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The Optics of Human Skin

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An integrated review of the transfer of optical radiation into human skin is presented, aimed at developing useful models for photomedicine. The component chromophores of epidermis and stratum corneum in general determine the attenuation of radiation in these layers, moreso than does optical scattering. Epidermal thickness and melanization are important factors for UV wavelengths less than 300 nm, whereas the attenuation of UVA (320-400 nm) and visible radiation is primarily via melanin. The selective penetration of all optical wavelengths into psoriatic skin can be maximized by application of clear lipophilic liquids, which decrease regular reflectance by a refractive-index matching mechanism. Sensitivity to wavelengths less than 320 nm can be enhanced by prolonged aqueous bathing, which extracts urocanic acid and other diffusible epidermal chromophores. Optical properties of the dermis are modelled using the Kubelka-Munk approach, and calculations of scattering and absorption coefficients are presented. This simple approach allows estimates of the penetration of radiation *in vivo* using noninvasive measurements of cutaneous spectral remittance (diffuse reflectance). Although the blood chromophores Hb, HbO_2, and bilirubin determine dermal absorption of wavelengths longer than 320 nm, scattering by collagen fibers largely determines the depths to which these wavelengths penetrate the dermis, and profoundly modifies skin colors. An optical "window" exists between 600 and 1300 nm, which offers the possibility of treating large tissue volumes with certain long-wavelength photosensitizers. Moreover, whenever photosensitized action spectra extend across the near UV and/or visible spectrum, judicious choice of wavelength allows some selection of the tissue layers directly affected.

Whenever the skin is involved as the site for photobiologic reactions, its optical properties play some role, and very often a major role, in affecting the response. Radiation must pass through the stratum corneum before reaching viable tissues, and hence the thickness, composition, and morphology of the stratum corneum is always a modifying factor. Having reached viable tissue, the radiation is scattered and absorbed by structures and chromophores which vary dynamically and between individuals. Ultimately, our quantitative understanding of all cutaneous and many systemic photobiologic responses, whether photochemically or photothermally induced, depends in part upon being able to quantitatively model and understand the transfer of optical radiation within skin.

New knowledge of cutaneous optics enters into the design of new therapies involving either photochemical reactions with known action spectra and metabolic consequences (phototherapies, photochemotherapies) or selective thermal destruction of pigmented target tissues. Different wavelengths across the optical spectrum, defined here as approximately 250 nm in the ultraviolet to approximately 3000 nm in the infrared, reach vastly different depths within tissue, and essentially all photobiologic effects are both wavelength and dose-dependent. If an action spectrum is broad, one therefore has some control, by choice of wavelength, over the depth to which tissues are directly affected by the radiation. Our rapidly increasing knowledge of cellular and molecular photobiology gained from *in vitro* bacterial and tissue culture studies can, in theory, be related to observed responses of cells *in situ* by comparing the dose-related effects of optical radiation *in vitro* to those *in vivo*. Conversely, on the basis of knowing the practical upper limits of spectral radiant exposure doses experienced by cell layers, blood, or other structures *in vivo*, one can then concentrate on basic studies of repair, mutation, and metabolic changes induced by equivalent doses *in vitro*. Optics of skin modify spectra for photobiologic responses, and the transmittance of radiation to a given tissue layer should be considered when analyzing such spectra. Unfortunately, the "target" tissue layer is often poorly defined, and other factors, such as competing photochemical pathways, can modify action spectra as well.

Another broad potential application involving the optics of skin is that of noninvasive *in vivo* optical spectroscopic measurements which can be used to monitor major cutaneous chromophores of interest. These include melanin, oxygenated and reduced hemoglobin, and bilirubin, all of which have been monitored with varying degrees of success by analysis of skin remittance (diffuse reflectance) spectra [1-12]. Although clinicians have used grossly visible cutaneous autofluorescence excited by UVA wavelengths as a diagnostic tool for decades, there has been no successful quantitative analysis of *in vivo* cutaneous fluorescence spectra. Such an endeavor would probably yield useful information.

Central to the basic understanding or application of the optics of skin is the development of a quantitative, general model for radiation transfer in this complex, dynamic, variable, and multilayered optical medium. This has yet to be accomplished in anything but an approximate fashion, because the microscopically complex structure of the skin makes an entirely rigorous analysis of its optics virtually impossible. However, on the macroscopic scale, phenomenological theories of radiation transfer in turbid media can be applied to model the optics for each skin layer. Fortunately, many of the major chromophores are normally confined to a single layer. Melanin is confined to the epidermis and stratum corneum, whereas the various forms of hemoglobin are confined to vessels of the dermis, and only indirectly exert any influence on optical radiation densities within the overlying epidermis. Considering the absorption spectra and localization of the major cutaneous pigments, and optical scattering for each layer, it is in theory possible to arrive at mathematical descriptions of cutaneous optics which include many of the major variables *in vivo*, and which can be used to analyze the skin and its photobiologic responses and to approximate actual optics of human skin.

AN OVERVIEW

Initially it is helpful to schematize the optics of normal skin as shown in Fig 1. At near-normal (nearly perpendicular) incidence, a small fraction of an incident radiation is reflected due to the change in refractive index between air ($n_D = 1.0$) and stratum corneum ($n_D \cong 1.55$) (13). For normally incident radiation, this *regular reflectance* of an incident beam from normal

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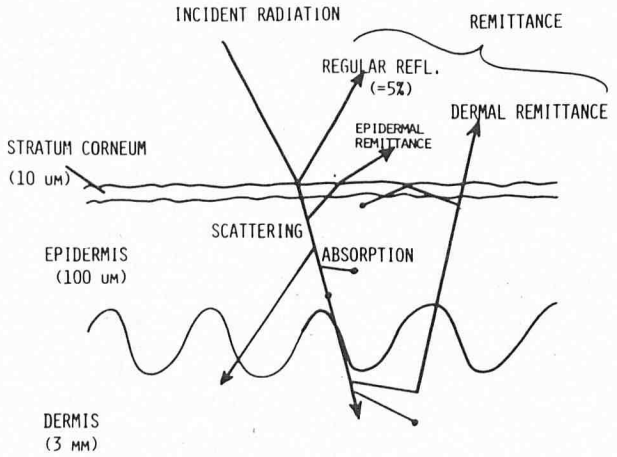


FIG 1. Schematic diagram of optical pathways in skin.

skin is always between 4% and 7% over the entire spectrum from 250–3000 nm, for both white and black skin [14,15]. This same air-tissue optical interface also causes internal reflection of diffuse, back-scattered radiation, which is an important consideration when analyzing remittance spectra of skin. Because the surface of the stratum corneum is not smooth and planar: (1) the regular reflectance from skin is not specular, i.e., skin reflectance does not maintain an image and (2) a beam of collimated incident radiation, upon passing through this surface and into the skin, is refracted and therefore made somewhat more diffuse by this rough surface. These effects are similar to those which make ground glass translucent, compared with the transparency of polished glass.

Regular reflectances occurring at the skin surface can be clinically important. Whereas normal skin has a single continuous air-tissue interface, the surface of psoriatic plaques is generally torturous and consists of stacked flakes of abnormal corneocytes, with some air spaces between them. These present multiple optical interfaces, and hence the regular reflectance occurring at the surface of psoriasis vulgaris plaques is greater than that for normal skin, giving the plaques a white, scaly appearance. When lipophilic compounds capable of spreading to and filling the spaces are applied, the regular reflectance of the plaque immediately decreases to values within the range for normal skin [16]. The broad spectral character, magnitude, and rapidity of the decreases in reflectance indicate that the mechanism involved is the closer matching of the refractive index between the applied compound and the skin, as compared to air and skin. As would be expected, similar application to normal skin does not affect its regular reflectance, because it possesses only a single interface. Because the observed decrease in psoriatic skin reflectance is unrelated to optical absorption by the applied compounds, a greater fraction of the incident radiation must penetrate the plaque, but not normal skin sites, after application of oils. These observations explain in part why nonphotosensitizing oily lubricants when applied prior to phototherapy treatments significantly enhance therapeutic effectiveness [16].

Within any of the layers of skin, the 93% to 96% of the incident radiation not returned by regular reflectance may be absorbed or scattered. These two processes taken together essentially determine the penetration of radiation into skin, as well as the remittance of scattered radiation from the skin. Scattering results from inhomogeneities in a medium's refractive index, corresponding to physical inhomogeneities. The spatial distribution and intensity of scattered light depends upon the size and shape of the inhomogeneities relative to the wavelength, and upon the difference in refractive index between the medium and the inhomogeneities. For molecules or small particles with dimensions less than roughly one-tenth of the wavelength, scattering is generally weak, nearly isotropic (equally distributed spatially), polarized, and varies inversely with the 4th power of wavelength (Rayleigh scattering). For particles with dimensions on the same order as the wavelength, scattering is much stronger, more forward-directed, and, while varying inversely with wavelength, is not such a strong inverse function. When the particle size greatly exceeds the wavelength (so-called Mie scattering), scattering is again diminished and becomes highly forward-directed. Within the skin all of these general types of scattering occur, but quantitatively, scattering by stuctures with dimensions on the order of optical wavelengths or somewhat larger must dominate over Rayleigh scattering. In particular, scattering by collagen fibers appears to be of major importance in determining the penetration of optical radiation within the dermis [15].

If scattering is marked, most photons experience multiple scattering before being absorbed or back-scattered from the sample. In this case, the spatial distribution of the radiation as it passes through the sample quickly becomes isotropic (i.e., diffuse), regardless of spatial distribution obtained for single scattering. If the radiation is isotropic, one can show that the average pathlength of photons through an infintesimal pathlength dx in any one direction is simply 2 dx [17]. For perfectly diffuse (isotropic) radiation, the situation therefore becomes somewhat simplified, and one can derive absorption and scattering coefficients for diffuse radiation, equal to twice those for collimated radiation because of the pathlength argument given above, in terms of measurements of transmittance and remittance. One popular model for this analysis is that derived by Kubelka and Munk [18–20]. The differential (continuous) model proposed by Kubelka and Munk is neither an elegant nor thorough model of optical radiation transfer, but it is simple and can be most readily applied to skin. In general, the more physically rigorous theories of radiation transfer require a knowledge of structure and optical parameters which is difficult to obtain for skin [21].

The Kubelka-Munk theory assumes that the sample possesses inhomogeneities which are small compared with the sample thickness; that the incident radiation is diffuse; and that regular reflection occurring at the boundaries of a sample can be neglected. Although not all of these assumptions are easily met, especially the latter two, the theory nonetheless offers a means for a simple quantitative treatment of skin optics. Radiation within the sample is divided into 2 opposing diffuse fluxes, I and J (Fig 2). The sample's back-scattering (S) and absorption (K) coefficients for diffuse radiation are defined in two differential equations as the fraction of diffuse radiation either back-scattered or absorbed per unit differential pathlength of the sample. These differential equations are:

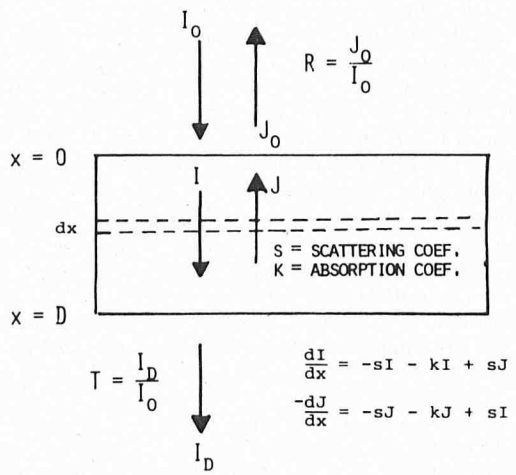


FIG 2. The Kubelka-Munk model for radiation transfer in a turbid, absorbing medium.

$$dI = (-KI - SI + SJ)\,dx \quad (1)$$

$$-dJ = (-KJ - SJ + SI)\,dx \quad (2)$$

which simply state that the change, dI, in flux I over some layer of thickness dx is equal to that fraction of I removed by absorption and back-scattering plus some fraction contributed to I by back-scattering from J. The 2nd differentiation equation is an analogous statement for J. Integration and substitution of boundary conditions gives a particular solution, which can then be rearranged to express S and K (the 2 unknowns) in terms of R and T (the measurable quantities). Written in the forms derived by Kubelka and Munk, these are:

$$K/S = [(1 + R^2 - T^2)/2R] - 1 \quad (3)$$

$$S = \frac{1}{d}[K/S(K/S + 2)]^{-1/2} \coth^{-1}\left[\frac{1 - R(K/S + 1)}{R[K/S(K/S + 2)]^{1/2}}\right] \quad (4)$$

Because a minimum of two different measurements are always necessary to determine the 2 unknowns S and K, measurements of both remittance and transmittance, or remittance with two different reflective "backgrounds," are required. In order to use this model practically, one must also account for regular reflection occurring at both sample boundaries, and adhere to the use of diffuse incident radiation. This has been accomplished for thin samples of human dermis *in vitro* [15]. Once S and K are known, the two fluxes I and J can be reconstructed, and the radiation density at a given depth can be estimated by summing I and J at that depth. Near the front surface of a scattering sample, the sum of I and J can easily exceed I_0, the incident density of optical radiation. In the extreme case, I plus J just inside the surface of a sample with 100% remittance is twice I_0. Such "concentration" of radiation density due to scattering occurs in fair-skinned individuals for most visible wavelengths, where remittance is high. If a sample is infinitely thick, or simply thick enough that T approaches zero, one can rewrite equation 3 as:

$$\frac{K}{S} = \frac{(R - 1)^2}{2R} \quad (5)$$

Here, the remittance of a thick sample depends solely upon the ratio of its absorption and scattering coefficients. The dermis is sufficiently thick that for wavelengths less than 600 nm, its transmittance approaches zero, which potentially simplifies analysis of remittance spectra. If one treats S as a known constant, K can be estimated directly from R.

Fortunately, the structures of skin which lead to strong scattering, and hence determines S, appear to be different than those chromophores present which determine K. For any given layer of skin, K is compositely determined by the concentration and distribution of those chromophores present. This is convenient because in normal skin certain chromophores such as hemoglobins, bilirubin, and melanin change rapidly, causing changes in absorption coefficients, whereas scattering coefficients should not change significantly until some gross alteration of structure occurs.

Finally, it is apparent that as the thickness of any particular sample decreases, R always decreases and T always increases. In the case of the stratum corneum, and to a large extent the entire normal human epidermis, the layer is thin enough that its contribution to remittance (other than the regular reflectance discussed above) is minimal over the entire visible and near infrared spectral regions [15].

OPTICS OF THE STRATUM CORNEUM AND EPIDERMIS

Many studies of the transmission of ultraviolet radiation through excised human epidermis and stratum corneum have been reported since the original work of Hasselbalch [22]. Much of the early work failed to account accurately for the diffuse nature of transmission through skin samples. Since the advent of commercially-available spectrophotometers with integrating spheres, several groups have measured and published total transmission spectra of human epidermis [23,24]. The ultraviolet-visible transmission of fair-skinned Caucasian stratum corneum or epidermis qualitatively resembles that of protein containing the aromatic amino acids tryptophan and tyrosine, with a minimum in transmittance near 275 nm due to absorption by these and other aromatic chromophores. Nucleic acids, with an absorption maximum near 260 nm, and numerous small aromatic molecules, especially urocanic acid, with an absorption maximum at 277 nm at pH 7.4, also contribute to the broad 275 nm absorption band seen in epidermis and stratum corneum. Melanin content and distribution usually plays a major but highly variable role in determining the transmission of optical radiation through the statum corneum and epidermis, depending upon the genetically determined capacity of an individual for constitutive and facultative pigmentation. The high absorbance of epidermis and stratum corneum for wavelengths less than 240 nm is largely due to peptide bonds.

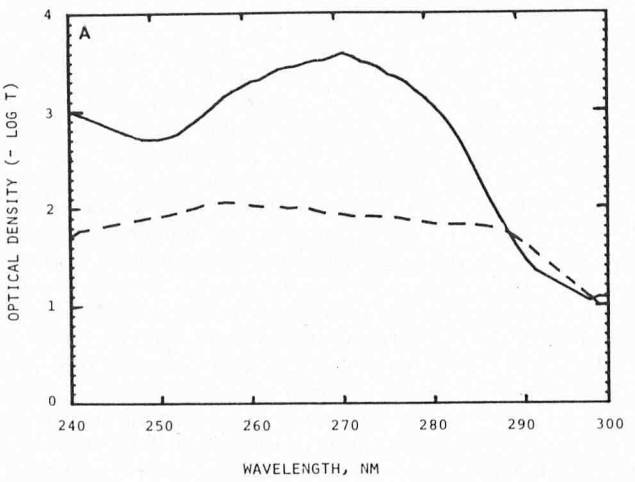
The measurement of epidermal transmittance is complicated by a broad fluorescence excitation band centered near 280 nm, associated with an emission band between 330 and 360 nm, consistent with tryptophan or tyrosine fluorescence [25]. This emission band is of sufficient intensity to cause suspicion of epidermal transmission spectra in the region less than 300 nm, when taken with integrating spheres equipped with broadband (UV-visible sensitive) photomultipliers, as in essentially all standard spectrophotometer systems. A second problem arises if the epidermal sheet is suspended in air or placed against a quartz slide, typically at the entrance port of an integrating sphere. Some total internal reflection of forward-scattered and refracted off-axis rays occurs, which are then lost for measurement purposes.

The autofluorescence error can be overcome by using a "solar-blind" detector, which is insensitive to wavelengths longer than 320 nm, and the problem of total internal reflection can be overcome by using normal saline as the optical medium on the dermal side of epidermal samples. This also maintains the samples in a physical environment similar to that *in vivo*. Representative fair-skinned Caucasian epidermal and stratum corneum transmission (T) spectra taken with such a system, and expressed in apparent optical density (O.D. = log T) units, are presented in Fig 3*a* and 3*b* and compared with conventional spectra not corrected for autofluorescence [25].

Absorption spectra of major epidermal pigments are given in Fig 4. It can be seen that epidermal or corneal transmittance spectra are compositely determined by absorption by these (and certainly other) substances. Variations in the concentrations, distributions, or amounts of these chromophores, and in epidermal thickness, largely determine individual and anatomic variations in epidermal spectral transmission. One would expect the protein- and nucleic-acid-bound chromophores to be of rather constant concentration and distribution in normal skin, since these chromophores are inherent necessities of the cellular tissue. Both melanin and urocanic acid, however, have variable concentrations and distributions and unlike protein or nucleic acid, ultraviolet optical absorption may be their major functional role in human skin.

There are conflicting reports on the possible photoinduction of urocanic acid synthesis in the epidermis [26,27] but melanin is certainly photoinducible. In the visible portion of the spectrum, melanin is essentially the only pigment affecting the transmittance of normal human epidermis, giving rise to the wide range of discernable skin colors from "black" to "white." The 300 nm transmittance of full-thickness suction-separated epidermis including the basal cell layer varies by 2 to 3 orders of magnitude from very fair-skinned Caucasian to darkly pigmented Negro individuals.

Melanin is not a "neutral density" filter of the skin; its absorption increases steadily toward shorter wavelengths over the broad spectrum of 250 to 1,200 nm. In the near infrared,



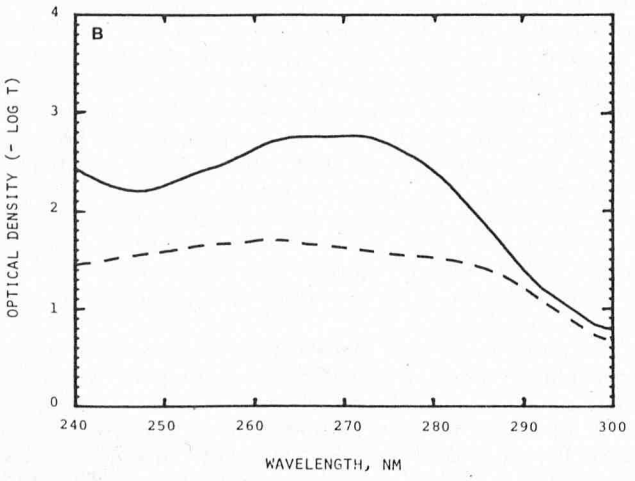


FIG 3. *a*, Apparent optical density of Caucasian human epidermis sample taken with (——) and without (- - - - -) correction for tissue autofluoresence. Overestimation of transmittance occurs due to autofluorescence. Sample was obtained from amputated thigh skin, was separated by immersion in 60°C water for 30 sec, and consisted of the entire epidermis minus the basal cell layer. *b*, Apparent optical density of stratum corneum from skin adjacent to that shown in Fig 3*a*. Sample was separated by 8-h incubation at 37°C in the presence of 10 mg/ml staphylococcal scalded skin syndrome epidermolytic toxin [45] in Hepe's buffer with 20% FCS, and consisted of stratum corneum plus stratum granulosum.

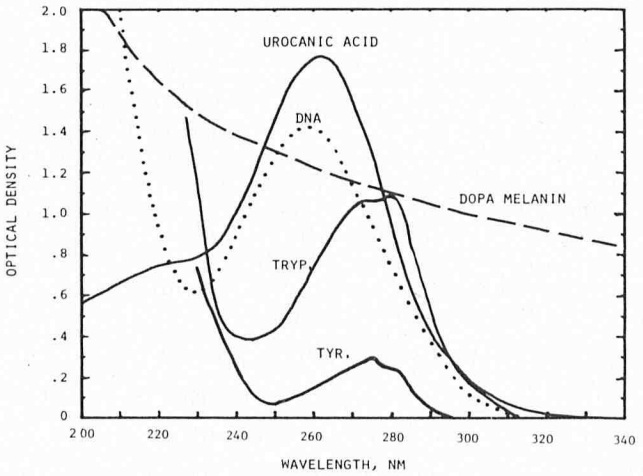


FIG 4. UV absorption spectra of major epidermal chromophores. DOPA-melanin, 1.5 mg% in H_2O; urocanic acid, 10^{-4} M in H_2O; calf thymus DNA, 10 mg% in H_2O (pH 4.5); tryptophane, 2×10^{-4} M (pH 7); tyrosine, 2×10^{-4} M (pH 7). The broad epidermal absorption band near 275 nm is the result of absorption by protein, urocanic acid, nucleic acids, and other aromatic chromphores.

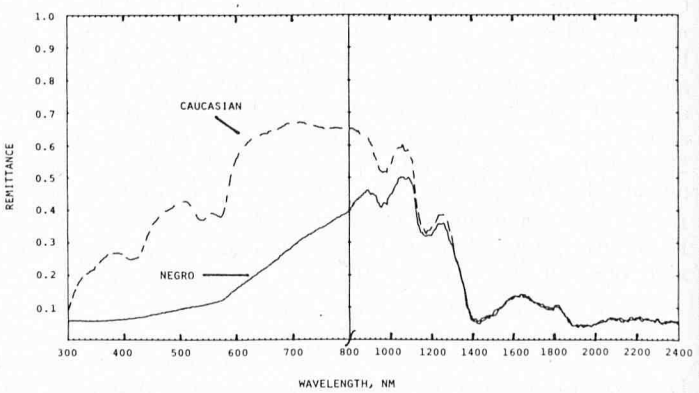


FIG 5. Spectral remittance of dark Negro and fair Caucasian skin (flexor surface of forearm in each case). The lack of significant absorption by melanin for wavelengths longer than approximately 1,100 nm, and increased absorption at shorter wavelengths, is apparent. Note also that, because of regular reflectance at the skin surface, remittance is never less than 5% in either case.

beyond about 1100 nm, absorption by melanin is essentially negligible. For wavelengths longer than 1100 nm, both skin transmittance [28] and remittance [29,30] (Fig 5) are unaffected by melanin pigmentation.

In addition to increasing melanogenesis, UV exposures of skin cause epidermal hyperplasia [31,32]. The relative degree of UV-induced photoprotection offered by melanogenesis versus epidermal hyperplasia depends upon the wavelengths in question, and individual factors. For wavelengths less than 300 nm, and certainly at 275 nm, hyperplasia can offer effective photoprotection, but at longer wavelengths, melanin is the only major epidermal chromophore in normal skin. The capacity for inducing various degrees of hyperpigmentation (tanning) is variable and complexly genetically determined. Precise dose-response, action spectrum, or photoprotective-effect studies for single exposures or for multiple exposures leading to steady-state equilibria of this interesting photoinducible, photoprotective system are lacking. The action spectrum for induction of melanogenesis grossly resembles that for induction of delayed erythema, but at longer wavelengths in the near UV or visible spectral regions, melanogenesis can be induced by suberythemogenic exposure doses [33,34]. UVA (320–400 nm)-induced tanning may be less protective against UVB (290–320 nm) radiation than UVB-induced tanning [35]. The mechanism for this difference is unknown.

Melanin is a remarkably stable protein-polymer complex, the chromophoric backbone of which survives attack by proteases, acids and bases. Caucasian melanosomes typically contain a greater number of melanin granules, but less total melanin, than Negroid or Mongolian melanosomes, and also appear to suffer greater degradation within keratinocytes. The optical effects associated with dispersed "melanin dust" in Caucasians versus intact melanosomes have not been quantitated, but it is likely that, unless the chromophoric backbone is degraded, dispersal of melanin pigment in Caucasian stratum corneum affords somewhat greater protection than would the same quantity of melanin sequestered in intact melanosomes. An interracial study of epidermal transmittance by Kaidbey, et al [36] suggests that the large racial differences in sensitivity to UV of 10- to 30-fold [37,38] correlate poorly with the small racial differences of approximately 3-fold noted in stratum corneum transmission. However, the minimal erythema dose of black and white subjects has never been directly compared with

accurate stratum corneum or epidermal transmittance measurements of samples from the same subjects, split at various levels in the tissue.

Urocanic acid is thought to play some role as an "endogenous sunscreen" of the epidermis and stratum corneum [39,40]. Recent observations [41] show that extraction of water soluble, diffusible, UV-absorbing compounds from skin into topically applied water accounts for the up to 50% increased sensitivity of skin to UVB radiation after hydrating the skin for prolonged periods. While most of the material extracted is lipid or protein, a small fraction (about 0.2%) of the material is urocanic acid. Because of its high extinction coefficient (18,800 lM^{-1} cm^{-1} at 277 nm, pH 7.4), however, urocanic acid accounted for approximately 75% of the optical absorbance of the extracted materials. Because extensive exposure to sunlight is often associated with sweating, which deposits urocanic acid on the skin surface [39], it is possible that sweating may serve to some extent as a thermally-induced photoprotective mechanism.

In those studies that have compared diffuse versus direct (total transmittance versus transmittance along an optical path in line with the incident beam) transmittance of epidermis or stratum corneum, the ratio of diffuse/direct transmission does not appear to be wavelength dependent [23,42] for either UV or visible wavelengths. This broadband independence of wavelength suggests that the diffuse nature of epidermal transmission of ultraviolet wavelengths is due more to the irregular refractive surface of skin than to particle scattering within the epidermis. Furthermore, other than regular reflectance, only about 5% of collimated incident radiation in the 350-3000 nm region is remitted by scattering within Caucasian epidermis [15]. This observation is consistent with a thin sample in which the back-scattering coefficient (S), is small compared with the reciprocal of the sample thickness (<100 cm^{-1}) and/or absorption relative to scattering is large. Epidermal transmittance spectra of fair Caucasians indicate that most of incident near UV, visible, and near infrared radiation is transmitted through epidermis; one must conclude from the above that whatever back-scattering occurs in normal epidermis over this spectral region is for practical purposes weak, and that any strong scattering within epidermis that does occur must be forward-directed, i.e., off-axis refraction occurring at the skin surface, and large-particle scattering within the tissue. It must be pointed out, however, that despite the central role of the epidermis in providing optical protection for humans, a thorough attempt to model epidermal optics is still lacking.

OPTICS OF THE DERMIS

The dermis has distinctly different optical properties than the epidermis, reflecting differences in structure and composition. Perhaps because the epidermis is easily isolated and forms the first "optical element" of skin, relatively few studies have concentrated upon dermal optics. Hardy, Hammell, and Murgatroyd [28] goniometrically measured visible and near infrared transmittance of skin sections *in vitro*, which included various fractions of dermis. The data indicates that the Beer-Lambert relation is invalid for dermis, and that transmittance is both higher and more forward-directed for longer wavelengths over the region between 0.5 and 1.23 μm. These observations suggest that scattering is of major importance in the dermis. Findlay [43] measured transmittance and remittance spectra of dura mater and pig dermis and found that thin sections, which appeared blue when placed on a black background, showed greater transmittance of longer wavelengths, similar to Hardy et al.'s findings, but exhibited greater remittance of shorter wavelengths. Summing Findlay's transmittance and remittance spectra gives values close to 1.0 (100%) across the entire visible spectrum, indicating that very little visible light was actually absorbed. The best explanation for his data is that scattering in the dermis must vary inversely with wavelength. Anderson, et al. [15] have presented calculations of spectral scattering (S) and absorption (K) coefficients for human dermis *in vitro* by application of a modified Kubelka-Munk theory to measurements of transmittance and remittance of thin dermal sections. Measurements were made under conditions appropriate to the assumptions inherent in this model. The spectral transmittance and remittance of a typical 200 μm thick human papillary dermis section, analogous to those of Findlay, are shown in Fig 6. Calculated values for S and K are shown in Fig 7. Dermal scattering is markedly increased at shorter wavelengths. The absorption coefficient, D, for bloodless dermis is smaller than S except at the prominent absorption bands of water in the infrared region. Dermal scattering therefore plays a major role in determining the depth to which radiation of various wavelengths penetrates the dermis, and largely accounts for observations [28, 44] that, in general, longer wavelengths across the UV-visible-near infrared spectrum penetrate the dermis to a greater extent than do shorter wavelengths.

The appearance of blue skin nevi can be explained based upon this fact. The average dermal pathlength and depth of penetration of remitted shorter wavelengths (blue) light is much less than that of longer wavelengths (red) light. This is because of increased scattering at shorter wavelengths. In blue nevi, melanin is pathologically deposited in the dermis. Blue light encounters less of the dermally deposited melanin than red light, and may therefore suffer less absorption. Such scattering is the only means by which a pigment, such as melanin, which absorbs shorter wavelengths more strongly than longer wavelengths, can produce blue colors.

In vivo, the blood-borne pigments hemoglobin, oxy-hemoglobin, beta-carotene, and bilirubin are the major absorbers of

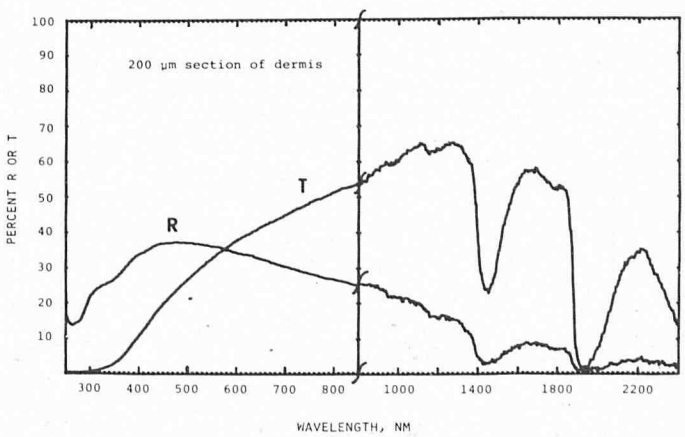


FIG 6. Spectral transmittance and remittance of 200 μm thickness section of human dermis.

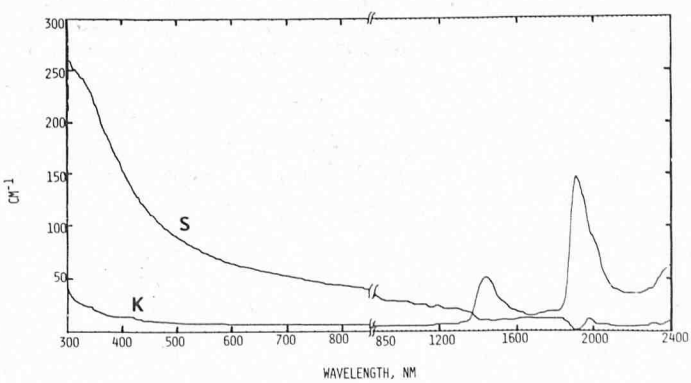


FIG 7. Diffuse scattering (S) and absorption (K) coefficients for human dermis *in vitro*, calculated from measurements of spectral remittance and transmittance of thin dermal sections under conditions appropriate to application of the Kubelka-Munk theory of radiation transfer [15].

visible radiation in the dermis. Absorption spectra for these dermal chromophores, and for dopa-melanin, are shown in Fig 8. In addition, typically less than 1% of the total hemoglobin in blood is methemoglobin, which has an absorption band in the red visible region. The effect of these substances on K is not seen in the *in vitro* dermal spectra presented above but can be estimated or inferred from *in vivo* remittance spectra. This is done in the near UV and visible spectrum by assuming S to be the same *in vivo* as measured *in vitro*, and using the *in vivo* remittance of very fair or vitiliginous skin as an approximation of R for an infinitely thick sample, with no melanin pigmentation. K can therefore be determined from eq. 5 above. The 2 fluxes I and J can then be reconstructed, and summed to find the total flux density at a depth x. It can be shown that this sum is $I_o e^{-1}$ when

$$x = \beta/K\left[1 + \ln\left(\frac{2}{1+\beta}\right)\right]$$

where β is given by

$$\beta = \left[\frac{K}{K + 2S}\right]^{1/2}.$$

For shorter wavelengths, the 1/e values can be estimated from epidermal transmittance spectra. The Table gives estimated depths for which radiation is attenuated to 1/e of the incident radiation density, for fair Caucasian skin *in vitro*. It must be realized that the values given in the Table are only estimations of the depths of penetration of various wavelengths, based on a highly simplified model, and for vitiliginous skin. The epidermis of pigmented individuals can greatly reduce these values, especially at shorter wavelengths, as discussed above.

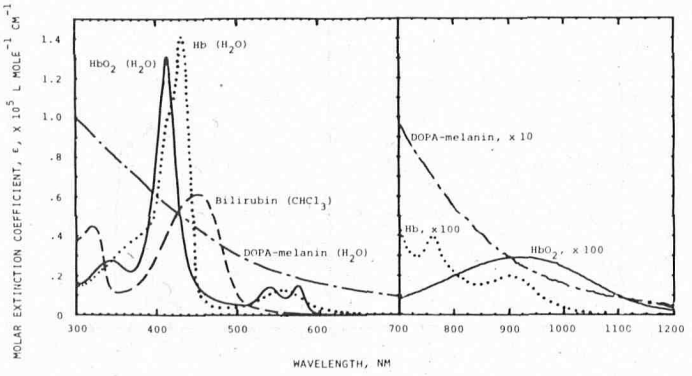


FIG 8. Absorption spectra of major visible-absorbing pigments of human skin, HbO_2 (——), Hb (. . . .), bilirubin (- - - -), and DOPA-melanin (—·—). Parentheses indicate solvent. The spectrum shown for DOPA-melanin is the absorbance on a scale of 0 to 1.5 of 1.5 mg% aqueous solution. Not shown is β-carotene, which has a broad absorption band qualitatively similar to that for bilirubin in the 400–500 nm region, with maxima at 466 and 497 nm in $CHCl_3$. Note scale changes in the near infrared.

Approximate depth for penetration of optical radiation in fair Caucasian skin to a value of 1/e (37%) of the incident energy density

Wavelength (nm)	Depth (μm)
250	2
280	1.5
300	6
350	60
400	90
450	150
500	230
600	550
700	750
800	1200
1000	1600
1200	2200

Since the penetration of optical radiation in the tissue is wavelength-dependent, stratification of pigments at different depths influences the spectral distribution of the radiation reaching a given stratum. For example, only the superficial vessels—capillaries and the venular plexus—will be exposed to significant blue or UV radiation. Conversely, an optical "window" exists in skin and most other soft tissue in the region 600–1300 nm. Whenever it is possible to use some portion of the penetrating 600–1300 nm wavelength region to cause phototoxicity, the volume and depth of tissue affected will be large. Preliminary measurements show that up to 1% of the 605 to 850 nm wavelength region penetrates the entire human chest wall, post mortem. The transmittance of wavelengths less than 550 nm is less than 10^{-5}, however [25].

SUMMARY

The stratum corneum and epidermis provide an optical barrier primarily by absorption of radiation, and to a lesser degree, by optical scattering. In the ultraviolet region less than 300 nm, aromatic amino acids, nucleic acids, urocanic acid, and melanin can be defined as major epidermal absorbers. Hyperplasia, melanogenesis, and perhaps urocanic acid synthesis, form an inducible photoprotective system. The relative importance of these variable protective factors is wavelength-dependent and varies between skin sites and individuals. In the wavelength region 350–1200 nm, melanin is the major absorber of radiation in the epidermis, especially at shorter wavelengths. One can manipulate the optics of the epidermis by various stimuli including UV radiation, by extraction *in vivo* of UV-absorbing compounds, most notably urocanic acid, and in the case of psoriasis by a superficial refractive index matching mechanism when oil is applied. A rigorous model, with data, for epidermal optics is lacking.

The dermis may be considered a turbid tissue matrix with which optical scattering is an inverse function of wavelength and largely defines the depth of optical penetration. Absorption bands of blood-borne chromophores, especially bilirubin and oxyhemoglobin, are apparent in remittance spectra of skin, and such spectra can be used to monitor or analyze serum bilirubin, vascular, or pigmentation responses. Despite many complicating factors, it is possible to approximate the optics of the dermis using radiation-transfer theories, and a simple model is presented.

REFERENCES

1. Edwards EA, Duntley SQ: The pigments and color of human skin. Am J Anat 65:1–33, 1939
2. Goldzieher JW, Roberts IS, Rawls WB, Goldzieher MA: "Chemical analysis of the intact skin by reflectance spectrophotometry. Arch Dermatol Syphilol 64:533–548, 1951
3. Edwards EA, Finkelstein NA, Duntley SQ: Spectrophotometery of living human skin in ultraviolet range. J Invest Dermatol 16:311–321, 1951
4. Sheard C, Brown E: The spectrophotometric analysis of the color of the skin. Arch Int Med 38:816–831, 1926
5. Daniels F, Imbrie JD: Comparison between visual grading and reflectance measurements of erythema produced by sunlight. J Invest Dermatol 30:295–301, 1958
6. Breit R, Kligman AM: Measurement of erythemal and pigmentary responses to ultraviolet radiation of different spectral qualities, The Biologic Effects of Ultraviolet Radiation (with Emphasis on the Skin). Edited by F. Urbach. Oxford, Pergamon Press, 1969, pp 267–275
7. Frank L, Rapp Y, Bergman LV: An instrument for the objective measurement of erythema. J Invest Dermatol 38:21–24, 1962
8. Tronnier H: Evaluation and measurement of ultraviolet erythema, The Biologic Effects of Ultraviolet Radiation (with Emphasis on the Skin). Edited by F. Urbach. Oxford, Pergamon Press, 1969, pp 255–265
9. Feather JW, Dawson JB, Barker DJ, Cotterill JA: A theoretical and experimental study of the optical properties of skin *in vivo*, Proceedings of the Symposium on Bioengineering and the Skin. Cardiff, MTP Press, Ltd., International Medical Publishers, 1980, in press

10. Ballowitz L, Avery ME: Spectral reflectance of the skin. Biology of the Neonate 15:348–360, 1970
11. Bruce RA: Noninvasive estimation of bilirubin and hemoglobin oxygen saturation in the skin by reflection spectrophotometry. Ph.D. Thesis, Duke University, Durham, North Carolina, 1978
12. Haunemann RE, DeWitt DP, Weichel JF: Neonatal serum bilirubin from skin reflectance. Pediat Res 12:207–210, 1978
13. Scheuplein RJ: A survey of some fundamental aspects of the absorption and reflection of light by tissue. J Soc Cosmet Chem 15:111–122, 1964
14. Parrish JA, Anderson RR, Urbach F, Pitts D: UV-A: Biologic Effects of Ultraviolet Radiation with Emphasis on Human Responses to Longwave Ultraviolet. New York, Plenum Press, 1978
15. Anderson RR, Hu J, Parrish JA: Optical radiation transfer in the human skin and application in *in vivo* remittance spectroscopy, Proceedings of the Symposium on Bioengineering and the Skin, Cardiff, Wales, July 19–21, 1979. MTP Press, Ltd., London, 1980, in press
16. Anderson RR, LeVine MJ, Parrish JA: Selective modification of the optical properties of psoriatic vs. normal skin. Book of Abstracts, 8th International Photobiology Congress, Strasbourg, France, July 1980, p 152
17. Kortüm G: *Reflectance Spectroscopy*. New York, Springer-Verlag, 1969
18. Kubelka P, Munk F: Ein Beitrag zür Optik der Farbanstriche. Z Technichse Physik 12:593–601, 1931
19. Kubelka P: New contributions to the optics of intensely light-scattering materials. Part I. J Opt Soc Am 38:448–457, 1948
20. Kubelka P: New contributions to the optics of intensely light-scattering materials. Part II: nonhomogeneous layers. J Opts Soc Am 44:330–335, 1954
21. Atkins JT: Optical properties of turbid materials, The Biological Effects of Ultraviolet Radiation (with Emphasis on the Skin). Edited by F Urbach. Oxford, Pergamon Press, 1969, pp 141–150
22. Hasselbalch KA: Quantitative Untersuchungen uber die Absorption der menschlichen Haut von ultravioletten Strahlen. Skand Arch Physiol 25:5–68, 1911
23. Everett MA, Yeargers E, Sayre RM, Olson RL: Penetration of epidermis by ultraviolet rays. Photochem Photobiol 5:533–542, 1966
24. Pathak MA: Photobiology of melanogenesis: biophysical aspects, Advances in Biology of the Skin, Vol. VIII, The Pigmentary System. Edited by W. Montagna, F. Hu. Oxford, Pergamon Press, 1967, pp 397–420
25. Anderson RR, Parrish JA: Unpublished observations.
26. Hais IM, Strych A: Increase in urocanic acid concentration in human epidermis following insolation. Coll Czech Chem Comm 34:649–655, 1969
27. Baden HP, Pathak MA: The metabolism and function of urocanic acid in skin. J Invest Dermatol 48:11–17, 1967
28. Hardy JD, Hammell HT, Murgatroyd D: Spectral transmittance and reflectance of excised human skin. J Appl Physiol 9:257–264, 1956
29. Jacquez JA, Huss J, McKeehan W, Dimitroff JM, Kuppenheim HF: Spectral reflectance of human skin in the region 0.7-2.6 μ. J Appl Physiol 8:297–299, 1956
30. Kuppenheim H, Heer RR, Jr.: Spectral reflectance of white and Negro skin between 400 and 1000 mμ. J Appl Physiol 4:800–806, 1952
31. Baden HP, Pearlman C: The effects of ultraviolet light on protein and nucleic acid synthesis in the epidermis. J Invest Dermatol 48:71–75, 1964
32. Epstein JH, Fukuyama K, Fye K: Effects of ultraviolet radiation on the mitotic cycle and DNA, RNA and protein synthesis in mammalian epidermis *in vivo*. Photochem Photobiol 12:57–65, 1970
33. Parrish JA, Zaynoun S, Anderson RR: Cumulative effects of repeated subthreshold doses of ultraviolet radiation. J Invest Dermatol, May, 1981
34. Langner A, Kligman A: Tanning without sunburn with aminobenzoic acid type sunscreen. Arch Dermatol 106:338–343, 1972
35. Kaidbey KH, Kligman AM: Sunburn protection by longwave ultraviolet radiation-induced pigmentation. Arch Dermatol 114:46–48, 1978
36. Kaidbey KH, Poh-Agin P, Sayre RR, Kligman AM: Photoprotection by melanin—A comparison of black and Caucasian skin. J Am Acad Dermatol 1:249–260, 1979
37. Olson RL, Gaylor J, Everett MA: Skin color, malanin, and erythema. Arch Dermatol 108:541–544, 1973
38. Hausser KW, Vahle W: Sunburn and suntanning, The Biologic Effects of Ultraviolet Radiation (with Emphasis on the Skin). Edited by F Urbach. Oxford, Pergamon Press, 1969, pp 3–21
39. Zeniske A, Krahl JA: The occurrence of urocanic acid in sweat. Biochim Biophys Acta 12:479–484, 1953
40. Everett MA, Anglin JH, Bever AT: Ultraviolet-induced biochemical alterations in skin. Arch Dermatol 84:717–724, 1961
41. Anderson RR, Blank IH, Parrish JA: Mechanisms of increased ultraviolet transmittance through human skin after topical applications (abstract), Program and Abstracts, 7th Annual Meeting of the American Society for Photobiology, Pacific Grove, California, June 1979, p 141
42. Lucas NS: The permeability of human epidermis to ultraviolet radiation. Biochem J 25:57–70, 1930
43. Findlay GH: Blue skin. Br J Dermatol 83:127–134, 1970
44. Bachem A, Reed CI: The transparency of live and dead animal tissue to ultraviolet light. Am J Physiol 90:600–606, 1929
45. Elias PM, Fritsch P, Dahl MV, Wolff K: Staphylococcal toxic epidermal necrolysis: Pathogenesis and studies on the subcellular site of action of exfoliation. J Invest Dermatol 65:501–512, 1975