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The optics of human skin: Aspects important for human health

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Abstract

Human health can be strongly influenced by exposure to solar radiation. Interactions relevant for health take place mainly in the skin. In this context the optics of human skin is of the utmost importance. Reflection, scattering and absorption are the optical properties affecting the nature of these interactions. By combining a bio-optical model of human skin with advanced radiative transfer theory, we simulated the transport of solar radiation through the skin. The calculated optical properties of the skin can then be combined with action spectra of various photobiological processes to calculate the efficiency spectra of these processes for different skin types. The main result of this study is that the interaction of solar radiation with skin is found to have considerable temporal variations due to the dynamic changes of the optical properties of the skin induced by solar radiation. In particular, variations in the brown colored melanin pigment are important for the optics of skin. The content of blood and proteins and the thicknesses of the skin layers may vary considerably and affect the efficiency of the photobiological processes.

Introduction

The optics of human skin has been investigated for more than a century (1). The significance of skin pigmentation for human health has been studied for just as many years, (*e.g.* 2). It is well established that the number of severe sunburns in

a lifetime increases the risk of *cutaneous malignant melanoma*, the most dangerous form of skin cancer (3). It is also well known that vitamin D is produced in the skin following exposure to shortwave ultraviolet radiation (UVB). These adverse and beneficial effects of ultraviolet radiation cause a dilemma (4), and optimal sun exposures and exposure patterns are sought. The problem is, however, more complicated than simply determining an “optimal sun exposure”. For instance, several studies have shown that outdoor workers may have *less* chance of developing melanoma than indoor workers, and when they do develop melanoma, it is more often the type *lentigo maligna melanoma*, which has a considerably better prognosis than other types of melanomas (e.g. 5 & 6).

The goal of this paper is to give a brief overview of the primary features of skin optics that are important for human health. Also, we would like to answer the question whether it is feasible to apply radiative transfer modeling (7) to elucidate features related to human health.

Skin layers

Human skin is a multi-layered structure. Roughly speaking the skin can be divided into two layers, the epidermis and the dermis. Below the dermis a subcutaneous fat layer is found (see Fig. 1). The epidermis can be further divided into several sub-layers (8). These are the stratum corneum, the stratum lucidum, the stratum granulosum, the stratum spinosum, and the stratum germinativum. The stratum germinativum is usually referred to as *the basal layer*.

Skin optics, *i.e.* the manner in which skin reflects and transmits light of different colors, or *wavelengths*, is determined by the *inherent optical properties* of the skin layers. Each of these layers has different inherent optical properties, primarily due to differences in the concentration of melanin, blood, and keratin between them.

The inherent optical properties of a particular layer can be represented by a set of non-dimensional numbers: 1) the optical depth; 2) the single scattering albedo; 3) the normalized volume scattering function. All of these depend on wavelength. The *optical depth* (τ in Fig. 1) of a layer is the integrated attenuation coefficient of a beam going perpendicularly through that layer. Thus, if the layer has an optical depth of 10, the beam is attenuated by a factor of $\exp(10)$. Light can be attenuated either by absorption or by scattering into another direction.

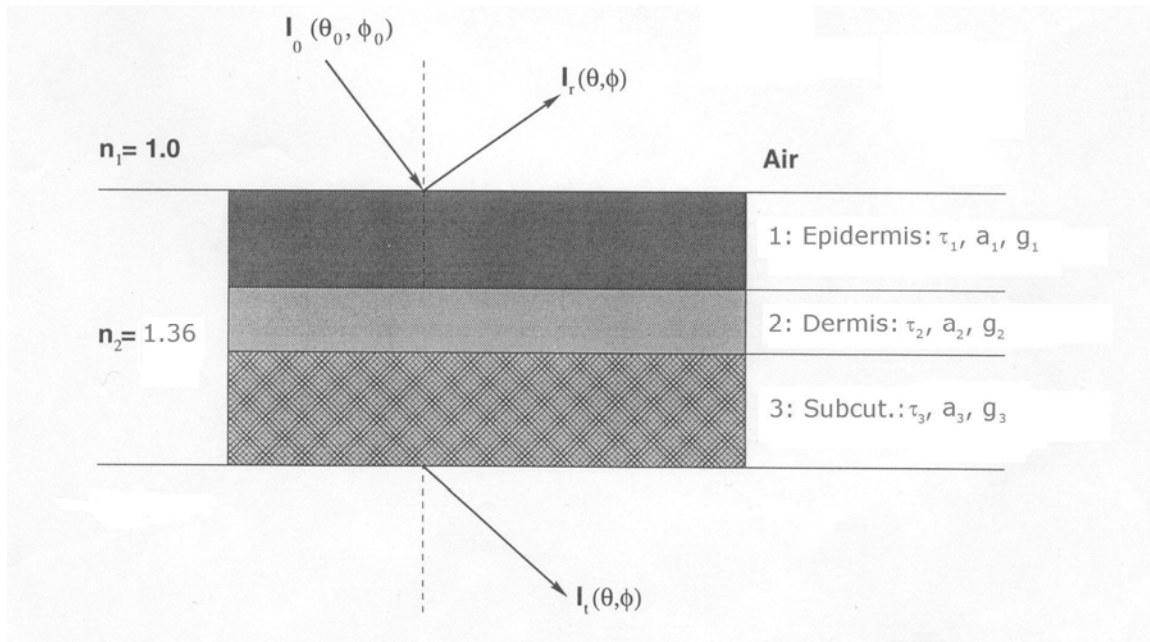


Figure 1. A sketch of human skin and the optical properties of the skin layers. An incoming beam, I_0 , is shown together with a (diffusely) reflected beam, I_r , and a transmitted beam, I_t . $n_1 = 1.0$ is the refractive index of air, $n_2 = 1.36$ is the refractive index of the skin matrix. τ , a , and g denote the non-dimensional optical properties of the individual skin layers, as described in the text.

The *single scattering albedo* (a in Fig. 1) gives the probability that an attenuation event is a scattering event. The *normalized volume scattering function* (represented by the parameter g in Fig. 1) gives the probability of scattering in a particular direction (7).

With the *coupled air-tissue discrete ordinate radiative transfer* algorithm (CAT-DISORT) accurate calculations can be made of the apparent optical properties of the skin layers (*i.e.* the bulk transmittance and reflectance) from given inherent optical properties of these layers (7, 9-13). The inherent optical properties themselves are calculated from the physiological properties of the skin layers using a *bio-optical model*. For each skin layer and wavelength, the bio-optical model can be used to determine the optical depth, the single scattering albedo and the volume scattering function from the melanin concentration, the blood concentration, the thicknesses and several other optically important physiological properties (9 & 13).

Scatters in skin

Skin without blood and melanin, *e.g.* scar tissue, appears diffusely white. This appearance is due to the inhomogeneous distribution of micro- and nano-scopic

particles with variable refractive indices in the skin. A photon entering the skin will be scattered around by these particles as the ball by the pins in a pinball machine and can, therefore, be reflected from the skin in any direction with almost equal probability. This multiple scattering gives the skin its diffuse appearance. The reason for the white color of un-pigmented skin is that many of the skin particles have dimensions that are larger than, or as large as, the wavelengths of visible light. In that case the scattering efficiency does not vary strongly with wavelength. Had the skin particles been much smaller than the wavelengths of visible light, the skin would have appeared blue – just as light scattering by molecules in the air makes the sky appear blue.

The scattering particles in the skin consist of either lipids or proteins embedded in the fluids in and between skin cells. These fluids mainly consist of water. The lipid scatterers are found in the stratum corneum, in the cell membranes, and in the intracellular particles. The most efficient scatterers with respect to both scattering probability and scattering angle are those with dimensions close to the wavelength of the incoming light. Thus, cells themselves, with dimensions of the order of 10 μm , scatter ultraviolet radiation much less efficiently than mitochondria with typical dimensions of the order of 1 μm , since ultraviolet radiation has wavelengths that are shorter than 0.4 μm (400 nm). The primary protein scatterers in skin are keratins and melanins in the epidermis, and collagen and elastin fibers in the dermis. Melanins are particularly good scatterers since they have very high refractive indices and are contained within *melanosome* particles of dimensions varying within the range 0.1 μm – 1 μm (100 nm – 1000 nm) (9 & 14).

Absorbers in skin

Considering the spectral regions UVB (280-320 nm), UVA (320-400 nm) and visible light (400-700 nm), skin has three primary absorbers: Blood (15), melanosomes (16), and keratin (17).

Blood

Since the blood vessels and capillaries are found only below the epidermis in which many of the primary optically induced processes related to human health occur, *i.e.* skin cancer induction and pre-vitamin D₃ photoproduction, the absorption of blood will not be described in detail here. It is, however, important to mention that even though the blood is found beneath the epidermal layers, the amount of blood does affect the amount of UV and visible light that reach these layers. This behavior can be intuitively understood by again considering the scattering of photons in the skin as the balls in a pinball machine; several of the photons that reach the dermis are scattered back into the epidermis from below and can reach targets such as DNA molecules when entering the epidermis a

second or third time. Therefore, if the absorption in the dermis is increased, *e.g.* due to a sun induced increase in the blood content, *erythema*, DNA in the overlaying epidermis is given a slight protection from below, even though the initial UV radiation comes from above.

The main blood absorption bands can be seen in Fig. 2 between the wavelengths 400- and 425 nm (violet light) and the wavelengths 500 and 600 nm (green light). At wavelengths longer than 600 nm (red and near infrared light) the blood absorption is very low. This wavelength dependence of the absorption is the reason for the red color of blood.

Melanin

In Figs. 2 and 3 simulated reflectance and transmittance spectra are shown. These simulations are in good agreement with measured spectra (18-20). As can be seen in Fig. 2 the melanosome concentration affects the skin reflectance strongly at all wavelengths from 300-700 nm, but less at the shortest UVB wavelengths (280-300 nm). If the relative spectral dependence of light absorption, *the apparent absorbance*, of the melanosomes is studied, a maximum will be found at approximately 450 nm (21). This dependence does not, however, imply that the absorption of the melanosomes is highest in this wavelength region. In fact the absorption increases steadily with decreasing wavelength into both the UVA and UVB spectral regions.

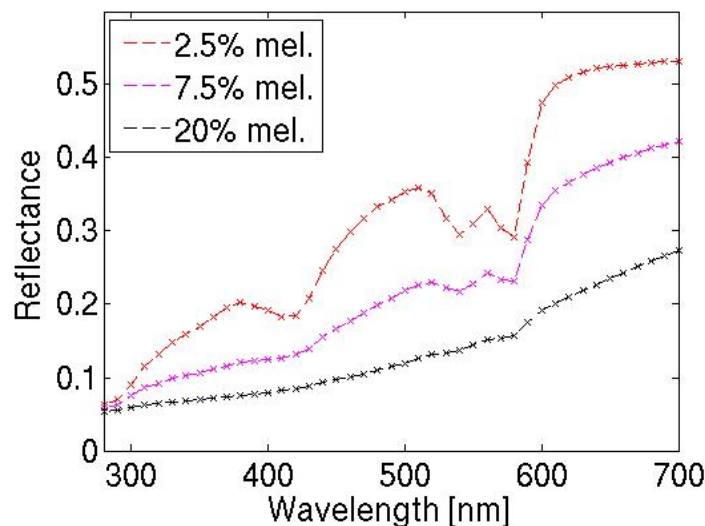


Figure 2. Skin reflectance in the wavelength regions of UVB (280-320 nm), UVA (320-400 nm) and visible (400-700 nm) for three different concentrations of melanosomes in the epidermis corresponding to skin types II, III and IV, respectively.

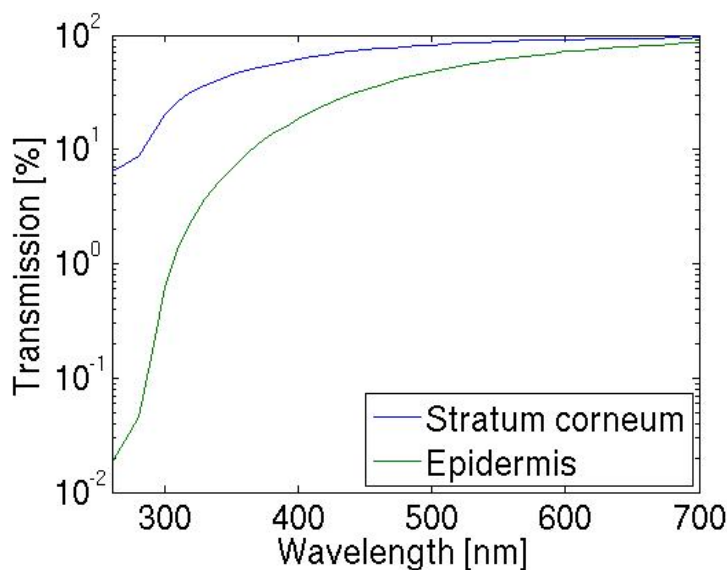


Figure 3. Transmittance of the stratum corneum (upper curve) and of the entire epidermis (lower curve) in the wavelength regions UVB, UVA and visible light for a volume concentration of 15% melanosomes in the epidermis corresponding to skin type III or IV.

The explanation for this seeming discrepancy is that the apparent absorbance of melanin depends on the relative difference between the optical properties of melanin and its surroundings, rather than the absolute absorption of the melanin itself. Therefore, one should be careful interpreting *in vivo* measurements of the apparent absorption.

It might seem surprising that the effects of increasing the melanosome concentration in the skin are relatively small at wavelengths shorter than 300 nm, in view of the fact that the melanosome absorption at these short wavelengths is higher than those at longer wavelengths. The reason is that the absorption by proteins (mainly keratin) in the epidermis surrounding the melanosomes increases relatively more strongly with decreasing wavelength into the UV spectral region than the absorption by the melanosomes. In fact, if the melanosomes in the most superficial layers of the epidermis have optimal sizes for scattering UVB radiation, increasing the melanosome concentration might even *increase* the skin reflectance at wavelengths shorter than 300 nm, as we have described previously (9).

Figure 3 shows the transmittance of the skin in the ultraviolet and visible spectral range for a person with skin type III or IV. As can be seen, the transmittance is high in the visible spectral region (20%-90%), decreases through the UVA spectral region from 20% to 2%, and decreases further in the UVB spectral region from 2% to 0.2%.

Keratin

Keratin is what nails, hairs and horns are made of. It is also a main component of the epidermis and, in particular, of the stratum corneum. In Fig. 4 an apparent absorbance spectrum of keratin is shown. This spectrum is calculated as

$$A_\lambda \equiv \log_{10} \left(\frac{I}{I_0} \right), \quad (1)$$

where I/I_0 is the relative change in reflectance due a given change in a particular absorber. As it can be seen, keratin almost exclusively absorbs UV radiation with a maximum at approximately 280 nm. When the skin is damaged by exposure to UV radiation the keratin-rich cells in the epidermis proliferate in order to repair the damage (22). This production of keratin-rich cells leads to a thickening of the epidermis and the stratum corneum in the days following the damage. UV light absorption by the keratin gives some protection against further damage by UV radiation. Miescher (22) found that a thickening of 8-9 μm of the stratum corneum halves the light sensitivity of the skin.

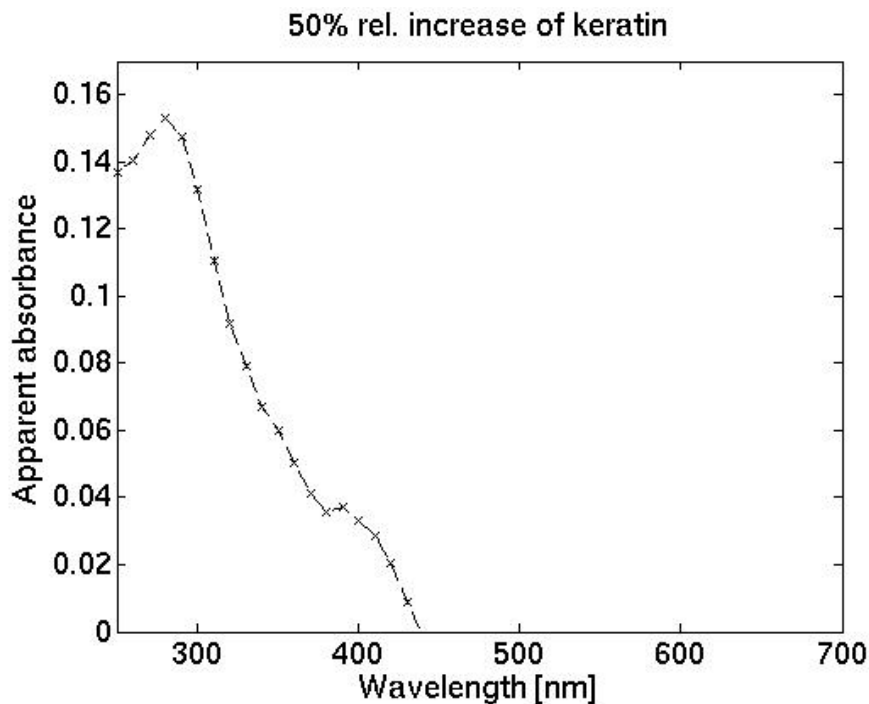


Figure 4. The apparent absorbance of a 50% relative increase of epidermal keratin in the wavelength regions UVB (280-320 nm), UVA (320-400 nm) and visible (400-700 nm).

The efficiency rate of photobiological processes

The efficiency rate of a particular photobiological process, x , at a specific wavelength, λ , and depth, z , can be defined as $d^2E_{x,\lambda} = F(\lambda,z) \phi_x(\lambda)d\lambda dz$, where $\phi_x(\lambda)$ is the action spectrum of the photobiological process of interest, and $F(\lambda,z)$ is the irradiance at a particular wavelength in the skin, as calculated with the CAT-DISORT model. The action spectra of previtamin D₃ photoproduction and photocarcinogenesis can be found in the literature (*e.g.* 23 & 24). The spectrum as a function of depth ($F(\lambda,z)$) depends on the spectrum of the light source and the optical properties of the skin layers. As mentioned above, the primary constituents influencing skin optics are melanin, keratin and blood. For the epidermis, melanin and keratin are particularly important. Even changing the depth distribution of melanin within the epidermis, *without changing the average melanin concentration*, has a large impact on the photobiological processes, as we have shown (12).

Optical diagnosis

Recently, we have updated the CAT-DISORT model (*submitted to J Photochem Photobiol*), so that it is possible, not only to calculate the light distribution as a function of depth and wavelength given concentrations of absorbers in the skin, but also to infer the concentrations of the absorbers from a set of multispectral images of skin. More interestingly, such inference can be done for suspicious pigmented skin lesions, and may upon further development become a valuable tool for dermatologists in their evaluation of irregular pigmented lesions suspected of being malignant melanomas.

Fig. 5 illustrates how an optical analysis may be helpful for a dermatologist. The upper part of the figure is a color image of a suspicious lesion, as it would look in a regular dermatoscope (a custom made magnifying glass for dermatologists). In such an image qualitative dark brown and black features may be recognized. In the lower part of the figure a pseudocolor calculated image of the same lesion is shown. This inferred image gives a *quantitative* measure of the upper epidermal thickness. The internal features of the inferred image are clearly enhanced compared with the regular color image.

Discussion

Little attention has been paid to the dynamic effects caused by exposure to UV radiation and the UV protection that these dynamic effects gives. A few groups

are investigating the effects of melanin proliferation in the epidermis on photobiological processes (11, 12 & 25), but with regards to the dynamic effects related to keratin proliferation we are not aware of any recent works.

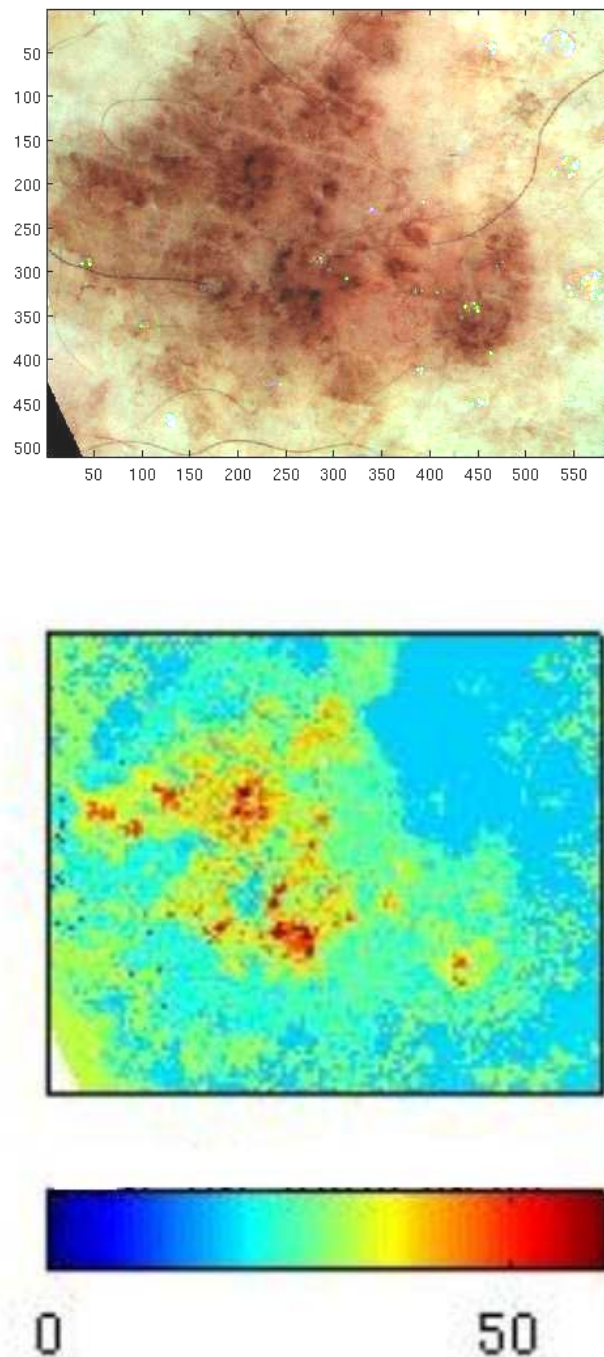


Figure 5. Upper: A standard color image of an irregular pigmented lesion. Lower: A pseudocolor image showing the inferred upper epidermal thickness for the same lesion. The pseudocolor scale in the lower figure goes from 0 μm (dark blue) to 60 μm (dark red).

In advertisements on television and in magazines we are constantly reminded of the cosmetic importance of removing dead skin cells, *i.e.* the stratum corneum, and shaving unwanted body hair, which also thins the stratum corneum. Given the protective importance of keratin in the stratum corneum, it seems likely that the current prevalence of melanoma on the legs of women (3 & 6) may be related to the modern fashion of removing leg hairs. This gives reason for concern, since it has become fashionable in the last few years for both genders in the western world to remove substantial amounts of body hair.

Another, and more complicated, issue concerns the long-term impact of UV exposure on skin optical properties. It is common knowledge that outdoor workers have thicker skin than indoor workers, and this enhanced skin thickness is likely to be the reason for the unexpectedly low melanoma incidence among outdoor workers. Oppositely, it could be that children who are kept protected against sunlight whenever they are outdoors will develop thinner epidermal layers than other children and thus be more vulnerable to extreme overexposures when they occasionally forget to use sunscreen. These are issues that should be investigated further.

Concluding remarks

- It is feasible to apply RT modeling to skin in the UV spectral range for applications related to human health. Such modeling is likely to become tool that will improve our understanding of photobiological processes and skin diseases in the coming years.
- There is large variability of the natural epidermal absorbers, both with regards to amount and distribution. This variability also occurs due to dynamic feedback mechanisms, for instance thickening of the keratin-rich stratum corneum, and increase of blood content below the epidermis.
- Photobiological processes in the skin are closely related to skin optics.
- Dynamic feedback mechanisms of the skin absorbers seem to be important.
- Too little regular sun exposure may weaken the natural defence of the skin against the damaging effects of extreme sun exposures.

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