflectances are observed in the infrared region, below 0.05. By applying the four-flux treatment of radiative transfer, the absorption coefficient and scattering coefficient in the human skin are determined. The scattering coefficient is large in the visible region but negligible in the infrared region. The absorption coefficient is very close to that of water and large in the infrared region.

KEY WORDS: absorption coefficient; human body; in vivo measurement; scattering coefficient; spectral radiative property; spectral reflectance.

1. INTRODUCTION

In this study, spectral radiative properties of the human body were studied experimentally in the region from the ultraviolet to the far-infrared to know the thermal response of the human body exposed to solar radiation and infrared radiation. In most of the previous studies [1–4], reflectances and transmittances were measured in vitro using cut-skin samples. Some measurements were carried out by using an integral sphere [5]. However,

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the measurements were not done in full consideration of the specific condition that a living body is a scattering–absorbing semitransparent medium and were done only in the visible and near-infrared regions. In the infrared region, the measurement was done by Kuppenheim and Heer [1]. In view of the previous state of the research, the authors developed new experimental apparatuses for a living human skin to measure both the specular and diffuse reflectances and the normal and diffuse transmittances. These spectral reflectances and transmittances themselves have enough practical value. Furthermore, the scattering coefficient and the absorption coefficient in the skin can be estimated from them and the radiative properties of the skin are understood more precisely.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

Two types of spectrophotometric systems are provided for the measurement of radiative properties of a living human skin. In the following, the constitutions of the systems and the experimental procedure are explained and the experimental error is estimated.

2.1. Goniometric Spectrophotometer

The schematic diagram of a goniometric spectrophotometer provided for measuring hemispherical reflectance is shown in Fig. 1. The monochromatic light from a monochromator (3) passes through a lens (4) and is incident normally on the living sample surface attached to the measuring hole just at the center of the cylinder. Reflected light is caught at an arbitrary angle by the detector (10). The detector can be moved on a moving rail (7) and is set at a position where it can measure the reflected light only from the inside of the radius, which satisfies the condition of one-dimensional radiative transfer. If the measurement does not satisfy the condition of one-dimensional radiative transfer, the obtained reflectance is in great error. The previous studies did not consider this condition. According to Crosbie et al. [6], when an incident light is parallel and the intensity distribution is uniform over the radius r_0, the radius r of the detecting surface should satisfy the following relation:

$$r_0 - r \geqslant \frac{1.5}{K_e} + 2t \qquad (1)$$

where K_e is the extinction coefficient and t is the thickness or the penetration depth. According to Anderson and Parrish [2], the conditions of $t \leqslant 3$ mm and $K_e \geqslant 1\ \mathrm{mm}^{-1}$ should be satisfied in the measurement. The

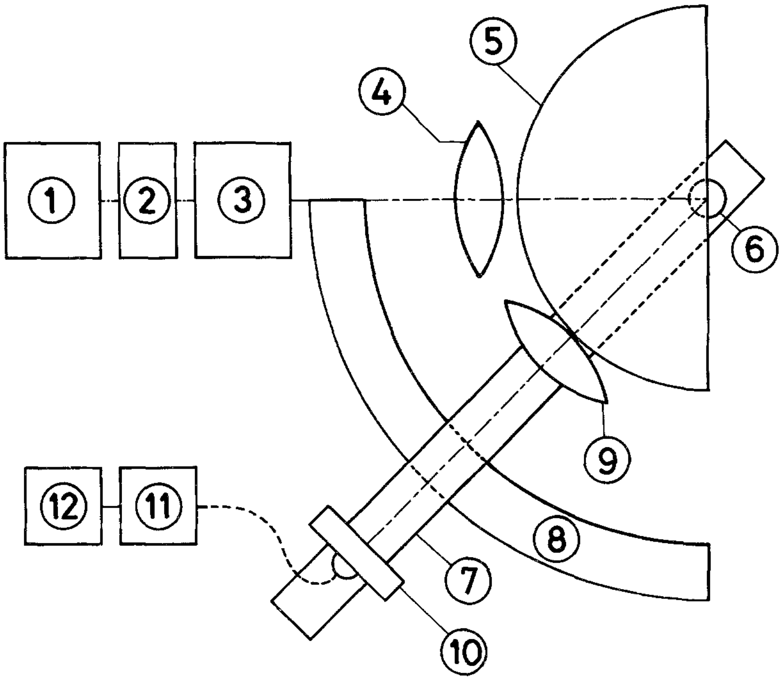

Fig. 1. Goniometric spectrophotometer. (1) Light source; (2) chopper; (3) monochromator; (4) lens; (5) cylindrical measurement section; (6) rotating axis; (7) rail; (8) curved rest; (9) lens; (10) detector; (11) lock-in-amplifier; (12) recorder.

internal surface of the measurement section (5) is covered with a paint coating of high absorptivity in order to avoid multiple reflections. The measurements were done by comparison with an aluminum standard diffuse surface, which was made by grinding with an abrasive of No. 320. The reflection characteristics of the standard diffuse surface were obtained in advance using a paraboloidal diffuse reflectometer [7], where vacuum-deposited gold and aluminum specular mirrors were used as absolute standards. The normal (specular) reflectance of a skin was obtained at an incidence angle of 12°. Hemispherical reflectance was calculated by the angular integration of partial bidirectional reflectance for normal incidence. The measurement is limited in the wavelength region from 0.45 to 2.2 μm because of the very low intensity of a partially bidirectionally reflected light.

2.2. Ellipsoidal Spectrophotometer

In order to decrease the experimental errors and to extend the measurement to the far-infrared region, the ellipsoidal spectrophotometer

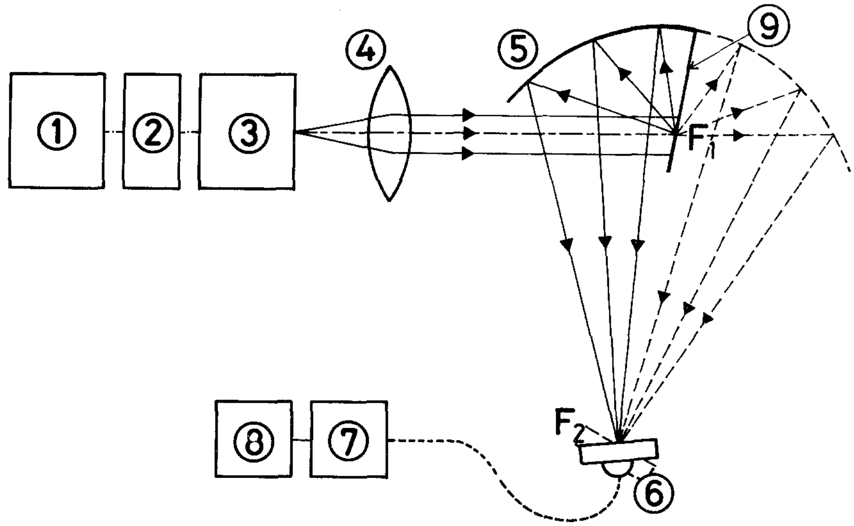

Fig. 2. Ellipsoidal spectrophotometer. (1) Light source; (2) chopper; (3) monochromator; (4) lens; (5) ellipsoidal mirror; (6) detector; (7) lock-in-amplifier; (8) recorder; (9) sample hole plate.

shown in Fig. 2 was provided. In this apparatus, the monochromatic light from a monochromator (3) passes through a lens (4), becomes a parallel light, and is incident on the sample surface placed at the first focus (F_1) of an ellipsoidal mirror 5. A detector (6) is placed at the second focus (F_2) and measures the light reflected toward the half of hemispherical space. The condition [Eq. (1)] of one-dimensional radiative transfer is satisfied by adjusting the radii of parallel incident light and detected area.

By the revolution of 180° around the horizontal axis including F_1, the ellipsoidal mirror and the detector are adjusted to be able to measure the diffuse transmittance for the parallel incident light as shown by the dashed lines in Fig. 2. The wavelength region covered by this system is from 0.3 to 20 μm. The main reason the covered wavelength region is increased is that the detector can catch half of the total diffuse light.

Light sources, lenses, gratings, and detectors which were used in the entire experiment are shown in Table I. The choice of the spectrophotometer was made according to the measurement condition.

2.3. Estimation of Error

The normal reflectances of the vacuum-deposited gold and aluminum specular mirrors used as the absolute standards were determined by

Table I. Light Sources, Lenses, Gratings, and Detectors Used in the Experiments

Wavelength (μm)	0.3	0.45	1.1	2.2	3	10	20
Light source	D_2 lamp		W-I lamp			ZrO_2 IR radiator	
Lens		BK-7				KRS-5	
Grating (lines/mm)		1200		400		100	60
Detector		Silicon photodiode				Pyroelectric cell	

Strong's method [8]. The purities of gold and aluminum used for vacuum deposition were 99.99%. The errors included in the reflectances of these specular mirrors were estimated to be 0.1%. The maximum error of the reflectance of the standard diffuse surface determined by the paraboloidal diffuse reflectometer using the above specular mirrors was estimated as $\pm 4\%$ of the measured value in the previous experiment [7]. Accordingly, the diffuse reflectance or the hemispherical reflectance determined for the present sample in the case of the ellipsoidal spectrophotometer includes the maximum error of $\pm 4\%$. However, in the case of the goniometric spectrophotometer, this error may increase to about $\pm 6\%$ of the measured value because of the difficulty of the measurement for the large polar-angle reflection.

3. RESULTS

Hemispherical reflectances, R_h, measured for two young men's parts (forearm, cheek, dorsum hand, hip) are presented in Figs. 3 and 4, which show the results for a man with a fair complexion and those for a man with

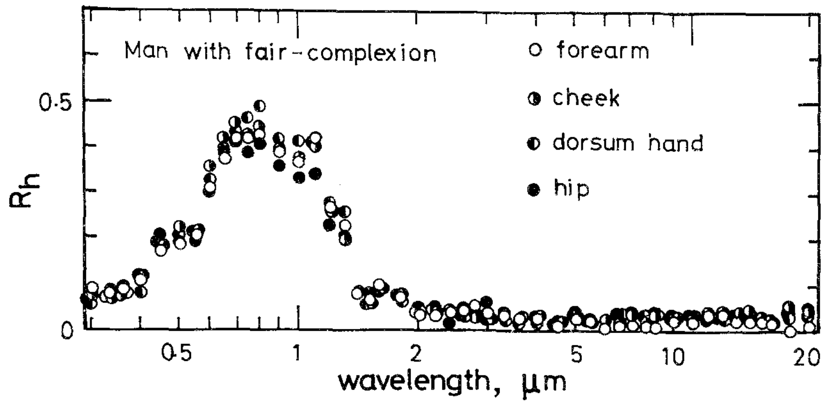

Fig. 3. Hemispherical reflectance for a person with a fair complexion.

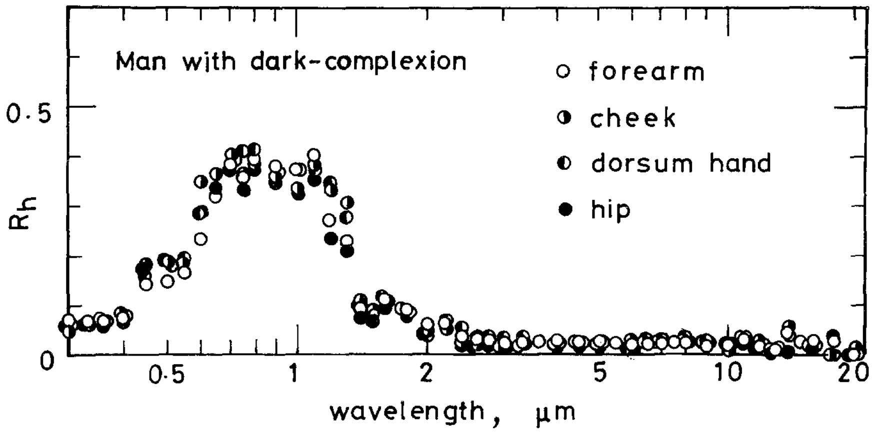

Fig. 4. Hemispherical reflectance for a person with a dark complexion.

a dark complexion, respectively. The former's skin is really white and the latter's skin is nearly light brown.

Hemispherical reflectance for the hair (head) was also measured. Two black-haired persons and one white (gray)-haired person were selected. The results are shown in Fig. 5.

In order to know the sunburn effect, we compared the R_h spectra of forearm, which were obtained in winter without sunburn, with those obtained for sunburnt forearm. The experimental results are shown in Fig. 6. The recovery of the reflectance after strong sunburn (4 h of

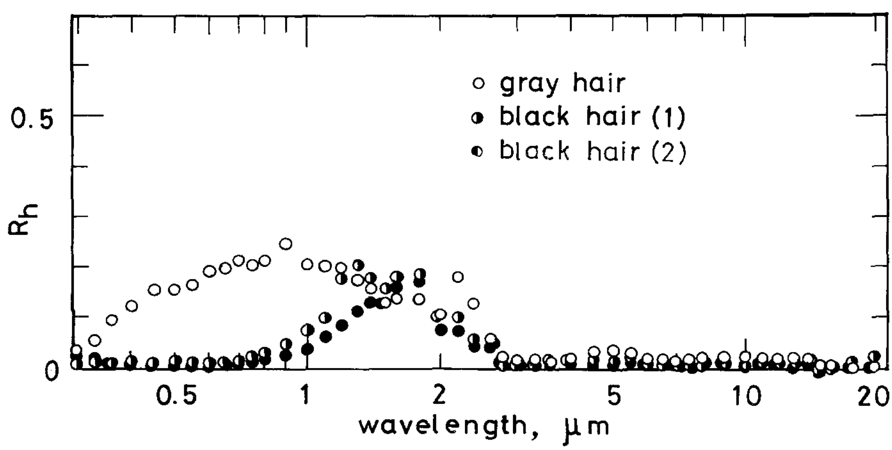

Fig. 5. Hemispherical reflectance of hair.

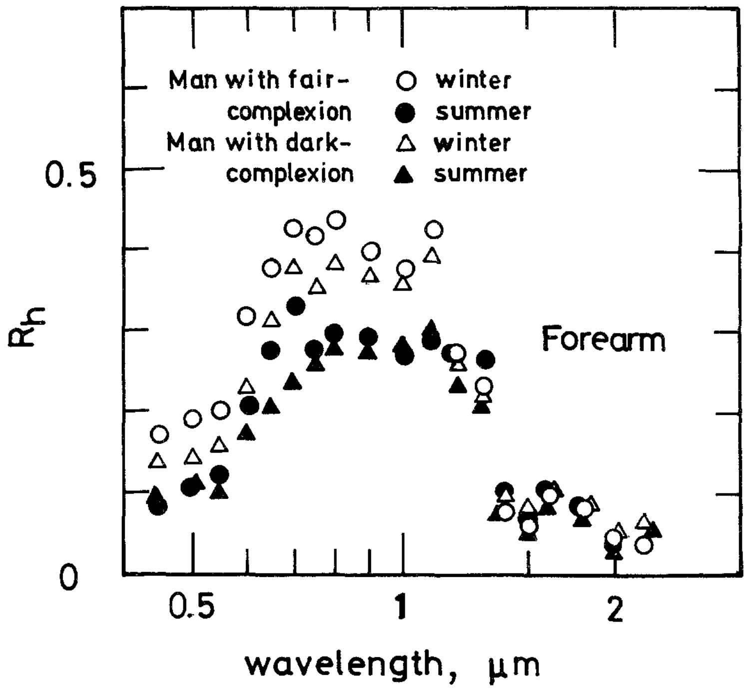

Fig. 6. Effect of sunburn on hemispherical reflectance.

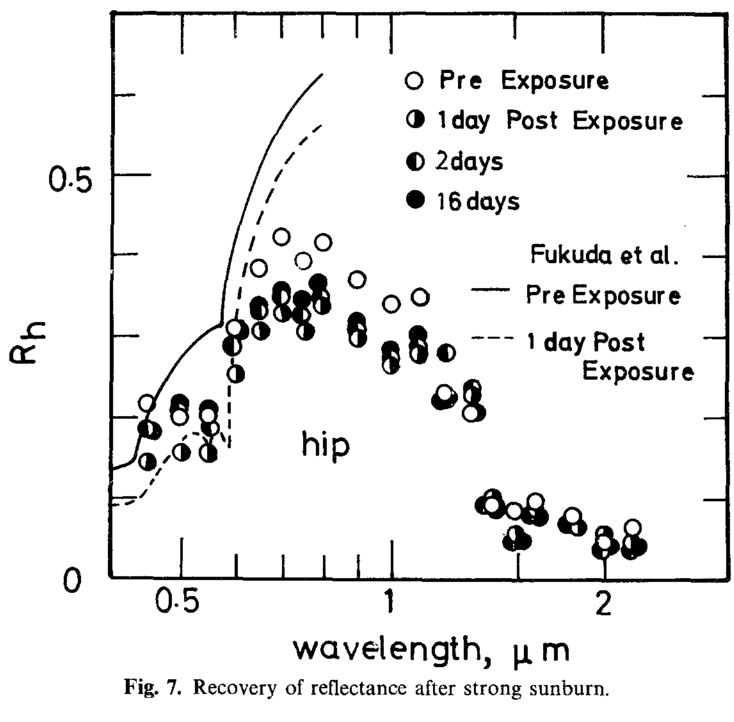

Fig. 7. Recovery of reflectance after strong sunburn.

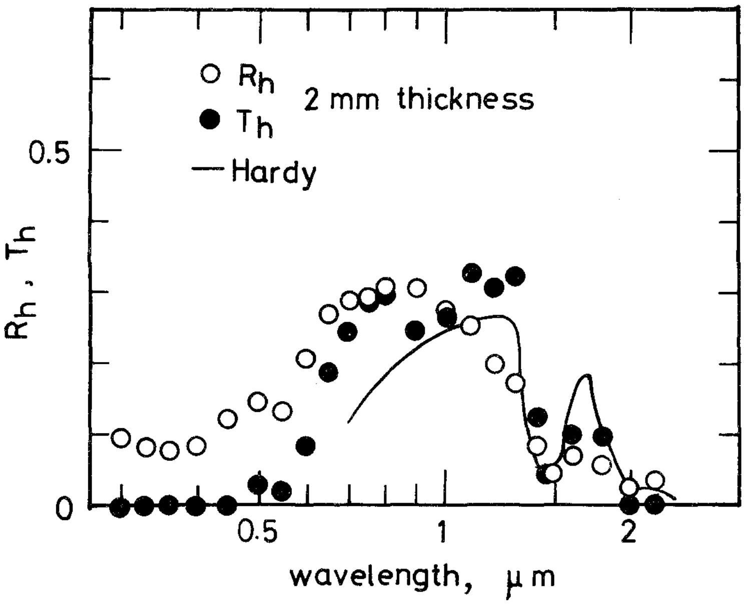

Fig. 8. Hemispherical transmittance and reflectance for a living skin of 2.0-mm thickness.

exposure on a summer day: 154 mW · min · cm^{-2}) was also measured and the results are shown in Fig. 7.

In order to know the radiative properties of the inside of the skin, the measurement of the reflectance only is insufficient. Accordingly, the hemispherical transmittance was measured on a thin stretched skin part. Figure 8 shows the experimental results of the hemispherical transmittance T_h and the hemispherical reflectance R_h of a living skin of 2-mm thickness for the normal incidence. In the wavelength region longer than 2.4 μm, the measured values of T_h were less than 0.001 and they are not shown. The solid line in the figure is the experimental value of transmittance obtained by Hardy [4] for a cut-skin sample of 1.1-mm thickness.

4. DISCUSSION

In Figs. 3 and 4, for hemispherical reflectances of forearm, cheek, dorsum hand, and hip, the following is observed. In the short-wavelength region ($\lambda \leqslant 0.45$ μm), the difference is not recognized between the two men (that is, between Fig. 3 and Fig. 4). In the visible region ($\lambda \geqslant 0.5$ μm), the difference between the two men is, at most, 0.05. In the near-infrared region, the difference increases to 0.1. Both R_h values decrease rapidly at the wavelength of 1.4 μm and reach the minimum values at $\lambda = 1.5$ μm. In the long-wavelength region ($\lambda \geqslant 1.5\ \mu m$), differences between the two persons and also differences among the various parts are not found. Especially in the wavelength region longer than 2 μm, R_h reaches a very low value, below 0.05.

The following points are noted for the obtained spectra.

(i) The low reflectance in the short-wavelength region ($\lambda \leqslant 0.58\ \mu m$) is due to the absorbing pigments, for example, melanin (0.3–0.4 μm), β-carotine (0.3–0.4 μm), Hb (hemoglobin), which has absorption peaks at wavelengths of 0.429 and 0.556 μm [3], and HbO_2, which has absorption peaks at wavelengths of 0.416, 0.542, and 0.576 μm [3].

(ii) The weak absorption at the wavelength 0.75 μm is due to the absorption band of Hb.

(iii) The absorption in the wavelength region from 0.9 to 1.1 μm is due to the absorption of water, of which most of a living body is composed.

(iv) The strong absorption at the wavelength 1.5 μm is due to the water absorption band.

(v) The decrease in reflectance in the wavelength region longer than 2 μm is due to the increase in the absorption coefficients of water and of organic matter and to the decrease in the scattering coefficient.

In the case of R_h for the hair in Fig. 5, the value of R_h for white hair is not so large because the hair does not form a flat surface and cavities absorb radiation. The large value of R_h for black in the near-infrared region seems to be due to the high concentration of melanin in the hair. Melanin blackens the hair, and at the same time it decreases the absorption due to water since the water content is much reduced in the hair. This inference is confirmed by weak absorptions at 1.5 and 2.0 μm due to water.

About the sunburn effect shown in Fig. 6, the following points are noted. In the wavelength region shorter than 1.2 μm, a decrease of 0.05–0.15 due to sunburn is found. This seems to be due to the increase in the amount of melanin caused by the increase in the ultraviolet radiation, which acts as a sunshade because of its high absorption coefficient. By using the goniometric spectrophotometer, the bidirectional dependence of diffuse reflection was investigated, It was found that the reflection from the forearm which was not sunburnt is close to the isotropic diffuse reflection and an incident light is scattered multiply in the visible region, and furthermore, the reflection from the forearm which was sunburnt is not isotropic, which indicates the superiority of the absorption by melanin to the scattering. In the wavelength region longer than 1.2 μm, the effect of sunburn was not found. About the recovery of the reflectance after strong sunburn shown in Fig. 7, the obvious phenomenon is pointed out. The recovery is

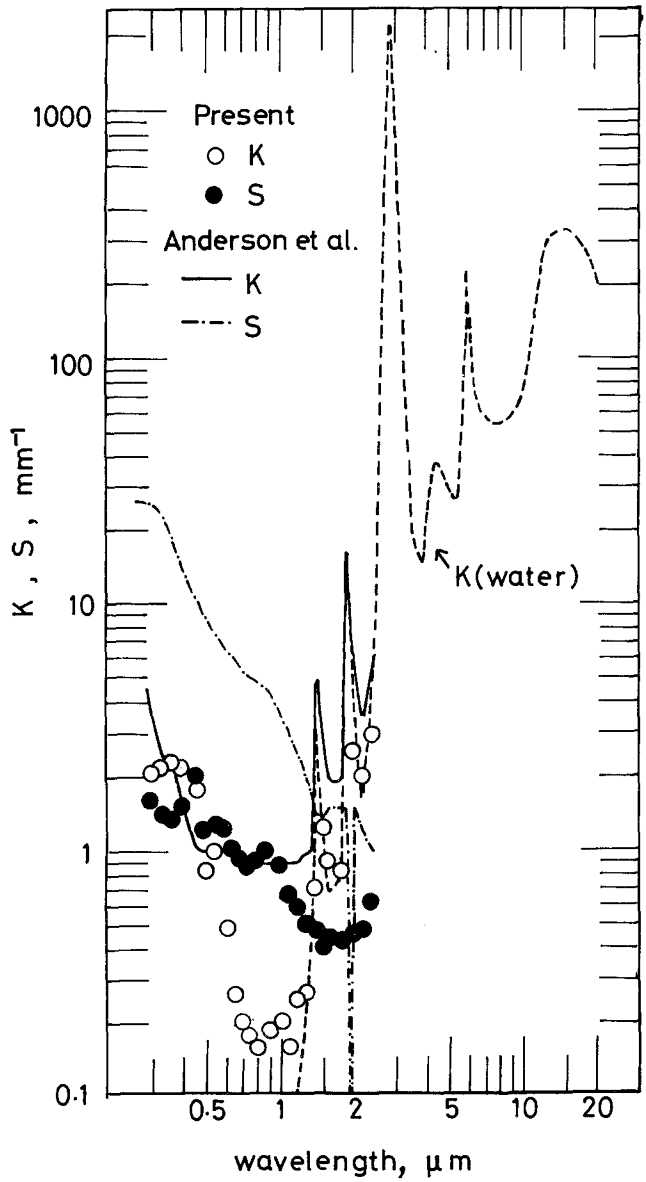

Fig. 9. Absorption coefficient and scattering coefficient of human skin.

very fast in the wavelength region shorter than 0.6 μm but is very slow in the wavelength region from 0.6 to 1.2 μm.

About the results shown in Fig. 8, the following points are noted. In the case of the present results, the absorption by Hb and HbO_2 is remarkable at the wavelength 0.55 μm and the absorptions at the wavelength 0.9 μm due to HbO_2 and at the wavelengths 1.5 and 2 μm due to water are found. In the curve given by Hardy, the absorption at the wavelength 0.9 μm is not found, which might be due to the low accuracy of the experiment.

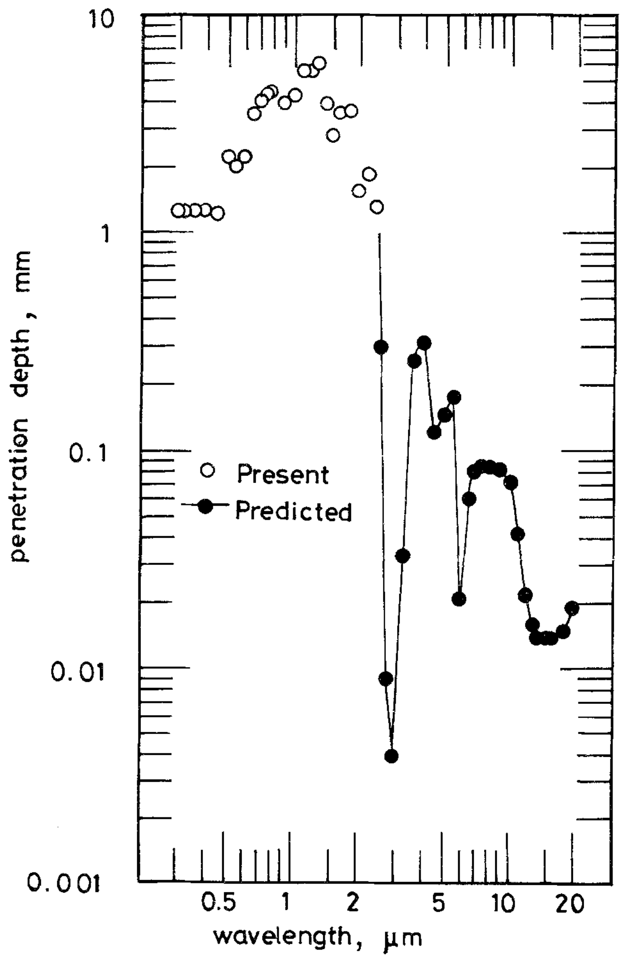

Fig. 10. Penetration depth in human skin for parallel incident light.

In order to know the radiative properties inside the skin, the authors applied the four-flux treatment of the radiative transfer [9] to the present result in Fig. 8. In the four-flux treatment, the collimated light and the diffuse light are treated independently. To simplify the analysis, isotropic scattering was assumed and the Kubelk Munk theory for isotropic scattering was modified. By using the measured values of the hemispherical reflectance and transmittance, the two parameters of the absorption coefficient K and the scattering coefficient S can be determined. The results are shown in Fig. 9. The absorption peak by Hb and HbO_2 is found at the wavelength 0.55 μm. The large absorption coefficients in the wavelength region from 0.3 to 0.6 μm seem to be due to melanin. In the wavelength region from 1.3 to 2.4 μm, the optical property is very close to that of water. This is understandable, since most of the human body is composed of water. It is supposed that the absorption coefficient of water can be substituted for that of the human skin. In the wavelength region from 0.45 to 1.3 μm, the scattering coefficient is very high in comparison with the absorption coefficient. But in the far-infrared region, the scattering coefficient is small in comparison with the absorption coefficient and can be neglected. The results obtained by Anderson and Parrish [2] for cut human skin are shown, too, and are much different from the present results. This shows that the in vitro measurement is inadequate and causes an error.

Figure 10 shows the results of the penetration depth when parallel uniform light flux is incident onto the human skin normally. The penetration depth was defined by the depth where transmittance is 0.01. In the farinfrared region, the predicted values were obtained by the assumption that the absorption coefficient of water can be substituted for that of human skin. In the infrared region, the incident light does not penetrate inside the human skin.

5. CONCLUSIONS

Measuring equipment for reflectance and transmittance of a semitransparent scattering medium was developed. The condition of one-dimensional radiative transfer is satisfied by this equipment and the correct values of reflectance and transmittance can be obtained in the wavelength region of 0.3–20 μm. Measurement of the radiative properties of a living human skin was performed in vivo. The measured parts are forearm, cheek, dorsum hand, hip, and hair. The values obtained by the present study are much different from those of previous in vitro measurements. Fairly large values for hemispherical reflectances are observed in the visible and near-infrared regions but very small values for hemispherical reflectances are observed in the infrared region, below 0.05. By applying the four-flux treatment of radiative transfer, the absorption coefficient and scattering coefficient in the human skin are determined. The scattering coefficient is large in the visible region but negligible in the infrared region. The absorption coefficient is very close to that of water and large in the infrared region. The seasonal variation of R_h and the sunburn effect on R_h were also examined. These effects are observed in the visible region but not in the infrared region.

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