Tissue Optics

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Introduction, Concept

The propagation of light in biological tissues is characterized by absorption and multiple scattering process. To describe the light propagation, it is usually based upon the assumption that the material is statistic scattering, i.e. the photon is scattered by discrete scatter centers which distribute in the observing area statistically. Three parameters used for optical characterization of biological tissues are explained in more deteil below.

The scattering coefficient μ_s

The scattering coefficient is defined as the product of cross-section and particle concentration. The concentration can be calculated from the total scattered light power for individual scattering process.

The anisotropy factor g

Depending on the form, magnitude and particle property, mainly a scattering process has a direction of forward ($0<g<1$), backward ($-1<g<1$), or isotrop ($g = 0$, for all scattering angles the probabilty is same). The character of scattering is described by aniosotropy factor. It is defined as the average consine of the scattering angle. Biological tissues have a strong forward scattering ($g = 0.8 \ldots 0.95$). The scattering character in the biological tissues can be described by Henyey-Greenstein's phase function.

The absorption coefficient μ_a

The absorption coefficient provides a measure of the light amount that tranform mainly into heat energy in the tissue. For non-scattering tissue, the relation of the power of the incident light and the transmitting light which passes through an absorber with thickness of d is given by Lamber-Beer law:

$$P_{trans} = P_{inc} \cdot e^{-\mu_a d}$$

Besides the above basic measures, some other parameters which can be easily obtained by measuremnet at present are often used in literature:

The extinction coefficient

$$\mu_t = \mu_s + \mu_a$$

If the light passes through a scattering medium with thickness of d, the unscattered transmission is weakend by

$$P_{trans} = P_{inc} \cdot e^{-\mu_t d}$$

The reduced scattering coefficient

$$\mu_s' = \mu_s(1 - g)$$

Based on diffusion theory, the light distribution in a strong scattering and weak absorbing medium depends only on the reduced scattering coefficient.

The albedo $$a = \frac{\mu_s}{\mu_a + \mu_s}$$

The mean free path *in two kinds of scattering process*

$mfp = 1/\mu_t$, and $mfp' = 1/\mu_t'$ is often used.

Most of the time, the scattering and absorption coefficients are given in mm^{-1} or cm^{-1} !

The reasons of the absorption and scattering

The absorption character of the human tissue depends strongly to the applied wavelength. The important absorbers are water (>1.4μm wavelength) and hemoglobin. In addition, the absorption coefficient also depends on oxygenation state. So the oxygen saturation can be determined by measuring at two different wavelengths (Pulse-Oxymetry). In "biological window" from 700nm to 950nm, the absorption coefficient is distinctly lower than the scattering coefficient, which results in a high penetration depth of the light (Applications: optical tomography, sensors for fuctional circulation diagnose). The reason of the light scattering hasn't been completely explained yet. So modelling calculation on dielectrical small sphere indicates the scattering particle size within the area of light. The promising candidate is cell organ. For liver cells, it is shown that the mitochondrien is the main reason for up to 80% of the light scattering.

The description of the light propagation in scattering medium

In order to design and use LITT (Laser Induced Thermal-Therapy), PDT (Photo Dynamic Therapy), OT (Optical Tomography) and other medical laser instruments, it is necessary to know the light distribution in tissues at a given incident light. According to application, there are a number of computer assisted calculation methods. Their basic priciples will be described beriefly here.

Diffusion model

The diffusion model can describe the place- and time-resolved light distribution in scattering tissues, if the scattering is far more than the absorption ($\mu_s >> \mu_a$) and the time range and the distance can be considered so that the light will be multiple scattered. Because the analytical solution can only be obtained in special case, numerical solutions by finite element is often used so that the inhomogenous structure and complicated boudary conditions can be taken into consideration. At present, the diffusion theory is used in optical tomography of the thick tissue layers (photon density waves, forward-calculation in iterative image reconstruction).

Monte-Carlo simulation

Monte-Carlo method is well-known in atom physics. It is successfully used in simulation of the light distribution in scattering tissues. It is a kind of statistical method, which

considers the light as particles(photons). Before being scattered, an incident photon in a scattering tissue will fly through a free path constrained by random process. The scattering angle from the random process of same distribution can be calculated from the aniosotropy factor g of the tissue. The phton will fly in a new direction till it is scattered again. The track of a photon is made until some stopping criteria (maximum path length, reach of the detector) are satisfied. In order to get a statistically reliable result about the photon distribution in tissue, typically 10^6 to 10^7 photons is necessary. The advantage of Monte-Carlo simulation rests in the simple treatment of the inhomogenous simulation area, therefore it is especially suitable for calculation of the light distribution in skin layer, which is a strongly layered medium. Farther, the Doppler spreading by moved erythrocyte as well as the depolarization behaviour can also be investigated by Monte-Carlo simulation.

Scattering measurement techniques

Before the light distribution can be calculated, the aniosotropy factor, scattering and absorption coefficient of the investigated tissue must be known. Because the measured values are strongly dependent on the measurement technique, there is an intense discussion on optical tissue parameters in the passed few years. The relationship between pathogenous state and the optical tissue parameters is particularly important for optical imaging technique.

The determination of the tissue parameters can be made by in-vivo and in-vitro measurement. On one hand, the in-vivo methods provide the average parameters of the total illuminated area, so the intended different tissue can be investigated together with in-vitro methods. On the other hand, the tissues which is taken from the living body and fixed under circumstances show optical characters different from the live tissue. So in individual case, it must be decided, which method is suitable.

In-vivo: tissue pulse response
If a short light pulse is sent to the investigated tissue, it will spread by multiple scattering. The reduced scattering coefficient and absorption coefficient can be determined from the delay time of the light which has been reflected from (=reflexion measurement) or transmitted through the tissue (=transmission measurement). Then the measured value is compared with that which is expected from diffusion theory. The time-resolved detection of the radiation generated from pulse laser is implemented by streak cameras or TCSPC-system.

In-vivo: Radial distribution
If the tissue is illuminated by a point, low-energy laser, a radial distributed backing light can be observed. The reduced scattering and absorption coefficient can be determined from the decrease of the radial intensity by diffusion theory. However, the problem of this technically simple measuring method is the surface reflexion, which overlaps the back-scattered light.

In-vitro:extinction technique
The extiction coefficient can be determined from the weakening of the trransmitted light in the thin skin layer.

In-vitro: Ulbricht's sphere

The tissue fragment is put between two difussing and reflecting hollow sphere, from which the reflected and transmitted light from the probe are measured. In combination with the extinction technique, all three tissue parameters can be determined at the same time. To infer the tissue parameters from teh measured reflextion and transmission values, different methods are used (Adding Doubling, 4-Flux Theory, Monte-Carlo).

Conclusion

The reduction of the tissue optical characters into 3 parameters simplifies the modelling of the light distribution, but also results in the variation of one scale on the parameters reported in literatures. Till now, no standard measuring method can be agreed.

Cheong gave a good review of the measuring methods and tissue parameters. These data have found fundemental beginning in the scattering measurement database built in the Institute of High Frequence Technique. It can be accessed on the Internet by http://www.ihf.rwth-aachen.de/kaks.html .

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