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Original article

Detection of tissue optical properties ; a comparison study

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Abstract

Determine the optical properties of biological tissue is an important issue in medical applications. These optical properties are absorption coefficient (μ_a), scattering coefficient (μ_s) and anisotropy factor (g). There are many theoretical methods to measure tissue optical properties. These theoretical methods can be applied by knowing number of experimental quantities, but, there are no ensure informations about the most accurate method. In this work, two different methods are used to determine the optical properties of biological tissue. They are Kubelka Munk (KM) model and three dimension diffusion approximation (TDDA). In KM, the optical properties are determined while in three dimension diffusion approximation, the diffuse reflection and transmission were determined. The results of K.M were compared with other works from the literature and the results were in good agreements while for TDDA, there was a disagreement and it need a reevaluation comparing with the other methods.

Key words: Optical properties, Kubelka Munk model, three dimension diffusion approximation

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Introduction

The Determination of the optical properties in biological tissue is an important issue in medical application, for example the estimation of light dosimetry requirements for laser treatment modalities ,(1- 7). Using the optical methods in medicine are preferred, because they are quantitative, noninvasive, relatively inexpensive and pose no risk of ionizing radiation,(8). Optical properties of the tissue are affected by different factors such as tissue content (any biological tissue contain different chromospheres as protein, hemoglobin, vitamins, water etc,),tissue thickness and clinical factor such as laser wavelength, power, type of beam (pulse or continuous),intensity , the time of tissue being exposure as well as the incident angel of the beam,(8).

Absorption coefficient μ_a, scattering coefficient μ_s (in the most cases reduce scattering coefficient μ') and anisotropy factor g parameters of tissues are the main optical properties of the tissue,(9). When a photon propagates over infinitesimal distance , the probability for absorption, or scattering in infinitesimal distance is μ_a, and μ_s respectively,(10). Anisotropy factor g defined as the average cosine of scattering angles, determines the probability distribution of scattering angles to the first-order approximation ,(11). It has value ranging from (-1 to 1), -1 for backward scattering, 0 unidirectional scattering, and 1 for forward scattering. It has the typical values of for biological tissue which are between 0.6 and 0.9 which means the scattering angle is from 25° to 45° , (10 &12). The absorption coefficient, μ_a , provides information on the concentration of chromospheres while the scattering coefficient and anisotropy factor, *g*, provide information on the form, size, and concentration of the scattering components in the medium.

This information can be used to distinguish between normal tissues, malignant lesions, and other disease. For example, hemoglobin and water content have been found to be significantly different in normal and cancerous tissues ,(4,13&15). The physiological state of biological tissue can be obtained from its optical properties, if an accurate bio-optical model for the tissue is available. Thus, it is desirable to develop an appropriate bio-optical models which they link the tissue optical properties with its physiological condition and accurate and reliable methods for determining optical properties of tissue. There are many models and experimental methods that are used to measure the optical properties of the tissue. However, for a complete evaluation of the optical properties of tissue, an integrating-sphere(single and double) method is usually used,(9).

The optical properties are here obtained when measurable parameters, such as reflectance and transmittance, are converted into parameters that characterize light propagation in tissue ,(1&10). This experimental method is used in vitro measurements of small tissue volumes (thin tissue sample), (14). The propagation of light in tissue can be described by solving the radiative transport equation. This theory is described as a complex solution. For the simplicity, the approximations are used to get simple model to use.

There are several models that calculate optical properties from experimental results, the diffusion theory, Kubelka-Munk model accept diffusely scattered light, while the inverse adding-doubling method can be used for each arrangement of optical properties and limit conditions. Another model is Monte Carlo simulations that simulate the transport of individual photons through tissue. These simulations are considered to yield the most correct solutions, since any geometry can be simulated by the program.

A noteworthy disadvantage is the long calculation times expected to acquire great measurements , (1, 4 & 16) .Researchers have proposed different methods to determine quantitatively absorption and reduced scattering coefficients. The optical properties are determined in many works , (12. 15& 19).

All these studies used to measure diffuse reflectance and transmittance experimentally then obtained optical properties of tissue using one of the models (Monte Carlo, Adding doubling or Kubelka Munk model). This paper introduces a mathematical method to determine the optical properties of the tissues by solving the equations of Kubelka-Munk method. Then another method(TDDA) was used to describe the internal distribution of the beam in the sample represented by diffuse reflectance and transmittance. Diffuse reflectance is an important factor for earlier detection and diagnostic of the cancer, (20).

These equations are preferred rather than Maxwell's equations due to inhomogeneity of the tissues,(21)

Mathematical analysis

a. Kubelka Munk model

The model is employed to determine absorption coefficient µa and reduced scattering coefficient μ_s' from the measured values of total diffuse reflectance Rd, diffuse transmittance Td and collimated transmittance Tc ,(20) .

$$m = \frac{1+R^2-T^2}{2R} = \frac{\mu_a+\sigma}{\sigma} \qquad (1)$$

$$b=\sqrt{m^2-1} \qquad (2)$$

$$S = \frac{1}{bd}\ln\left[\frac{1-R(m-b)}{T}\right] \qquad (3)$$

Where S is the fraction of loss due to scattering and A is the fraction of loss due to absorption.

$$A=(m-1)\ S \qquad (4)$$

$$A=2\ \mu_a \qquad (5)$$

So absorption coefficient can be derived as

$$\mu_a=\frac{A}{2} \qquad (6)$$

Also S is equal to the following equation, (22):

$$S=\frac{3}{4}\mu_s(1-g)\ \frac{1}{4}\mu_a \qquad (7)$$

$$\acute{\mu}_s=(1-g)\ \mu_s \qquad (8)$$

From equations (7) and (8) reduce scattering coefficient can be derived

$$\acute{\mu}_s = \frac{4}{3}\ S + \frac{1}{3}\ \mu_a \qquad (8a)$$

Using Bouguer-Beer-Lambert law

$$T_C=\exp(-\mu_t\ d) \qquad (9)$$

$$\mu_t = \frac{1}{d}\ln\frac{1}{T_c} \qquad (10)$$

The equation of scattering coefficient can be derived from the equation of attenuation coefficient

$$\mu_s = \mu_t - \mu_a \tag{11}$$

$$g = 1 - \frac{\mu_s'}{\mu_s} \tag{12}$$

b. Reflection and Transmission for the slab

To solve these equations prior information about optical properties are needed also information about refractive index and, thickness of the tissue and value of specular reflection of the laser in the tissue r_{ce} , r_{cb} is approximated to be 4% , (23 & 24).
The total diffuse reflection for the slab

$$R_d = \frac{1}{2}\,\frac{1-r_{21}}{1+r_{21}}\,\frac{\varphi(r,d)+\varphi(r,0)\,r_{cb}\exp(-\mu t\,d)}{(1-r_{ce})P\,[1-r_{ce}\,r_{cb}\exp(-2\mu t\,d)]} \tag{13}$$

The total diffuse transmission for the slab

$$T_d = \frac{1}{2}\,\frac{1-r_{21}}{1+r_{21}}\,\frac{\varphi(r,0)+\varphi(r,d)\,r_{cb}\exp(-\mu t\,d)}{(1-r_{ce})P\,[1-r_{ce}\,r_{cb}\exp(-2\mu t\,d)]} \tag{14}$$

Where r_{21} is reflection factor (represents the ratio of the upward hemispherical fluxes at boundary in the diffusion approximation)

$$r_{21} = \frac{1}{n^2} \tag{15}$$

Where n refractive index of the tissue sample

b1.DIFFUSE RADIANT FLUENCE RATE IN A SLAB

Fluence rate known as the total amount of photon power density available measured in the unit of (W/m^2).

$$\varphi(r,z) = 3\,\mu_s(1-r_{ce})P[(\mu_t + g\mu_a)I_v(r,z) + gI_s(r,z)] \tag{16}$$

$\varphi(r,z)$ is determined for two cases ,first at the surface where z=0 it is written as $\varphi(r,0)$, and inside the tissue where z=d it is written as $\varphi(r,d)$

$$I_V = \sum_{n=1}^{\infty} \frac{\sin(k_n z+\gamma_n)}{N_N}\,\frac{Z_N}{k^2{}_n+\mu_t^2}\,H_n(r) \tag{17}$$

$$I_s = \sum_{n=1}^{\infty} \frac{\sin(\gamma_n)(k_n z+\gamma_n)\,z_n}{N_N}\,[1+\exp(-\mu_t d)]H_n(r) \tag{18}$$

Where

I_V : The volume integral

I_s : The surface integral

if r > w_l

$$H_n = \frac{2}{w_l^2}\,\lambda_n w_l k_0(\lambda_n r) I_1(\lambda_n w_l) \quad (19)$$

$$H_n = \frac{2}{w_l^2\;\lambda_n^2}\;1 - \lambda_n w_l k_1(\lambda_n r) I_0(\lambda_n w_l) \quad (20)$$

Equation (20) is used if r $\leq w_l$

H_n *is* the radial integral for a flat beam with radius w_L is

I_O,I_1, K_o,K_1 are Bessel function

$$Z_n = \sin\gamma_n[\mu_t + \exp(-\mu_t d)(k_n \sin k_n d - \mu_t \cos k_n d)] + \cos\gamma_n[k_n - \exp(-\mu_t d)\,(\mu_t \sin k_n d - \mu_t \cos k_n d)]$$
(21)

$$N_n = \frac{\sin 2\gamma_n - \sin(2k_n d + 2\gamma_n) + 2k_n d}{4k_n} \quad (22)$$

N_n is normalized factor

$$\tan\gamma_n = -A\,k_n \quad (23)$$

γ_n can be derived From equation (23)

$$\gamma_n = \tan^{-1}(-A\,k_n) \quad (24)$$

$$\tan(k_n d) = \frac{2Ak_n}{A^2\,K_N^2 - 1} \quad (25)$$

By using Newton Raphson method k_n can be calculated from equation (25)

$$A = \frac{2}{3\,\mu_{tr}}\,\frac{1+r_{21}}{1-r_{21}} \quad (26)$$

$$\lambda_n^2 = k_n^2 + \mu_{eff}^2 \quad (27)$$

$$\mu_{eff} = \sqrt{\mu_a \mu_{tr}} \quad (28)$$

μ_{eff} effective attenuation coefficient and μ_{tr} Transport attenuation coefficient

$$\mu_{tr} = \mu_t - g\mu_s \quad (29)$$

$$\mu_t = \mu_a + \mu_s \quad (30)$$

Results and Discussion

1. Optical properties measurements using Kubelka Munk model

The model is used to determine absorption coefficient (μa) and scattering coefficient (μ_s) from the measured values of the total diffuse reflectance (R_d), the diffuse transmittance (T_d) and collimated transmittance T_c. These equations (Kubelka-Munk equations) are used during the domination of scattering, (25 & 26).The diffuse reflection ,transmission and collimated transmission were measured experimentally by integrated sphere method. In this work the diffuse reflection ,transmission and collimated transmission are taken from the literature, (18& 27). The results that is obtained by applying the equations of K.M written by a visual basic program then it was compared with literatures results.

1.1 Absorption and Scattering coefficient measurement

The experimental value of diffuse reflection and transmission were taken from the literatures ,(18 & 27). These values are used as input data to equations (6 & 11) to measure the absorption and scattering coefficients respectively. In the literature ,(18) , the measurements applied to the human blood with the thickness of 0.09 mm. The measured diffuse reflectance and transmittance and collimated transmittance at He-Ne laser of 633nm wavelength were found to be 0.007, 0.207 and 0.108 respectively. The absorption coefficient was obtained by applying equation (6) the result was found to be 86.23cm^{-1}.

Equation (11) was used to obtain scattering coefficient, where in the human blood the measured scattering coefficient was found to be 161.8cm^{-1}. These results were compared with the result of the literature (in the literature the results were obtained by the Inverse Adding Doubling method). The difference between the two results was 15% and 19% of absorption and scattering coefficient respectively In applying the program for the second time, the inserted values $R_{d,}$ T_d and T_c were taken from reference, (27) .

The measurement of human breast tissue is carried out with a sample thickness of 1mm at a wavelength range of (500-1000 nm). The measured diffused reflectance and transmitted were obtained by using the integrating sphere. While there is no information about collimated transmittance, we measured it by applying Beer Lambert law at each wavelength (see equation (9)). The obtained absorption coefficients were found to be equal to 0.1cm^{-1} at the wavelength range of 500 to 600 nm. The results were in perfect agreement with that taken from literature ,(27) , (i.e. 0% error). At 700 and 800 nm, the results were comparable to each other, which were found to be 0.04 and 0.042 cm^{-1} for absorption coefficient, and the literature result was found to be equal to 0.05 cm^{-1}. The difference was in acceptable limit. At 900 and 1000 nm wavelength, the absorption coefficient was found to be equal to 0.059 and 0.066 cm^{-1} respectively, also they were in good agreement with literature 0.06 & 0.07cm^{-1} (i.e. 1% & 6% error). While the scattering coefficient at 500nm wavelength was found 0.3 mm^{-1} and the literature result was 0.3 mm^{-1} ,(27). (i.e. the error 0%). At 600 nm wavelength scattering coefficient was found to be 0.42 mm^{-1} and the literature result was 0.45mm^{-1} (i.e. 7% error). At 700nm wavelength, the scattering coefficient was found to be 0.4 mm^{-1} and literature result ,(27) ,was found to be 0.38 mm^{-1} (i.e. 5% error). At 800nm wavelength scattering coefficient was found to be 0.3mm^{-1} and from literature,(27) ,it was found to be 0.28 mm^{-1} (i.e. 6% error). At 900nm wavelength scattering coefficient was found to be 0.26mm^{-1} and for the literature ,(27), it

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was 0.28 mm^{-1} (i.e. 7% error). At 1000nm wavelength scattering coefficient was found to be $0.21mm^{-1}$ and for the literature ,(27) ,it was 0.2 mm^{-1} (i.e. 4.7% error). All the discussed results above are listed in tables (1 and 2). A Kubelka Munk model was used to obtain the absorption and scattering coefficient as a function of diffuse reflection and transmission. It is simple mathematical method, and applied when scattering is dominant in the tissue and while compared with Monte Carlo and Adding Doubling models, it was found that it is a reliable method and can be used in detection of optical properties with confidence.

Table 1: Comparing K.M with Inverse Adding Doubling

	Rd	Td	µa (cm^{-1})	µs (cm^{-1})
AID method [18]	0.007	0.207	102.2	134.4
K.M method	0.007	0.207	86.23	161.8
Error			15%	19%

Table 2:Comparing K.M with Monte Carlo method [27]

λ (nm)	R_d	T_d	(MC) µa mm^{-1}	(K.M) μ_a mm^{-1}	Error %	(MC) µs mm^{-1}	(K.M) μ_s mm^{-1}	Error %
500	0.218	0.1818	0.1	0.1	0	0.3	0.3	0
600	0.3091	0.3727	0.1	0.1	0	0.42	0.45	7
700	0.2818	0.4363	0.042	0.05	19	0.4	0.38	5
800	0.254	0.4545	0.04	0.05	25	0.3	0.28	6
900	0.218	0.4727	0.06	0.059	1	0.26	0.28	7
1000	0.19	0.4636	0.066	0.07	6	0.21	0.20	4.7

2. Three dimension diffusion approximation (TDDA) results

In the current work, three dimension diffusion approximation was discussed to describe the internal distribution of photons in the sample represented by diffuse reflectance and transmittance as a function of optical properties of the tissue sample. Precedent Information of the absorption coefficient, scattering coefficient and anisotropy factor are needed to measure diffuse reflection and transmission. The optical properties were taken from the literatures ,(18&23).

The fluence rate was measured in two cases, firstly on the surface where z=0 (i.e. $\varphi(r,0)$)and at z=d (i.e. $\varphi(r,d)$). Newton Raphson method was used to obtain K_n also the trapezoidal rule of integration method was used to find Bessel functions. The block diagram of the program that calculate diffuse reflection and transmission are shown in figure (1).

2.1 Diffuse reflectance and transmittance measurement

The obtained optical properties, which are obtained by using one of the theoretical models, were taken from literature [18] were, μ_a=102.2cm^{-1}, μ_s=134.4cm^{1}, g=0.9, d=0.009 cm, p=50mw, spot size of laser beam (w_l)=0.3 cm and n=1.38, by applying the equations of TDDA, the diffuse reflectance and transmittance that found from equations , (13& 14) , were found to be 0.009 and 0.15 respectively, and by comparing it with that obtained from the literature , (18). , the results were found to be (0.007 and 0.207). The differences between the two results were found to be 28% and 25% respectively. The optical properties obtained from the literature , (23) , were that for the kidney tissue μ_a=10 cm^{-1}, μ_s=500 cm^{-1}, g=0.9, d=0.02cm, p=1w, spot size of =0.2cm and n=1.4. The obtained R_d and T_d values were found to be 0.1 and 0.08 respectively. The result was compared with the literature results , (23) , which were (Rd=0.1 and Td=0.1). The result of diffuse reflectance was perfectly equaled but there was difference in diffuse transmittance of about 20%. All these results are shown in table; (3). As seen through the comparison table the difference between the experimental results that were taken from the literature and the results of the studied models are disagreement and it needs to be re-evaluated comparing with the other methods.

Conclusion

The current work describes two different methods to determine the optical properties of biological tissue. It is also a compared between these two methods and the other methods (Monte Carlo , Inverse Adding Doubling and integrated sphere results) with further illustration about the method's reliability. The analysis of results can be summarized by the following points:

- The small percentage of error seen by comparing K.M model show that the method is practically reliable. Comparing by the other methods, it seems the most simple, fast and reliable method to determine the tissue optical properties.
- Measurement of the diffuse reflectance and the diffuse transmittance is an important issue to know the optical properties of the tissue. Our introduced model are disagree with the experimental method and it needs re evalution comparing with the other methods. So that one can enhance the accuracy in determining diffuse reflection and transmission of the laser light in the tissue.

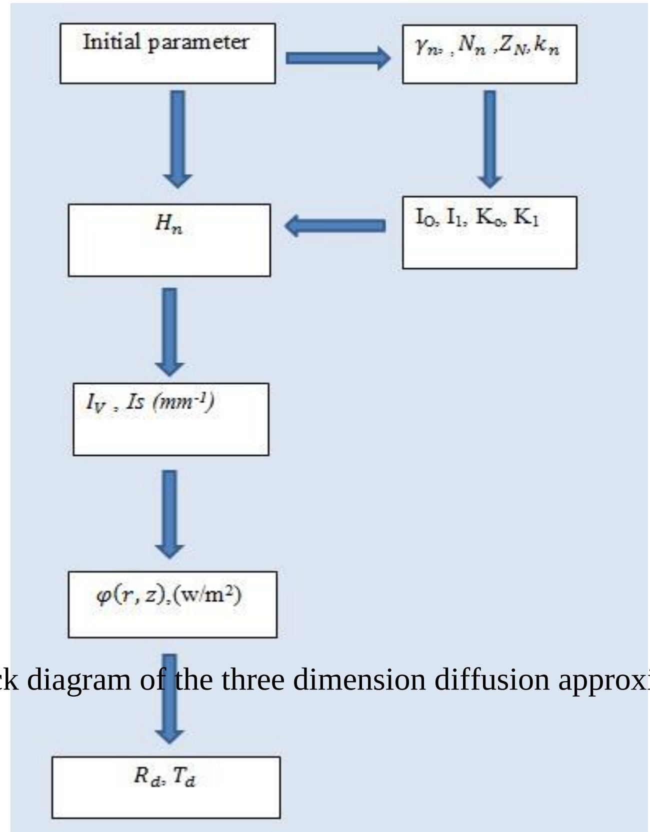

Figure 1 : Block diagram of the three dimension diffusion approximation method

Table 3: Comparing TDDA with Intgrated sphere results

Reference	Rd	Td
[18]	0.007	0.207
TDDA	0.009	0.150
Error%	0.28%	0.27%
[23]	0.1	0.1
TDDA	0.1	0.08
Error	0%	0.2%

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