Skin Optics

Oregon Medical Laser Center News
Jan 1998. Steven L. Jacques

In response to requests for a summary of skin optical properties, this article presents how to choose the approximate optical coefficients for absorption and reduced scattering of skin with variable amounts of melanin and blood perfusion. It is merely an approximation and a starting point for describing the skin optics of any particular individual.

1. Epidermis

The total optical **absorption coefficient (mua.epi)** of the epidermis depends on a minor baseline skin absorption and a dominant melanin absorption due to the melanosomes in the epidermis. The independent parameters of **wavelength (nm)** and **volume fraction of melanosomes (f.mel)** can specify mua.epi in units of cm^{-1}.

1.1 Baseline absorption coefficient of melaninless epidermis, mua.skinbaseline

It has been difficult to accurately distinguish the baseline absorption coefficient values associated with melaninless epidermis and bloodless dermis. So the baseline absorption of both epidermis and dermis are approximated by the following mua.skinbaseline, expressed as a function of wavelength (nm):

$$mua.skinbaseline = 0.244 + 85.3exp(-(nm - 154)/66.2) \quad [cm^{-1}]$$

The above expression is based on measurements of bloodless rat skin using an integrating sphere calibrated with careful phantom measurements (Ruiping Huang, S. Jacques, unpublished data). Iyad Saidi generated data (450-750 nm) for in vitro neonatal skin samples using an integrating sphere after accounting for excess absorption due to residual hemoglobin and bilirubin in the samples [Ref: Saidi thesis (1994)]. Those data are approximated by the expression:

$$mua.skinbaseline = (7.84x10^8)(nm^{-3.255}) \quad [cm^{-1}]$$

The Saidi data for neonatal skin is only a little higher in absorption than Huang's rat data. Optically, rat skin and neonatal skin are quite similar. The Huang data was based on a more careful calibration of the integrating sphere apparatus and is consistent with the rather low absorption found by many for bloodless tissues, and extends from 350-1100 nm. We use the rat skin data as a first approximation for mua.skinbaseline.

1.2 Absorption coefficient of a single melanosome, mua.mel

The absorption of epidermis is usually dominated by melanin absorption in most individuals. Melanin is a polymer built by condensation of tyrosine molecules and has a broad absorption spectrum exhibiting stronger absorption at shorter wavelengths. Melanin is found in the melanosome, a 1-2 um diameter membranous particle whose internal membranes are studded with many melanin granules about 10 nm in size at sites of melanin synthesis. On average, the interior of a melanosome has an absorption coefficient, **mua.mel**, whose magnitude and dependence on wavelength (nm) is approximated:

$$mua.mel = (6.6 \times 10^{11})(nm^{-3.33}) \quad [cm^{-1}]$$

For example,

Ruby laser	(694 nm)	mua.mel = 230cm^{-1}
Alexandrite laser	(755 nm)	mua.mel = 170cm^{-1}
Nd:YAG laser	(1064 nm)	mua.mel = 55cm^{-1}

This expression is based on various published studies of the threshold exposure for explosive vaporization of melanosomes by pulsed lasers at various wavelengths [Ref: Jacques, McAuliffe: Photochem Photobiol (1991)]. There is considerable variation in the melanin content of melanosomes so the above expression is only an approximation, but gives the general magnitude and wavelength dependence of mua.mel.

1.3 Volume fraction of melanosomes in epidermis

The next question is "How many melanosomes per unit volume are in the epidermis?" The estimated concentration ranges are expressed as the volume fraction of the epidermis occupied by melanosomes (f.mel) [Ref:Jacques (1996)]:

light-skinned adults	f.mel = 1.3-6.3%
moderately pigmented adults	f.mel = 11-16%
darkly pigmented adults	f.mel = 18-43%

The above estimates are based on the wavelength dependence of the optical density of epidermal melanin in the **650-800 nm** range as specified by skin reflectance measurements on normal vs melaninless vitiligo skin sites and assuming a **60-um epidermal thickness** and that total photon path in the epidermis is twice the epidermal thickness [Ref: Jacques (1995)]. Obviously, this is only an approximation and hence a **descriptive convention** rather than an accurate specification. If one wishes to specify the optical absorption of a particular skin site on a particular individual, one can make a reflectance measurement from that site., but the analysis goes beyond the goal of this article ...maybe later :-).

1.4 Net epidermal absorption coefficient, mua.epi

The **net epidermal absorption coefficient**, mua.epi, combines the baseline skin absorption and the melanin absorption and is calculated:

```
mua.epi  =  (f.mel)(mua.mel)  +  (1 - f.mel)(mua.skinbaseline)
```

For example, a moderately pigmented adult with a 10% volume fraction of melanosomes will have absorption coefficients as listed below and shown in Figure 1:

	mua.skinbaseline	mua.mel	mua.epi
[nm]	[cm^{-1}]	[cm^{-1}]	[cm^{-1}]
694	0.268	228	23
755	0.254	172	17
1064	0.244	55	5.7

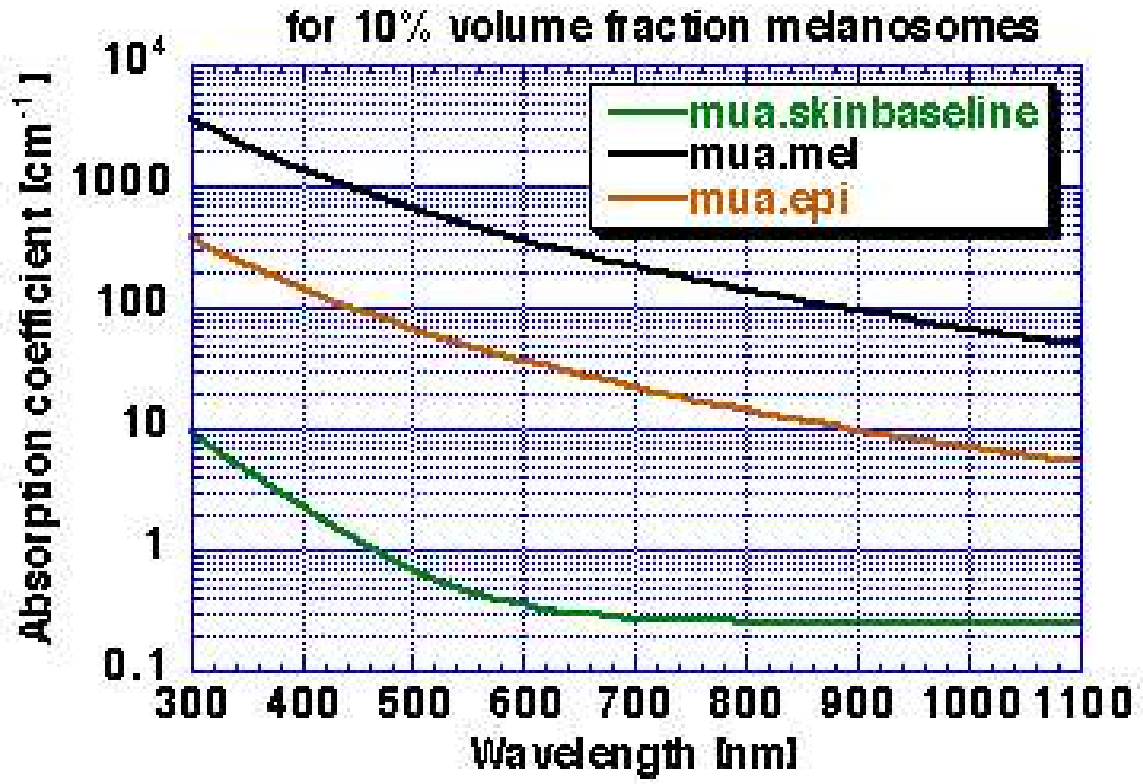

Figure 1: Absorption coefficient of epidermis with f.mel = 10%

1.5 Scattering coefficient of the epidermis.

First, consider the scattering coefficient of the epidermis, **mus.epi**. Although there is surely some difference between mus.epi and the scattering coefficient of the dermis, **mus.derm**, the differences are not large. Moreover, the thinness of the epidermis makes the details of mus.epi of minor importance for visible and near-infrared applications involving photon diffusion. Of course, subtle difference in mus.derm are important for devices and techniques which primarily depend on photon interaction with the epidermis such as measurements based on single scattering from the epidermis like elastic backscatter, coherence backscatter, or polarized backscatter.

The second major scattering property of a tissue is its anisotropy, g, which is defined as the mean cosine of the deflection angle due to a scattering event. Typical values of g are in the range of 0.7-0.95 for skin tissue, and vary with wavelength. However, for the common case of photon diffusion which involves many scattering events, the details of mus.epi and g.epi become less important than the lumped parameter musp.epi, called the **reduced scattering coefficient**:

```
musp.epi  =  (mus.epi)(1 - g.epi)
```

This article will only discuss musp.epi and musp.derm.

In summary, musp.epi = musp.derm to first approximation. See section 2.4 below for discussion of musp.derm.

2.Dermis

The total optical **absorption coefficient (mua.derm)** of the dermis depends on a minor baseline skin absorption and a dominant hemoglogin absorption due to the cutaneous blood perfusion. The independent parameters of **wavelength (nm)** and **volume fraction of blood (f.blood)** can specify an **average mua.derm** in units of cm^{-1}. Such an average mua.derm neglects the depth dependence

of the blood which affects the optics. Remember that yellow light penetrates skin more readily than purple and hence different wavelengths sample blood at different depths with different efficiencies. A more careful description will specify a depth profile for blood in the dermis.

2.1 Baseline absorption coefficient of bloodless dermis, mua.skinbaseline

As discussed in section 1.1, the baseline absorption of epidermis and dermis are sufficiently similar that we can treat them both by the parameter **mua.skinbaseline**.

2.2 Absorption coefficient of whole blood, mua.blood

The dominant absorber in the dermis is the hemoglobin of the cutaneous blood. Figure 2 shows the **absorption coefficient of whole blood, mua.blood**, defined as a having a **45% hematocrit**:

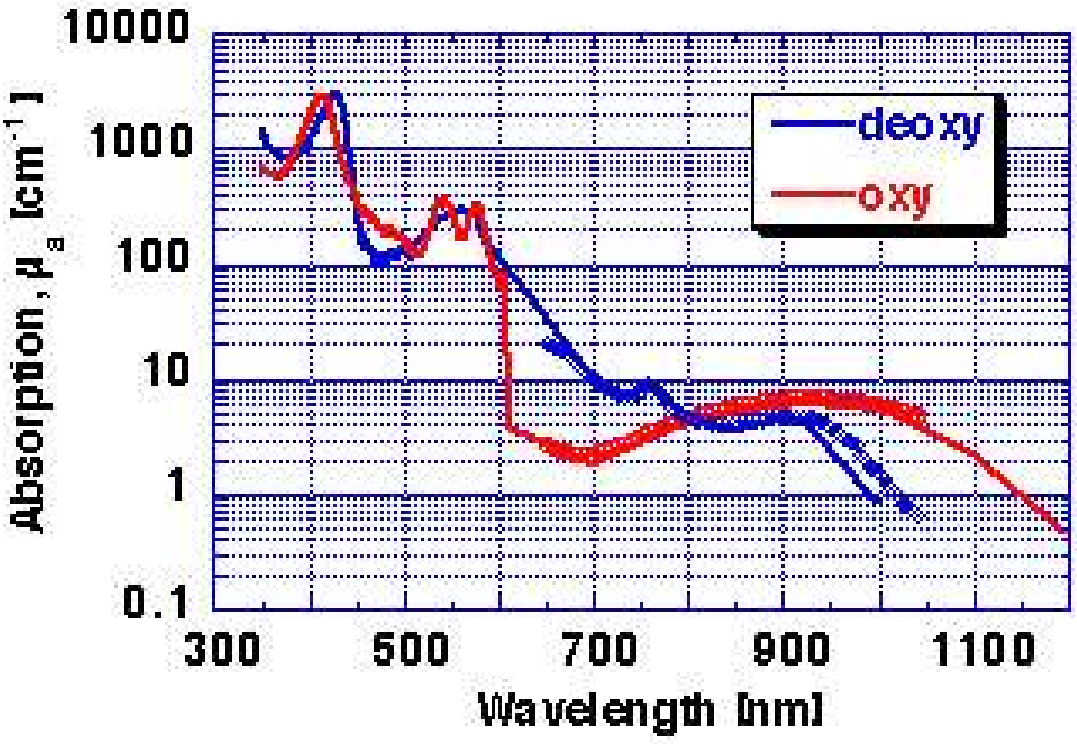

Figure 2: Absorption coefficient of whole blood (45% hematocrit).
RED = oxy-hemoglobin, BLUE = deoxy-hemoglobin.
My apologies for poor data in 600-650 nm range. Lost some data files :-(, but will repair.
Data as symbols in 650-1042 nm range is data of Wray et al. 1998 scaled to match the whole blood data in units of cm^{-1}.

2.3 Absorption coefficient of dermis perfused with blood, mua.derm

The next question is "How much blood is in the skin?" One can adopt a descriptive convention and specify the **average volume fraction of blood**, f.blood, assuming that the blood is uniformly distributed in the skin. A typical value for this average f.blood is 0.2%. But in reality the cutaneous blood content is concentrated in a venous plexus about 100-200 um from the surface and the volume fraction in this region is likely to be about 2-5%, which is a common blood volume fraction in other well-perfused tissues. In other parts of the dermis, the local f.blood is much lower. On average, however, to an external observer a homogeneous blood distribution with a low f.blood and a heterogeneous distribution with a superficially localized high f.blood appear roughly equivalent.

Following the descriptive convention of describing an equivalent average homogeneous f.blood, the **net absorption of the dermis**, mua.derm, is calculated:

```
mua.derm  =  (f.blood)(mua.blood) + (1-f.blood)(mua.skinbaseline)
```

2.4 Scattering coefficient of dermis

The reduced scattering of dermis, musp.derm, combines the contributions due to **Mie scattering** by the large cylindrical dermal collagen fibers and the **Rayleigh limit scattering** by the small-scale structure associated with the collagen fibers and other cellular structures. The combination yields the observed scattering properties of dermis. Using Mie theory, one can calculate the scattering coefficient, mus.derm, and the anisotropy, g.derm, then calculate the musp.derm.

The epidermis with its keratin fibers appears to behave somewhat like dermis, and musp.epi is tentatively approximated by the musp.derm.

A histological study of collagen fibers was made on 9 post-mortem neonatal skin samples [Ref: Saidi (1995)]. Collagen fibers were about 2.8±0.8 um in diameter on average with a number density of about 3.0±0.5 x 10^6 [cm^2] per cm length of fibers or 3 x 10^6 [cm^3] per unit volume. The volume fraction of dermis filled by collagen fibers was 0.21±0.10. Adult collagen fibers are on the higher end of this range, and the subsequent fitting matches adult dermal scattering data [Ref: Jacques (1991)]. Using the cylindrical Mie theory outlined in Bohren and Huffman and the number density and average size of collagen fibers in skin, the GREEN line in Fig. 4 was calculated which shows the contribution due to Mie scattering by collagen fibers [Ref: Jacques (1996)]. This Mie scattering behavior can be mimicked by the expression:

$$musp\_Mie.fibers(nm) = (2x10^5)(nm^{-1.5})\ [cm^{-1}]$$

Dermis also exhibits a nm^(-4) type of scattering in the Rayleigh limit of Mie scattering by small-scale structures much smaller than the wavelengths of UVA-Vis-NIR light. Collagen fibers show a small-scale structure on the order of 70 nm observered in electron micrographs of collagen fibers as striations. The staining pattern of an electron micrograph should not be over interpreted as the pattern of refractive index mismatch which yields light scattering. However, just as a working hypothesis, consider that a population of light-scattering structures comprising the collagen fiber volume fraction can be approximated by 100-nm diameter spheres which are responsible for the Rayleigh scattering. Using a volume fraction of 22% collagen, one can estimate a number density of equivalent 100-nm spheres comprising the collagen fibers. Assume these structures have a refractive index mismatch of 1.5/1.33 for protein/water. Given the number density, size, and refractive mismatch, one can use Mie theory for spheres to predict the contribution to musp.derm from this small-scale structure. Since 100-nm structures are so small, the Mie Theory treament behaves as the Rayleigh limit exhibiting the well-known nm^-(4) behavior. This prediction yields the BLUE line of Fig. 4 [Ref: Jacques (1996)]. There is certainly room for a more careful characterization of such postulated small-scale scattering. However, the above crude approximate estimate matches the magnitude and wavelength dependence of the Rayleigh scattering component observed in dermis:

$$musp\_Rayleigh(nm) = (2x10^{12})(nm^{-4})\ [cm^{-1}]$$

Combining the GREEN (Mie) and BLUE (Rayleigh) lines of Fig. 4 yields the dashed BLACK line which matches the observed RED data for dermis.

```
musp(nm)  =  musp_Rayleigh(nm)  +  musp_Mie.fibers(nm)
```

Hence, the scattering behavior of dermis is accounted for by the combination of Mie and Rayleigh scattering primarily from collagen fibers. The scattering behavior is dominated by Rayleigh

scattering from small-scale structure at short wavelengths below 650 nm and is dominated by Mie scattering from fibers at longer wavelengths above 650 nm, approximately. But the visible to near-infrared spectral region is significantly affected by both types of scattering.

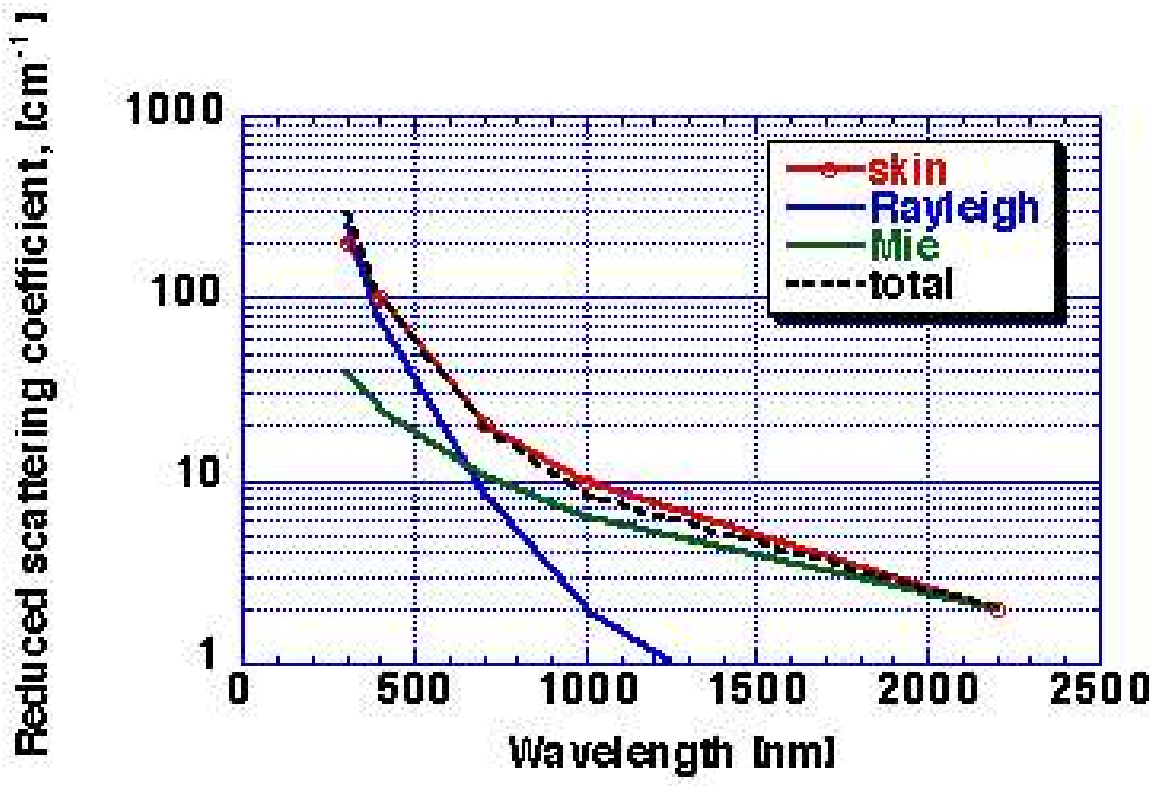

Figure 4: Reduced scattering coefficient, musp.derm, of dermis. RED = tissue data, GREEN = Mie Theory based on collagen cylinders. BLUE = Rayleigh limit scattering due to small-scale structure of collagen fibers. BLACK DASHED LINE = Mie + Rayleigh, which matches tissue data.

3. Conclusion

The optical properties of skin are understandable. The **absorption** is described in terms of **melanin and hemoglobin** absorption proportional to the **volume fractions of melanosomes and whole blood**, with a **slight baseline skin absorption**. The dermal **scattering** is described in terms of the relative contributions of **Mie and Rayleigh scattering due to collagen fibers**. The epidermal scattering, which is affected by its keratin fibers, is sufficiently close to that of dermis and sufficiently thin to not be critical, that dermal scattering can be used to describe skin scattering in general when discussing processes or devices which rely on photon diffusion.

Finally, adult skin optics are quite variable in the scattering properties, the degree of melanin pigmentation, and the amount and distribution of blood perfusion. This article has outlined only an average skin's optical properties. Individual skin sites require individual characterization.

[January Front Page]
[Newsletter Contents Page]