近紅外光光子與組織交互作用
fNIRS — Photo Migration

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本週課程內容

- Basic principles of NIRS
- Photon migration in tissues

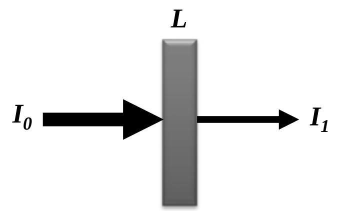
- **Application of Near Infrared Spectroscopy in Biomedicine.** Thomas Jue, Kazumi Masuda. Springer, 2013.
  - Principles and instrumentation (chap 1), photo migration (chap 2~3)

fNIRS基本原理
Basic Principles

Beer-Lambert Law

- Describe the attenuation of light propagating in a homogeneous medium.
- $I_1 = I_0 \exp(-\mu_a(\lambda)L)$

I_0: the incident light
I_1: the light leaving the medium
L: the propagation path length
μ_a: the absorption coefficient



non-scattering & homogeneous medium

A Mixture of Chromophore

- The sum of the products of the concentration of each chromophore c_n with its molar extinction/absorption coefficient ε_n.
- $\mu_a(\lambda) = \sum_n \varepsilon_n(\lambda) c_n$

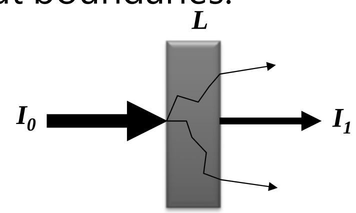
< Blood >
- White blood cells and platelets <1%
- Red blood cells ~44%
- Plasma ~55%

The individual extinction coefficient of each chromophore represent their absorption at a particular concentration ($cm^2 \cdot mol^{-1}$).

Scattering Events

- Refractive index mismatches at boundaries.
- $I_1 = I_0 \exp(-\mu_s(\lambda)L)$

μ_s: the scattering coefficient

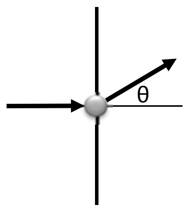


- The scattering path length, defined as $1/\mu_s$, is the expected value of distance that a photon travels between scattering events.

Anisotropy Factor

- The phase function, f(cosθ), describes the angular probability of photon being scattered.
- The anisotropy factor, g, can be represented as the mean cosine of the scattering angle.
- $g = \int_{-1}^{1} cos\theta \cdot f(cos\theta) dcos\theta$

g = 0 → isotropic scattering
g = 1 → straight line
g = -1 → complete backward scattering



g of biological tissue

- Biological tissues are strongly forward-scattering media.
  - $0.69 < g < 0.99$ ($48.70^o > \theta > 8.11^o$)
- The reduced scattering coefficient μ'_s
- $\mu'_s = \mu_s(1-g)$

Optical Density (OD)

- OD is the amount of attenuation that occurs when light passes through an optical component.
  - comes from both the absorption and scattering of light.

- **Transmission,** $T = I_1/I_0$
- $OD = log_{10}(1/T) = -log_{10}(T)$

< Example >
Attenuate light by a factor of 10^3,
$T = 10^{-3}$,
$OD = -log_{10}(10^{-3}) = 3$

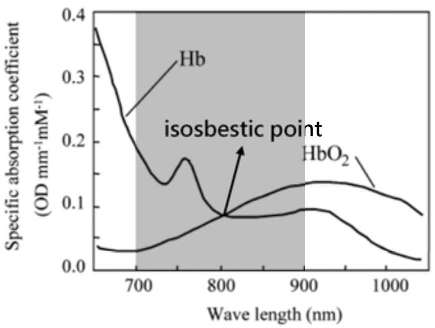
Total attenuation coefficient

- μ_t is defined as the sum of the absorption and scattering coefficients
- $1/\mu_t$ is called the mean free path.

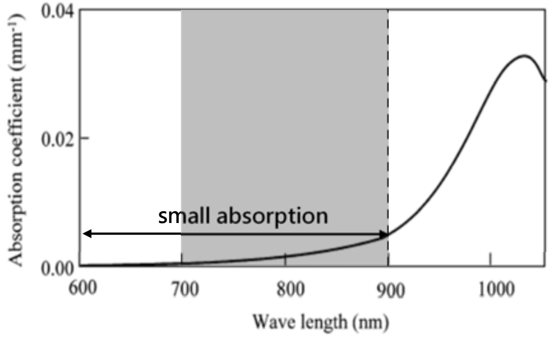
Absorption coefficients of tissues

Wavelength between 700 and 900 nm are suitable for spectroscopy

oxygenated/deoxygenated hemoglobin



water



Optical properties of tissues

Table 1.1 Optical properties of muscle, fat, bone, dermis, and epidermis

Sample	λ (nm)	μ_a (mm^{-1})	μ_s' (mm^{-1})	References
Muscle				
Human forearm (in vivo)	800	0.015	1.0	Ferrari [6]
Human forearm (in vivo)	825	0.021–0.027	0.45–0.87	Zaccanti [7]
Human calf (in vivo)	825	0.018–0.028	0.51–0.85	Zaccanti [7]
Bovine muscle (in vitro)	633	0.096	0.53	Kienle [8]
Bovine muscle (in vitro)	751	0.037	0.34	Kienle [8]
Human calf (in vivo)	800	0.017 ± 0.005	0.80–1.1	Matcher [9]
Fat				
Human mamma (in vivo)	800	0.0017–0.0032	0.72–1.22	Mitic [10]
Human mamma (in vivo)	800	0.0023–0.0026	0.80–1.1	Suzuki [11]
Bovine fat (in vitro)	751	0.0021	1.0	Kienle [8]
Bone				
Pig skull (in vitro)	650	0.05	2.6	Firbank [12]
Pig skull (in vitro)	960	0.04	1.32	Firbank [12]
Human skull (in vivo)	849	0.022	0.91	Bevilacqua [13]
Dermis				
Pig dermis (in vitro)	790	0.018	1.4	Beek [14]
Pig dermis (in vitro)	850	0.033	0.9	Beek [14]
Epidermis				
Pig epidermis (in vitro)	790	0.24	1.9	Beek [14]
Pig epidermis (in vitro)	850	0.16	1.4	Beek [14]

fNIRS光子組織穿行
Photo Migration

Model Photon Migration

- Diffusion theory: Radiation transport equation (RTE)
- Monte Carlo (MC) methods
- Finite element method (FEM)

Radiation Transport Equation

$$\frac{1}{c}\frac{\partial \phi(r,\hat{s},t)}{\partial t} = \underbrace{-\nabla \cdot \phi(r,\hat{s},t)\hat{s} - (\mu_a+\mu_s)\phi(r,\hat{s},t)}_{\text{loss}} + \underbrace{\mu_s \int_{4\pi} \phi(r,\hat{s},t)\Psi(\hat{s},\hat{s}')d\hat{s}' + S(r,\hat{s},t)}_{\text{gain}}$$

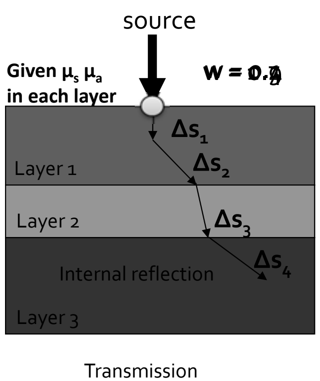
Net number of photons | flux of photons along the direction | absorption & scattering | scattering from other directions | source

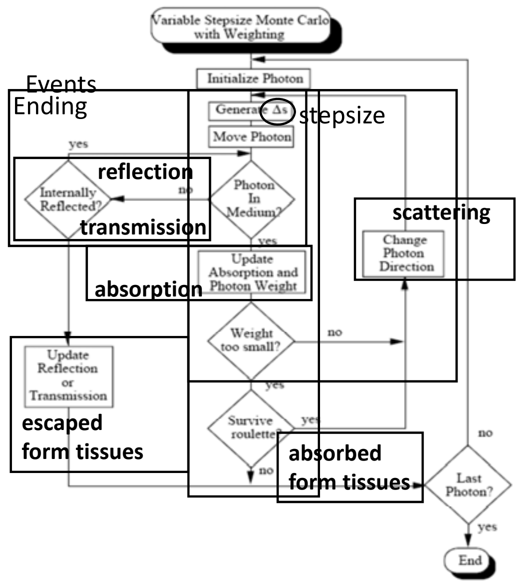
ϕ: average flux density
r: position
$\hat{s}$: direction vector
t: time
μ_a, μ_s: absorption and scattering coefficient
c: speed of light in the medium
S: light source
Ψ: scattering phase function

The RTE is a balance equation describing the change of numbers of photon ϕ in time due to changes in photon flow.

D.A. Boas. Imaging the Body with Diffuse Optical Tomography. IEEE Signal Processing (2001).

MC Simulation
solve photon distribution





Models for MC Simulation

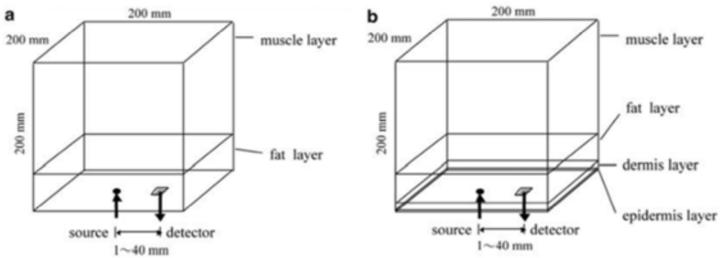
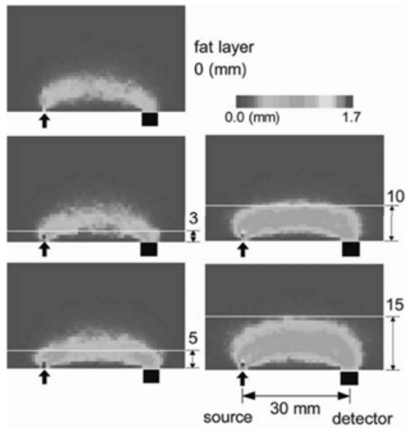


Table 2.1 Reduced scattering coefficient and absorption coefficient of each layer

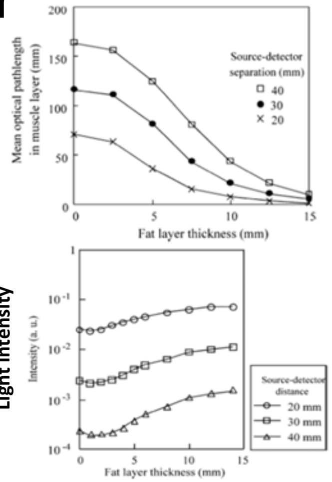
Layer	Reduced scattering coefficient (mm^{-1})	Absorption coefficient (mm^{-1})	References
Epidermis	5.0	5.9	[21]
Dermis	1.3	0.03	[22]
Fat	1.2	0.003	[23]
Muscle	0.6	0.02	[24]

Effect of Fat Layer



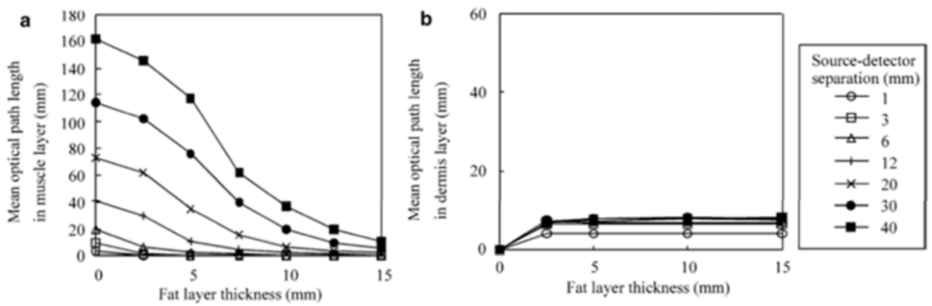
Spatial Sensitivity

Light intensity



Effect of the Skin

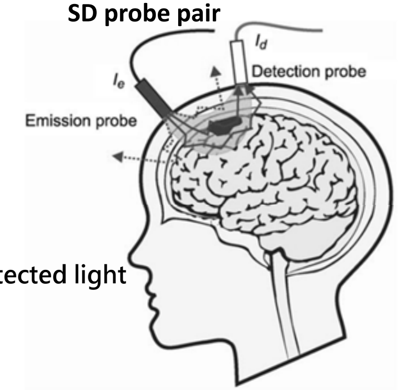
- The effect of blood in the skin can be ignored when the source-detector separation is large (>20 mm).



Photon Migration in Brain

- Modified Beer-Lambert Law
- $OD = \ln\left(\frac{I_e}{I_d}\right) \approx \mu_{a\ head}\langle L_{head}\rangle$+G

SD probe pair



$\mu_{a\ head}$: assume the absorption in the head is homogeneous
$\langle L_{head}\rangle$: the mean optical path length of the detected light
G: the scattering loss (cannot be measured)

Modified Beer-Lambert Law

- Based on an assumption that the scattering loss does not change during the measurement period.
- $\Delta OD = ln\left(\frac{I_e}{I'_d}\right) - ln\left(\frac{I_e}{I_d}\right) = ln\left(\frac{I_d}{I'_d}\right) = \Delta\mu_{a\ head}\langle L_{head}\rangle$

Change caused by brain activations (dynamics of HbO and HbR)

Brain Activation

- Assumption:
  - the concentration of hemoglobin is only changed during the measurement period by brain activation.
- $\Delta\mu_{a\ head}(\lambda) = \varepsilon_{HbO}(\lambda)\Delta c_{HbO} + \varepsilon_{HbR}(\lambda)\Delta c_{HbR}$

Measurements under two or more wavelengths (760 and 850 nm) are demanded.

Partial Optical Pathlength

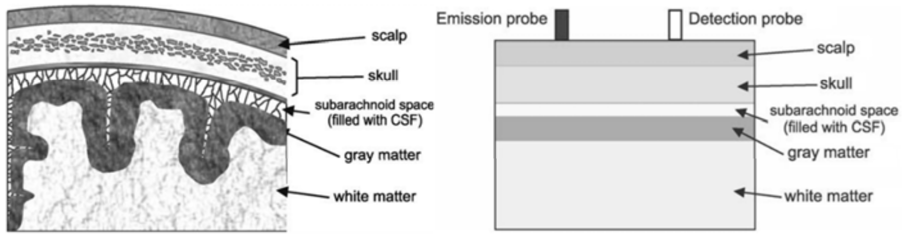
- Assuming that the head consists of several homogeneous tissues.
- Partial optical pathlength
  - The mean optical pathlength that the detected light travels in each tissue region
- $\Delta OD = \sum_{i=1}^{M} \Delta\mu_{a\ i}\langle L_i\rangle$

Head Model

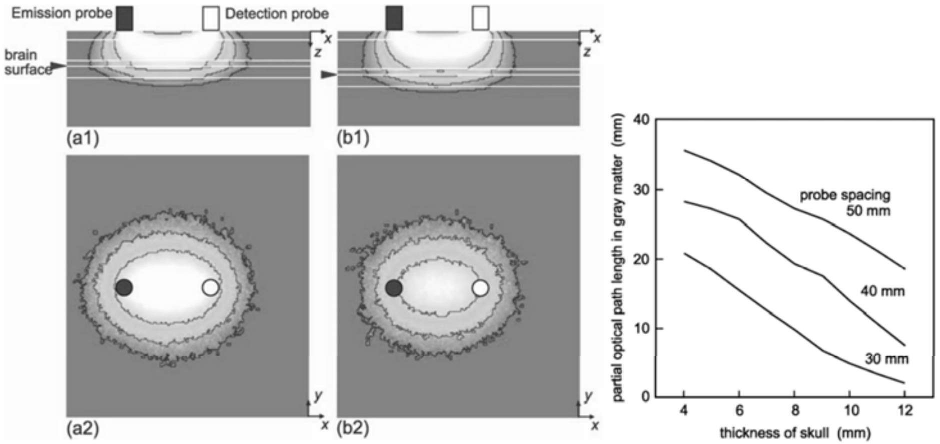
Table 3.1 Typical optical properties of tissues of an adult head model at 800-nm wavelength

Tissue types (mm^{-1})	Transport scattering coefficient (mm^{-1})	Absorption coefficient (mm^{-1})
Scalp	1.9	0.018
Skull	1.6	0.016
Subarachnoid space (CSF)	0.24	0.004
Gray matter	2.2	0.036
White matter	9.1	0.014

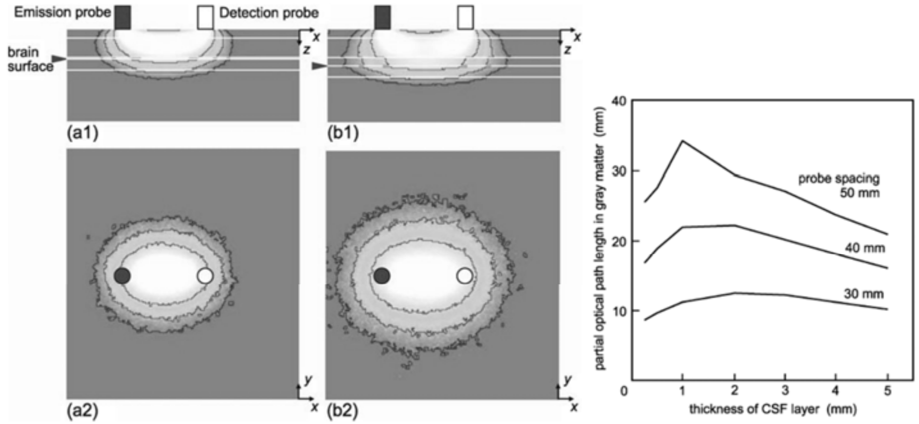
Data chosen from the reported data for dermis [64], pig skull [62], CSF layer [16], and human brain [63]



Influence of Skull Layer



Influence of CSF Layer



THE END

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