Tissue optical properties

Biomedical Optics

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Optical properties vs Optical measurements

- refractive index \( n \)
- absorption \( \mu_a \)
- scattering \( \mu_s \)
- anisotropy \( g \)
- reduced scattering \( \mu_s(1-g) \)
- transmission \( T \)
- reflectance \( R \)

Optical Properties of Tissue

- Absorption cross section
- Absorption coefficient
- Scattering cross section
- Scattering coefficient
- Phase function
- Scattering –anisotropy
- Reduced scattering coefficient
- (Reduced) albedo

The refractive index \( n \)

- Wave fronts from a point source in the context of Snell's law. The region below the gray line has a higher index of refraction and proportionally lower wave velocity than the region above it.
The refractive index $n$

- The dimensionless quantity $n(\omega)$, index of refraction, is the ratio of the speed of the light in vacuum to the speed of the wave in the material.

$$n(\omega) = \sqrt{\varepsilon_r \mu_r} = \sqrt{1 + \chi(\omega)}$$ if absorption negligible

$$k = \frac{\omega}{c} n(\omega) = \frac{\omega}{c} \sqrt{1 + \chi(\omega)}$$

$$v = \left( \frac{c}{n(\omega)} \right)$$

$N = (n+ix)$ if absorption plays a roll

$$k = \frac{(n+ix)\omega}{c}$$

$$\mu_r(\lambda) = \frac{4\pi k(\lambda)}{\lambda}$$

Absorption, Fluorescence and Scattering

- Absorption
- Scattering
- Intrinsic Fluorescence

Light Transport Model

Reflectance

Fluorescence

Refractive index

$$\tilde{n}(\lambda) = n(\lambda) - i\alpha(\lambda)$$

$$\text{Re}[\tilde{n}(\lambda)] = n(\lambda)$$

$$c_m(\lambda) = \frac{c}{n(\lambda)}$$

$$\lambda_m = \frac{\lambda}{n(\lambda)}$$

$$f = \frac{c}{\lambda} = \frac{c_m}{\lambda_m}$$

Absorption, Fluorescence and Scattering

- Absorption
- Fluorescence
- Scattering

Beer's Law

Mie Theory

Concentrations

Scatterer size, density
Refractive index, etc
Energy Levels

Jablonski diagram

Energy levels are characteristic states of a molecule

- *Translational* - motion of the molecule’s center of mass through space
- *Spin* - nuclear and electron spin
- *Rotational* - rotation of the molecule about its center of mass
- *Vibrational* - vibration of the molecule's constituent atoms
- *Electronic* - interactions of the electrons and nuclei within a molecule

Energy Level example

<table>
<thead>
<tr>
<th>Energy</th>
<th>Energy Level Separation (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translation</td>
<td>Very small</td>
</tr>
<tr>
<td>Spin</td>
<td>$10^{-32}$</td>
</tr>
<tr>
<td>Rotation</td>
<td>$10^{-28}$</td>
</tr>
<tr>
<td>Vibration</td>
<td>$10^{-25}$</td>
</tr>
<tr>
<td>Electronic</td>
<td>$10^{-19}$</td>
</tr>
</tbody>
</table>

- When a 514 nm photon from an argon ion laser is absorbed by a hemoglobin molecule it will transfer its energy to the hemoglobin molecule:
  $$\frac{hc}{\lambda} = \frac{6.62618 \cdot 10^{-34} \cdot 3.0 \cdot 10^8}{514 \cdot 10^{-9}} = 3.86 \cdot 10^{-19}$$

- The photon is absorbed by the heme chromophore within the hemoglobin protein. The heme chromophore is roughly 1 nm in size.

- After the heme chromophore absorbs one photon, the jump in energy density is roughly the photon energy divided by a nm$^3$ volume:
  $$\frac{3.86 \cdot 10^{-19}}{10^{-7}} = 387 \left[ J / cm^3 \right]$$

- The energy density of boiling water is 418 [J/cm$^3$]
Mechanism of light absorption

**Electronic transitions**

1. Inter-nuclear distance is greater in the excited state than in the ground state.
2. Franck-Condon principle: electronic transition is much faster than rearrangement of nuclei to the distance between nuclei is not able to change during electronic transition. 

Vertical transition results in occupation of higher vibrational energy levels → Vibrational energy dissipates producing heat → Light absorption is always accompanied by sample heating.

**Consequences:**

\[
\Delta E = \frac{me^4}{8\varepsilon_0 \hbar^2} \left( \frac{1}{n_1^2} - \frac{1}{n_2^2} \right)
\]

Biologically: typically UV or blue

**Vibrational transitions**

The transition is the movement of an electron from a lower to a higher energy level. This results in the absorption of a photon. The energy of the photon is equal to the difference in energy between the two states. The equation for the energy of a photon is:

\[
\Delta E = h \nu = h \frac{c}{\lambda}
\]

where \( h \) is Planck's constant, \( \nu \) is the frequency of the photon, and \( \lambda \) is the wavelength of the photon.

**Representative values:**

- Representative values: 
  - \( \nu \approx 3 \times 10^{14} \text{ Hz} \) for visible light 
  - \( \lambda \approx 5 \text{ mm} \) for radio waves 

**Rotational transitions**

The transition is the movement of an electron from a lower to a higher energy level. This results in the absorption of a photon. The energy of the photon is equal to the difference in energy between the two states. The equation for the energy of a photon is:

\[
\Delta E = \frac{\hbar^2 J^2}{2 I B}
\]

where \( \hbar \) is Planck's constant, \( J \) is the angular momentum, and \( I \) is the moment of inertia.

**Representative values:**

- Representative values: 
  - \( I = 6 \text{ amu} \) for a carbon nucleus 
  - \( r = 1 \text{ Å} \) for a carbon nucleus 

- \( \lambda_{0.1} \approx 0.5 \text{ mm} \) for microwave regime
Absorption

Extraction of energy from light by a molecular species

- Diagnostic applications: Transitions between two energy levels of a molecule that are well defined at specific wavelengths could serve as spectral fingerprint of the molecule
  - Various types of Chromophores (light absorbers) in Tissue
  - Wavelength-dependent absorption
  - Tumor detection and other physiological assessments (e.g. pulseoximetry)
- Therapeutic applications: Absorption of energy is the primary mechanism that allows light from a source (laser) to produce physical effects on tissue for treatment purpose

Absorption

- Absorption occurs when the photon frequency matches the “frequency” associated with the molecule’s energy transition
  - Electrons absorb the energy of the light and transform it into vibrational motion
  - The absorption of a photon results in:
    - quantized change in charge separation
    - quantized excitation of vibrational modes
  - Electrons interact with neighboring atoms => convert vibrational energy into thermal energy

Absorption

- Absorption is the annihilation of photonic energy while interacting with
  - electrons,
  - atoms, or
  - molecules and the conversion into
    - heat or into
    - photons with a much lower frequency, e.g.,
      - fluorescence or
      - phosphorene

Absorption

In biomedical optics, absorption of photons is a most important event:

- Absorption is the primary event that allows a laser or other light source to cause a potentially therapeutic (or damaging) effect on a tissue.
  - Without absorption, there is no energy transfer to the tissue and the tissue is left unaffected by the light.
- Absorption of light provides a diagnostic role such as the spectroscopy of a tissue.
  - Absorption can provide a clue as to the chemical composition of a tissue, and serve as a mechanism of optical contrast during imaging.
Chromophores

- Molecules that absorb light are called chromophores.

- There are two major types of absorption processes:
  - vibrational transitions
  - electronic transitions

Vibrational transition

<table>
<thead>
<tr>
<th>Bond</th>
<th>Cycles/cm $\nu$</th>
<th>Wavelength, 1/$\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-H stretch</td>
<td>2850-2960</td>
<td>3.378-3.509</td>
</tr>
<tr>
<td>C-C stretch, bend</td>
<td>700-1250</td>
<td>8.000-14.29</td>
</tr>
<tr>
<td>C=C stretch</td>
<td>1620-1680</td>
<td>5.952-6.173</td>
</tr>
<tr>
<td>C-C stretch</td>
<td>2100-2260</td>
<td>4.425-4.762</td>
</tr>
<tr>
<td>CO$_2^+$</td>
<td>1410-1450</td>
<td>6.897-7.092</td>
</tr>
<tr>
<td>NO$_2^+$</td>
<td>1350-1420</td>
<td>7.042-7.407</td>
</tr>
<tr>
<td>NO$_2^+$</td>
<td>1230-1250</td>
<td>8.000-8.130</td>
</tr>
<tr>
<td>SO$_2^+$</td>
<td>1080-1330</td>
<td>8.850-9.259</td>
</tr>
<tr>
<td>O-H stretch</td>
<td>3590-3650</td>
<td>2.740-2.786</td>
</tr>
<tr>
<td>C=O stretch</td>
<td>1640-1780</td>
<td>5.618-6.098</td>
</tr>
<tr>
<td>N-H</td>
<td>3200-3600</td>
<td>2.857-3.125</td>
</tr>
</tbody>
</table>

Absorption spectrum of water
Absorption

Biological chromophores
1. The peptide bonds and amino acids in proteins
2. Purine and pyrimidine bases in nucleic acids and their derivatives
3. Highly conjugated double bond systems

Biological Chromophores

Highly conjugated double bond systems
- Spectrum is often in the visible region
- Metal porphyrin ring system is mainly responsible for the color in heme proteins
- The most intense band is called the Soret band after its discoverer

<table>
<thead>
<tr>
<th>Molecule</th>
<th>λ (nm)</th>
<th>ε (x10^-3) (cm².mol⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tryptophan</td>
<td>280, 219</td>
<td>5.6,47</td>
</tr>
<tr>
<td>Tyrosine</td>
<td>274,222,193</td>
<td>1.4,8,48</td>
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<tr>
<td>Phenylalanine</td>
<td>257,206,188</td>
<td>0.2,9,3,60</td>
</tr>
<tr>
<td>Histidine</td>
<td>211</td>
<td>5.9</td>
</tr>
<tr>
<td>Cystine</td>
<td>250</td>
<td>0.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Molecule</th>
<th>λ (nm)</th>
<th>ε (x10^-3) (cm².mol⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adenine</td>
<td>260.5</td>
<td>13.4</td>
</tr>
<tr>
<td>Adenosine</td>
<td>259.5</td>
<td>14.9</td>
</tr>
<tr>
<td>NADH</td>
<td>340,259</td>
<td>6.23, 14.4</td>
</tr>
<tr>
<td>NAD+</td>
<td>260</td>
<td>5.9, 18</td>
</tr>
</tbody>
</table>
Electronic transition

- pyroles
- porphyrins
- heme
- chlorophyll
- cytochromes
- phycobiliproteins
- carotenoids
- ferredoxins
- flavins
- melanin

Porphydrin

Lipids

Absorption coefficient $[m^{-1}]$

Heam B
**Hemoglobin**

Mean free absorption pathlength = 500 mm

Ref. Mycek and Pogue, *Handbook of Biomedical Fluorescence*


**Fluorescence Spectroscopy**

Major biological fluorophores:
- structural proteins: collagen and elastin crosslinks
- coenzymes for cellular energy metabolism (electron acceptors):
  - flavin adenine dinucleotide (FAD)
  - nicotinamide adenine dinucleotide, reduced form (NADH)
- aromatic amino acids: side groups on proteins
- porphyrins: precursors to heme

**A fluorescence scenario**

Healthy → Trending Towards Cancer:
- increased FAD fluorescence
- reduced collagen fluorescence (farther from surface)
- polyp formation → neovascularure; increased absorption & decreased fluorescence

Ref. Mycek and Pogue, *Handbook of Biomedical Fluorescence*

courtesy M. A. Mycek
How to talk about absorption

Absorption - Beer-Lambert law

- The decline of irradiance of the amount $dI_0$ of EM radiation is proportional to the incident quantity $I_0$ and the distance $dl$
  - $I_0$ at $l$, $I_0(\lambda)$
  - Amount of absorption $(\alpha)$
  - Thickness layer $(dl)$

\[ \partial I = -I \cdot \alpha \cdot \partial l \]

\[ I_1 = I_0 e^{-\alpha l} \]

- Dimension of $\alpha$?
- $\alpha = \varepsilon c$

Absorption Coefficient

Beer’s law

- The transmitted intensity $(I)$ is defined as:

\[ I = I_0 10^{-\varepsilon c L} \]

Where,
- $\varepsilon$ is the molar extinction coefficient $(1/\text{mM.cm})$
- $C$ is the concentration (mM)
- $L$ is the path length (cm)
- $I_0$ is the initial intensity

Absorption

- Assumptions
  - Cross section is independent of relative orientation of the impinging light and absorber uniform distribution of $N_a$ (molecules/cm$^3$) identical absorbing particles
  - Absorption Coefficient, $\mu_a$ [1/m]
    - $\mu_a = N_a \sigma_a$
    - Absorption cross-sectional area per unit volume of medium
  - Absorption mean free path, $l_a$ [m]
    - $l_a = \frac{1}{\mu_a}$
    - Represents the average distance a photon travels before being absorbed
Absorption Coefficient

Beer's law in exponential form

- The transmitted intensity \( I \) is defined as:

\[
I = I_o e^{-2.303 \varepsilon c L} = I_o e^{-\mu_a L}
\]

Where,

- \( \varepsilon \) is the molar extinction coefficient \((1/\text{mM.cm})\)
- \( C \) is the concentration \((\text{mM})\)
- \( L \) is the path length \( (\text{cm}) \)
- \( I_o \) is the initial intensity

Absorption Coefficient

The absorption coefficient

- The absorption coefficient \( \mu_a \) is defined as:

\[
\mu_a = 2.303 \varepsilon C
\]

Where,

- \( \varepsilon \) is the molar extinction coefficient \((1/\text{mM*cm})\)
- \( C \) is the concentration \((\text{mM})\)

Absorption

Modes of measurement

- Absorption (A) or optical density (O.D.)

\[
A = \log_{10} \left( \frac{I_o}{I} \right);
\]

- % Transmission (%T)

\[
\%T = \frac{I}{I_o}, \quad A = \log_{10} \left( \frac{1}{T} \right);
\]

Determining Concentrations (C)

\[
\log_{10} \frac{I_o}{I_f} = \varepsilon(\lambda)CL
\]

Path length, \( L \)
Absorption

Sample and reference measurements
- Use identical cuvettes in sample and reference arms and ensure that they have the same path length; cuvette should have low absorption in region of interest
- Fill the sample cuvette with the sample of interest
- Fill the reference cuvette with everything in the sample cuvette, except the absorber
- Run a wavelength scan of the sample

Absorbance

Optical density per unit length
\[ OD_\lambda = \frac{A_\lambda}{x} = \frac{1}{x} \log_{10} \left( \frac{1}{T} \right) = -\frac{1}{x} \log_{10} \left( \frac{I}{I_0} \right) \]

\[ OD_\lambda = A_\lambda = \log_{10} \left( \frac{1}{T} \right) = -\log_{10} \left( \frac{I}{I_0} \right) \]

\[ OD_\lambda = A_\lambda = \log_{10} (e) \mu_a x = \varepsilon c x \]

\( \varepsilon = \) extinction coefficient

[Diagram of absorption setup]

Absorption

[Diagram of absorption setup]

[Equations for absorbance and extinction coefficient]

\[ \sigma_a = \frac{P_{abs}}{I_0} \]
Absorption coefficient \( \mu_a \)

\[ \sigma_a = Q_a A \]  

\[ [cm^2] = [-][cm^2] \]

generates cross-sectional area

effective cross-sectional area

\[ \mu_a = \rho_a \sigma_a \]

density

\[ T = \exp[-\mu_a L] \]

L is a photon's path length of travel. The probability of survival (or transmission \( T \)) of the photon after a path length \( L \) is:

\[ T = \exp[-\mu_a L] \]

Related properties

- Attenuation coefficient is essentially (but not quite always) synonymous with absorption coefficient
- Molar absorption coefficient or Molar extinction coefficient, also called molar absorptivity, is the absorption coefficient divided by molarity (and usually multiplied by \( \ln(10) \), i.e. decadic)
- Mass attenuation coefficient, also called mass extinction coefficient, is the absorption coefficient divided by density
- Absorption cross section and scattering cross section are both quantitatively related to the absorption coefficient (or attenuation coefficient)
- The absorption coefficient is also sometimes called opacity
Bilirubin

- The structure of bilirubin.
  - The diameter is approximately 1nm

![Bilirubin molecule](image)

- the geometrical area is $A = 7.8 \times 10^{-15} \text{ cm}^2$.

Absorption

Wavelength dependence of absorption

- In the ultraviolet and blue, the absorption increases with shorter wavelengths due to protein, DNA and hemoglobin.

- In the red to near-infrared (NIR), hemoglobin is the primary absorber in tissue and the absorption coefficient is much lower than in the UV-VIS.

Bilirubin spectrum

- At 460 nm, the extinction coefficient of bilirubin is $\varepsilon = 53846 \text{ [cm}^{-1}\text{M}^{-1}]$
- If $C$ is concentration [M] and $L$ is path length [cm]. Therefore,
  - $\mu_a = \varepsilon C \ln(10)$
  - A typical jaundiced neonate might have a bilirubin concentration of 10 mg/dl, or $(0.100 \text{ g/liter})/(574.65 \text{ g/mole}) = 0.17 \times 10^{-3} \text{ M/L}$.
  - The bilirubin absorption coefficient at 460 nm is roughly
  - $\mu_a = \varepsilon C \ln(10) = (53846 \text{ [cm}^{-1}\text{M}^{-1}])(0.17 \times 10^{-3} \text{ M})(2.303)) = 21 \text{ cm}^{-1}$.

Example

- If the concentration $C$ is equivalent to $\rho_a = (0.17 \times 10^{-3} \text{ [moles/liter]}) \times (6 \times 10^{23} \text{ [mole}^{-1}] / (1000 \text{ cm}^3/\text{liter}) = 1.02 \times 10^{17} \text{ [cm}^{-3}]$
  - The efficiency of absorption is estimated: $Q_a = \mu_a/(\rho_a A) = (21 \text{ [cm}^{-1}] )/(1.02 \times 10^{17} \text{ [cm}^{-3}] )^{-1}(A = 7.8 \times 10^{-15} \text{[cm}^2])) = 0.026$
  - The effective cross-section is $\sigma_a = Q_a A = (0.026)(7.8 \times 10^{-15} \text{ [cm}^2]) = 2.1 \times 10^{-16} \text{ [cm}^2])$.
  - Bilirubin's effective cross-sectional diameter is 0.16 nm or 16% the size of its geometrical diameter.
Absorption

Concentration of molecules
- Absorption depends on the number of molecules in which transitions are induced.
- Absorption spectra can be used quantitatively
- The effect of sample concentration on the absorption is the basis of most analytical applications

Absorption Spectrum of Human Tissue

Typical tissue absorption!
- adipose tissue ~ 1% blood by volume
- blood = 45% red blood cells by volume
- red blood cell = 1/3 hemoglobin by weight
- Hemoglobin molecular weight = 65,000 mg/m mole
- Hb concentration = 23 mM

Absorption is Caused by Multiple Chromophores
Hemodynamics calculations

\[ \mu_a = \ln 10 \cdot \alpha \]

\[
\begin{bmatrix}
\mu_{a1} \\
\vdots \\
\mu_{a2}
\end{bmatrix}
= \ln 10 \cdot
\begin{bmatrix}
\varepsilon_1^{Hb} & \varepsilon_1^{HbO_2} \\
\varepsilon_2^{Hb} & \varepsilon_2^{HbO_2} \\
\vdots & \vdots
\end{bmatrix}
\begin{bmatrix}
C^{Hb} \\
C^{HbO_2}
\end{bmatrix}
\]

- Measure the absorption coefficients
- Look up the molar extinction coefficients (e.g. http://omlc.ogi.edu)
- Calculate the concentrations

parameters of interest:
- Oxygen saturation
- Total hemoglobin

theory works for N=2 chromophores, too!

Most common Hb-spectra

- If the hemoglobin molecule is bound to oxygen then one has oxy-hemoglobin or HbO_2 [blue]
- If the hemoglobin molecule one has deoxy-hemoglobin or Hb [red]

Less common spectra of blood

- If the hemoglobin molecule is bound to carbon monoxide then one has carboxy-hemoglobin or HbCO
- If the hemoglobin molecule has broken down then one has meta-hemoglobin.

Therapeutic or diagnostic window

- In the red to near-infrared (NIR), absorption is minimal
  - Absorption is the primary event that allows a laser or other light source to cause a potentially therapeutic effect on a tissue. Without absorption, there is no energy transfer to the tissue and the tissue is left unaffected by the light.
  - Absorption of light provides a diagnostic role such as the spectroscopy of a tissue
Melanin

- Melanin is a very complex absorbing material. Melanins from natural sources fall into two general
  - eumelanin
    - A black-to-dark-brown insoluble material found in human black hair and in the retina of the eye.
  - pheomelanin
    - A yellow-to-reddish-brown alkali-soluble material found in red hair and red feathers. A variety of low molecular weight pheomelanins are called "trichromes".
- The melanins are considered to be polymers, however, the details of the polymerization and the role of protein linkages in the natural melanin complex are not known.

Melanin Spectra

The absorption coefficient of the melanosome interior

Absorption coefficient of melanosomes, $\mu_a$

- Measure the optical transmission through individual melanosomes using a microscope and calculate $\mu_a$ from the attenuated transmission.
- Measure the threshold pulsed laser radiant exposure that causes explosive vaporization of melanosomes and deduce $\mu_a$.
Optical depth of the epidermis, $\delta$

- If one is interested in the amount of light transport into the skin and out of the skin which is important for dosimetry of laser treatments and interpretation of optical spectroscopy and imaging, then one would like to know the optical depth ($\mu_a \delta$, where $\delta$ is epidermal thickness) of the epidermis. The epidermis is so thin that its optical effect can be treated as a simple absorption filter (epidermal transmission $T = \exp(-\mu_a \delta)$ for collimated beam normal to skin surface).

Concentration of Melanosomes

- The concentration of melanin within melanosomes is quite variable. Ten-fold variation is to be expected.
- However, the general shape of the melanosome absorption spectrum is approximated:
  - $\mu_a = 1.70 \times 10^{12}$ nm$^{-3.48}$ [cm$^{-1}$] for skin
  - $\mu_a = 6.49 \times 10^{12}$ nm$^{-3.48}$ [cm$^{-1}$] for retina
- where nm refers to the wavelength expressed in nanometers.
Skin Model 1

\[
I(\lambda) = I_0(\lambda) \cdot R_d(\lambda) \cdot e^{-2\varepsilon_m(\lambda) c_m l_m - 2\varepsilon_h(\lambda) c_h l_h}
\]

Skin Model 2

\[
I_{TOT} = I_0 \left( R_1 + T_1^2 \cdot R_2 + T_1^2 \cdot T_2^2 \cdot R_3 + T_1^2 \cdot T_2^2 \cdot T_3^2 \cdot R_4 \right)
\]

Epidermis

- The total optical absorption coefficient ($\mu_{a,\text{epi}}$) of the epidermis depends on a minor baseline skin absorption and a dominant melanin absorption due to the melanosomes in the epidermis.
  - Baseline absorption coefficient of melaninless epidermis
  - Absorption coefficient of a single melanosome
  - Volume fraction of melanosomes in epidermis
  - Net epidermal absorption coefficient

Epidermis

\[
\begin{align*}
\mu_{a,\text{skin baseline}}(\lambda) &= 0.244 + 85.3 \exp(-(\lambda - 154)/66.2) \quad [\text{cm}^{-1}] \quad \text{Bloodless rat skin} \\
\mu_{a,\text{skin baseline}}(\lambda) &= (7.84 \times 10^8)(\lambda^{-3.255}) \quad [\text{cm}^{-1}] \quad \text{Neonatal skin} \\
\mu_{a,\text{mel}}(\lambda) &= (6.6 \times 10^{11})(\lambda^{-3.33}) \quad [\text{cm}^{-1}] \quad \text{Based on vaporization}
\end{align*}
\]

- at the ruby laser wavelength (694 nm) \( \mu_{a,\text{mel}} = 230 \text{ cm}^{-1} \)
- at the alexandrite laser wavelength (755 nm) \( \mu_{a,\text{mel}} = 170 \text{ cm}^{-1} \)
- at the NdYAG laser wavelength (1064 nm) \( \mu_{a,\text{mel}} = 55 \text{ cm}^{-1} \)
### Epidermis

<table>
<thead>
<tr>
<th>Skin type</th>
<th>Fraction melanin</th>
</tr>
</thead>
<tbody>
<tr>
<td>light-skinned adults</td>
<td>$f_{mel} = 1.3-6.3%$</td>
</tr>
<tr>
<td>moderately pigmented adults</td>
<td>$f_{mel} = 11-16%$</td>
</tr>
<tr>
<td>darkly pigmented adults</td>
<td>$f_{mel} = 18-43%$</td>
</tr>
</tbody>
</table>

Net epidermal absorption coefficient of epidermis

$$\mu_{a.epi} = (f_{mel})(\mu_{a.med}) + (1-f_{mel})(\mu_{a.skinbaseline})$$

$f_{mel} \approx 10\%$

### Absorption coefficient of epidermis

<table>
<thead>
<tr>
<th>Wavelength [nm]</th>
<th>$\mu_{a.skinbaseline}$ [cm$^{-1}$]</th>
<th>$\mu_{a.med}$ [cm$^{-1}$]</th>
<th>$\mu_{a.epi}$ [cm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>694 nm</td>
<td>0.268</td>
<td>228</td>
<td>23</td>
</tr>
<tr>
<td>755 nm</td>
<td>0.254</td>
<td>172</td>
<td>17</td>
</tr>
<tr>
<td>1064 nm</td>
<td>0.244</td>
<td>55</td>
<td>5.7</td>
</tr>
</tbody>
</table>

### Dermis

- The total optical absorption coefficient ($\mu_{a.derm}$) of the dermis depends on a minor baseline skin absorption and a dominant hemoglobin absorption due to the cutaneous blood perfusion.
- Baseline absorption coefficient of bloodless dermis
  - $\mu_{a.skinbaseline}$
- Absorption coefficient of whole blood
  - $\mu_{a.blood}$
Absorption coefficient of whole blood

\[ \text{Absorption Coeff. (1/M Mm)} \]

\[ \text{wavelength (nm)} \]

- **Deoxyhemoglobin**
- **Oxyhemoglobin**

**Dermis**
- The total optical absorption coefficient \( \mu_{a,\text{derm}} \) if the dermis is perfused with blood
  - Absorption coefficient of dermis perfused with blood
    - \( \mu_{a,\text{derm}} = (f_{\text{blood}})(\mu_{a,\text{blood}}) + (1-f_{\text{blood}})(\mu_{a,\text{skin baseline}}) \)

**Absorption coefficients in skin**

**Mean free absorption pathlength = 500 mm (!)**