Tissue Optics

… the interaction of light with tissue

Project presentation as a part of the graduate summer school **Biophotonics ’03**

by

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Outline

- **Light propagation in tissue:**
  - Reflection, Scattering μ_s, absorption μ_a, and anisotropy *g*
- **The Henyey-Greenstein function**
- **Rayleigh limit scattering, Mie scattering, and Raman scattering**
- **Monte Carlo simulation**
- **Measurements of optical properties**
  - Steady-state measurements
  - Time-resolved measurements
- **Summary**

Reflection

- **Light reflected at surface (Fresnel's law):**

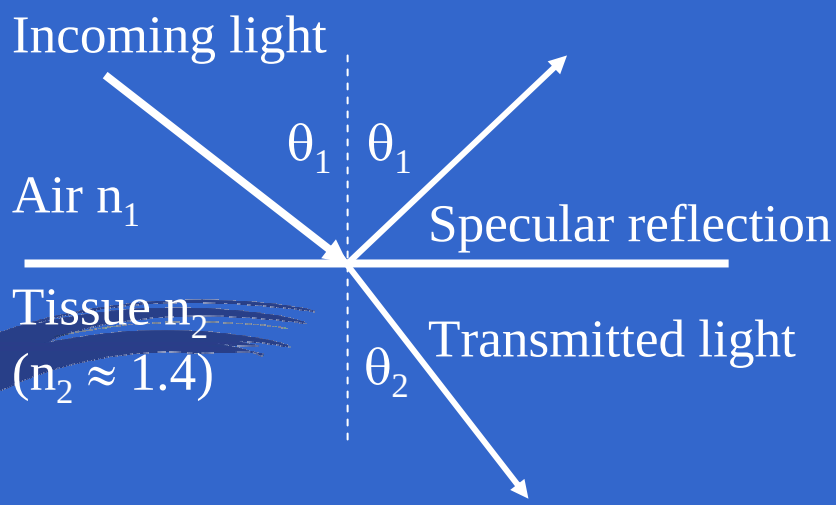
$$r = \frac{1}{2}\left[\frac{\tan^2(\theta_1 - \theta_2)}{\tan^2(\theta_1 + \theta_2)} + \frac{\sin^2(\theta_1 - \theta_2)}{\sin^2(\theta_1 + \theta_2)}\right]$$

- **Angle of transmission (Snell's law):**

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

- **Critical angle (internal reflection for light propagating inside tissue):**

$$\theta_c = \arcsin(n_1 / n_2) \approx 46^o$$



Absorption

- Absorption in tissue is dominated by protein and DNA in the UV, by water in the IR, and by hemoglobin and melanin in the visible.
- Absorption cross-sectional area: $\sigma_a = Q_a A$ [cm^2], where Q_a is the efficiency and A is the geometrical area
- Absorption coefficient: $\mu_a = \rho_a \sigma_a$ [cm^{-1}], where ρ_a is the density
- Transmission: $T = \exp(-\mu_a L)$ [-]

Absorption

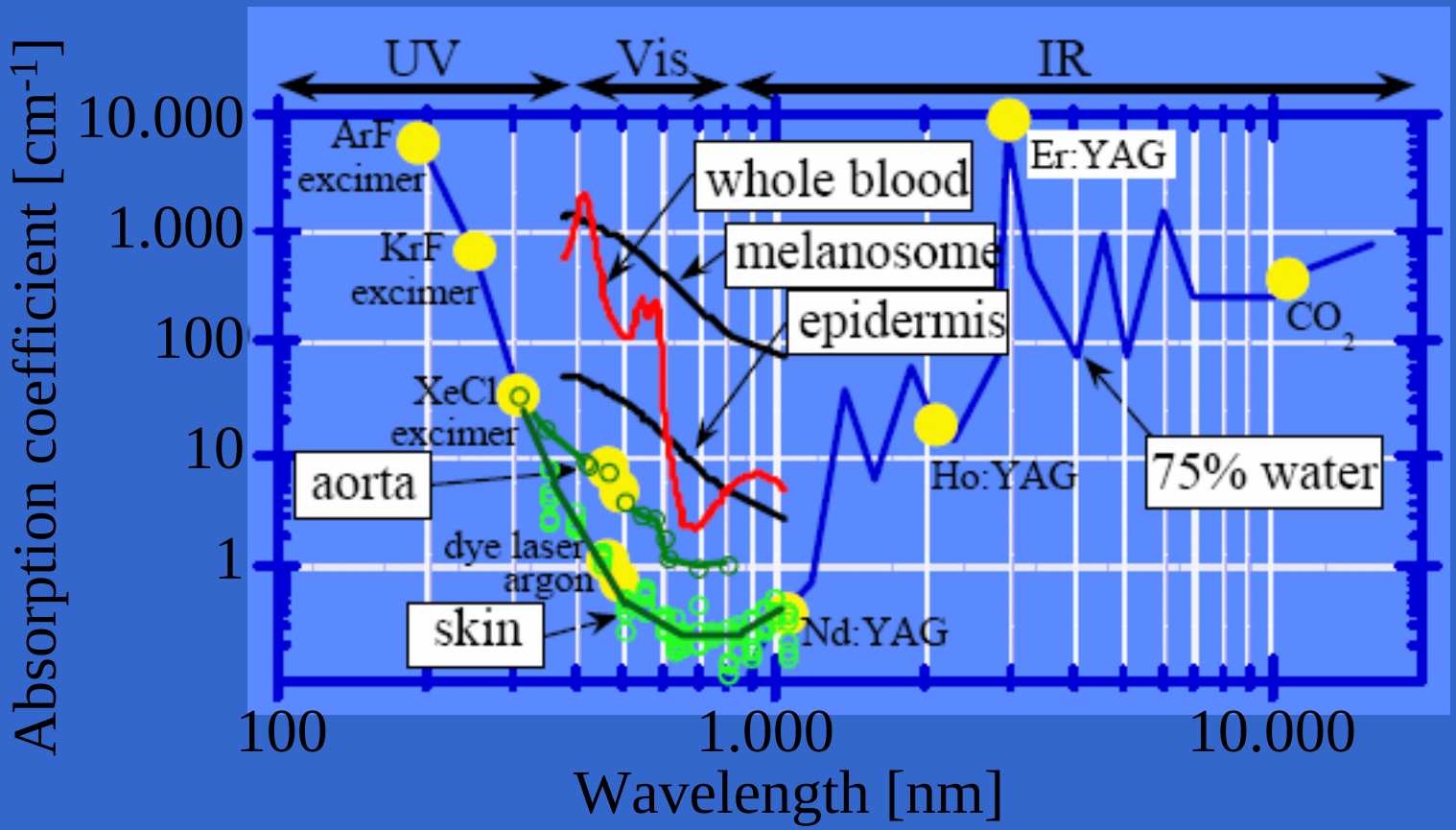


Figure from Ref. [1]

Scattering

Elastic scattering

- No change of photon energy
- Particle size << λ (e.g. atom/molecule): **Rayleigh** scattering ($\propto \lambda^{-4}$ unless resonant); Isotropic
- Otherwise: **Mie** scattering ($\propto \approx \lambda^{-2}$); Anisotropic

Inelastic scattering

- Energy of emitted photon different from incident photon energy

Quasi elastic scattering: The photon is scattered by a moving particle such as a blood cell $\Rightarrow$ a small change in energy occurs due to the Doppler shift.

Scattering: Raman

Raman scattering

- Scattering molecule is excited to a virtual level from which it immediately relaxes to ground state. The molecule will now be in a vibrational state with a higher, a lower, or equal energy compared to the initial state ⇒ emitted light has longer, shorter, or equal wavelength compared to the incident light
- Two former: Inelastic Raman scattering
- Latter: Rayleigh scattering (much stronger than the inelastic Raman scattering)

Scattering

- Scattering cross section: $\sigma_s = Q_s A$ [cm^{-1}], where Q_s is the efficiency and A is the geometrical area.
- Scattering coefficient: μ_s [cm^{-1}]
- Total attenuation coefficient: $\mu_t = \mu_a + \mu_s$

Scattering: Anisotropy

- Scattering in tissue: Not isotropic, but strongly forward directed
- Efficiency of scattering: The anisotropy, g [-]
- g ∈ [-1 1]

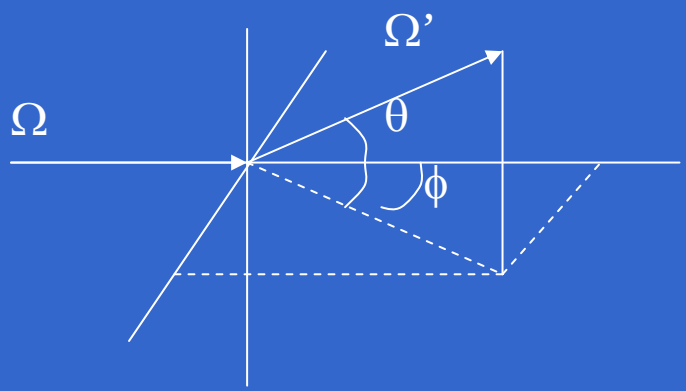
Total backscattering

Total forward scattering

- Mammalian tissue: g ≈ 0.7-0.95
- Geometrical parameters:

$$g = <\cos\theta> = \int_{4\pi} \cos\theta \cdot p(\cos\theta) d\Omega$$

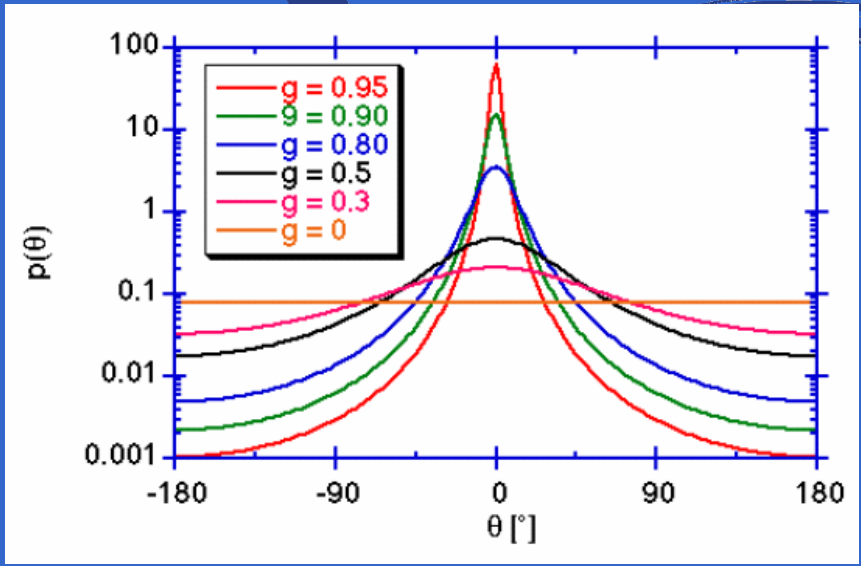
$$\text{with} \quad \int_{4\pi} p(\cos\theta) d\Omega = 1$$



Scattering: The Henyey-Greenstein function

- Approximates single photon scattering by tissue [1] *

$$p(\Omega' \cdot \Omega) = p(\cos\theta) = \frac{1}{4\pi} \frac{1-g^2}{(1+g^2-2g\cos\theta)^{3/2}}$$



* See also S. L. Jacques et al., *Lasers Life Sci.*, 1:309-333 (1987) for a modified Henyey-Greenstein function

Scattering: Reduced coefficient

- From the diffusion approximation $\mu_s' = \mu_s(1-g)$ [cm^{-1}], where μ_s' is the *reduced scattering coeffient*, which determines the light propagation in diffusely scattering media
- $\mu_s'^{-1}$: measure of the effective mean free path between artificial isotropic scattering events in a multiple-scattering environment (i.e. average distance a photon travels before the scattering can be regarded isotropic)
- The linear transport coefficient μ_{tr}: describes the inverse of the effective mean free path between interaction events in a strongly scattering medium and is given by

$$\mu_{tr} = \mu_a + \mu_s(1-g) = \mu_a + \mu_s'$$

Monte Carlo simulation

- Computational method for calculating photon propagation in tissue
- Based on random walk of photons in an absorbing and scattering medium
- A photon package is injected into the tissue model, and is traced until it exits the tissue or is terminated through absorption

Monte Carlo simulation

Advantages

- Any physical parameter, such as the path, absorption position etc., can be logged
- No limitations in tissue geometry or homogeneity

Drawback

- Substantial computation time needed to have good statistics

Monte Carlo simulation

- Photon package with weight W enters the tissue. The step size to the next point of interaction, s, is calculated as

$$s = \frac{-\ln(1-\varsigma)}{\mu_t}$$

, where ζ is a random number between 0 and 1

- Once the photon package has taken a step, a fraction of the photon weight is deposited due to absorption. This fraction is calculated by

$$\Delta W = \frac{\mu_a}{\mu_t}$$

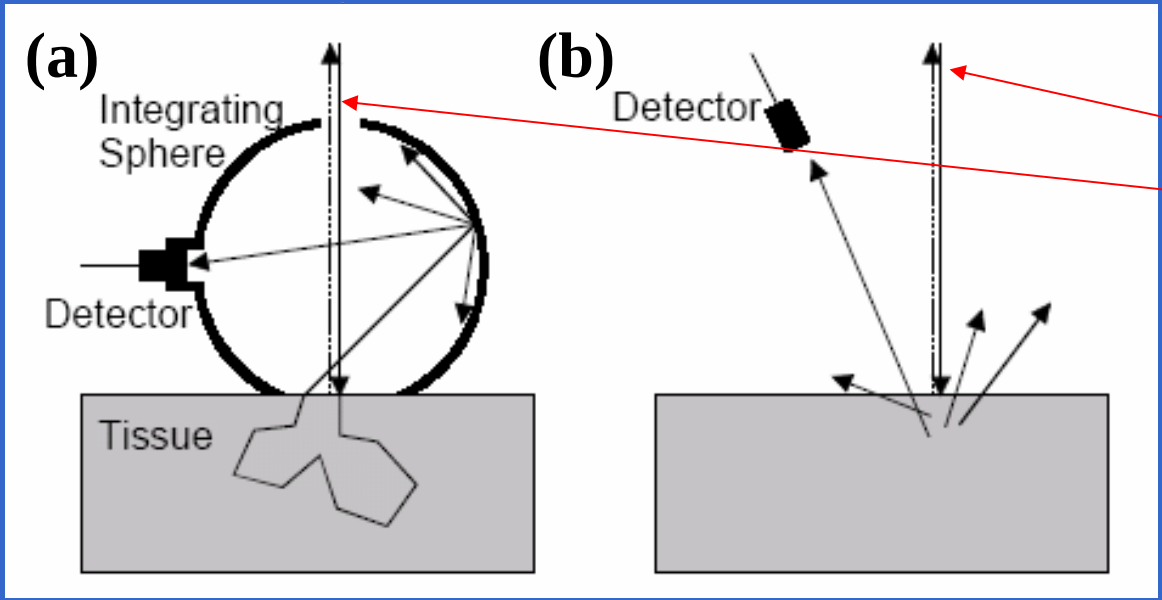
- The weight of the photon package is reduced by ΔW, and the scattering angle is calculated. The deflection angle is calculated from the Henyey-Greenstein phase function, while the azimuthal angle is given by a new random number.
- The whole process is repeated until the package leaves the tissue or the weight is reduced below a threshold. In the latter case a new random number decides whether the photon package is considered to be totally absorbed, or, in order to conserve energy, if the weight is to be multiplied by a certain factor to continue the random walk

Measurement of tissue optical properties

- Two measurements $\Rightarrow \mu_a$ and μ_s'
- Three measurements $\Rightarrow \mu_a$, μ_s , and g
- E.g. measurements of light by two fibres at different distances from a source fibre will yield two measurements that map into a grid of two optical properties thereby specifying these properties
- Methods
  - Steady-state measurements
  - Time-resolved measurements

Steady-state techniques I

- **Measurement of total diffuse reflectance from tissue**

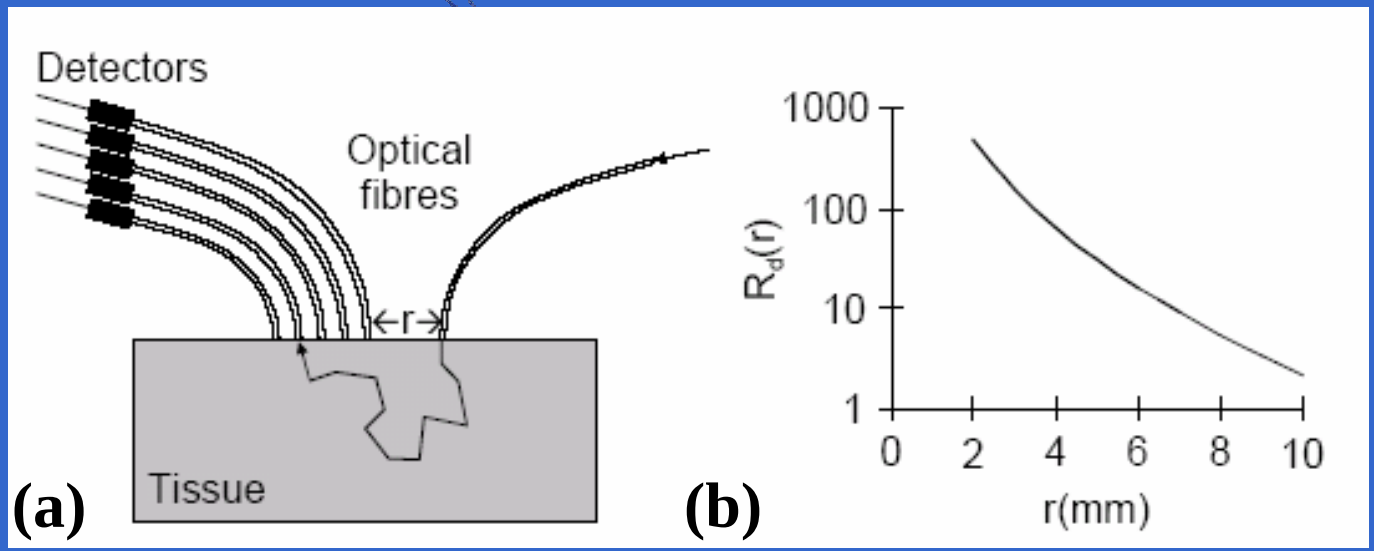


(a) Integrating sphere measures diffuse reflectance

(b) Detector placed at a distance measures a fraction of the total diffuse reflectance

Steady-state techniques II

- **Measurements of local diffuse reflectance [3]**

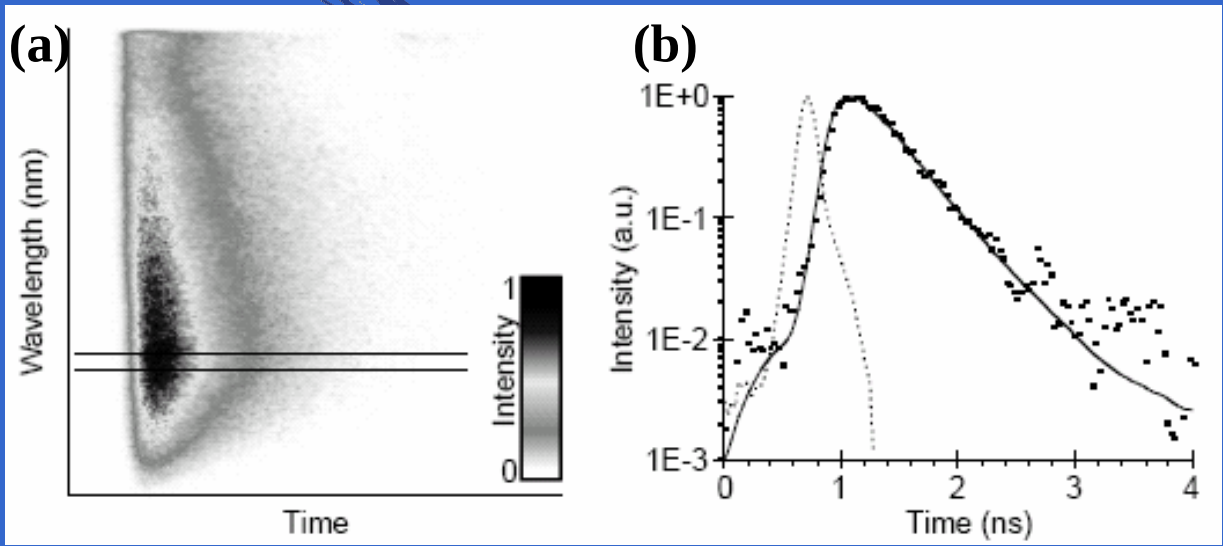


(a) A system based on optical fibres measures local diffuse reflectance

(b) Typical reflectance curve (signal) obtained from the diffusion equation

Time-resolved techniques

- **Time- and wavelength resolved measurement of light propagation in tissue using femtosecond white light [3]**



(a) Intensity as a function of time and wavelength

(b) Time-dispersion curve obtained from an image by summing the intensity in a wavelength band (see (a)). Dashed line: Impulse response of the system; Solid line: Model curve fitted to measured data

Summary

- Light transport in tissue can be modeled by diffusion theory or Monte Carlo simulations.
- Two measurements can yield values of absorption and reduced scattering coefficients while three measurements can yield μ_a, μ_s, and g

References

[1] S. Jacques; Presentation at Bio-Photonics ’03, Ven (2003)

[2] C. af Klinteberg, PhD thesis, Lund Institute of Technologhy, Sweden (1999)

[3] C. af Klinteberg et al., OSA TOPS on Medical and Biological Appl. **6,** p. 30-35 (1996)