Alternative Oblique-incidence Reflectometry for Measuring Tissue Optical Properties

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To deduce the optical properties, the absorption coefficient μ_a and reduced scattering coefficient μ_s', of turbid medium, Lin *et al.* (Appl. Opt. 34 : 2362-1995) proposed an oblique incidence reflectometry in which the diffusion approximation was assumed. In this paper we propose an alternative method which does not assume the diffusion approximation but uses a Monte Carlo light propagation model. Two features are extracted from the diffuse reflectance distribution detected on the medium surface, and optical properties are then estimated by looking up the predetermined table generated by Monte Carlo simulations. The validity of the proposed method has been confirmed by computer simulations.

Key words: optical property, turbid medium, oblique incidence, diffuse reflection, computer simulation, Monte Carlo simulation

1. Introduction

Multiple light scattering phenomena in turbid medium are determined by the optical properties of the medium such as the refractive index *n*, the absorption coefficient μ_a, the scattering coefficient μ_s, and the anisotropy factor g, in addition to the geometry of the medium. The scattering property is often represented by a single parameter, $\mu_s' = (1-g)\mu_s$ called reduced or transport scattering coefficient. In the case of biological tissue, optical properties of absorption and scattering are known to potentially provide beneficial information concerning the physiological condition of the tissue. The measurement of tissue optical properties is therefore an important issue in the field of biomedical optics.

A number of methods have been developed to measure tissue optical properties, including a conventional method using the integrating-sphere[1)], methods using steady-state diffuse reflectance, using time-resolved measurement [2)] or frequency-domain measurement [3,4)]. Among them, the methods using the steady-state diffuse reflectance of an incident beam have an advantage in the sense that they are noninvasive, inexpensive, and real-time measurement.

The steady-state measurements have been studied by several research groups [5-10)]. Most techniques use a normal incidence, record the diffuse reflectance at some points on the tissue surface with either fiber optics or a CCD camera, and estimate the tissue optical properties. The diffusion equation or a Monte Carlo simulation is used for estimating the optical properties. Wang and Jacques proposed using an oblique incidence and estimating the reduced scattering coefficient μ_s' from the distance between the center of the diffuse reflectance distribution and the light entry point [8)]. Lin *et al*. then presented a method for estimating both the reduced scattering coefficient μ_s' and absorption coefficient μ_a from the shape of the diffuse reflectance in addition to the distance mentioned above [9)]. These methods do not use the absolute value of diffuse reflectance in their estimation, which makes clinical application feasible. The advantage in introducing the oblique incidence is that the asymmetric shape of diffuse reflection provides additional information which is not obtainable with the symmetric shape resulting from the normal incidence.

In Lin's method, however, the tissue optical properties to be investigated are restricted because their estimation is based upon the diffusion equation which is the first order approximation of the radiative transfer equation. Since the diffusion theory is based on the assumption of a highly scattering medium, it cannot accurately model the light propagation in medium with relatively high absorption coefficient. Furthermore, with Lin's method it is possible that the solution may fall into a nonphysical one by applying a nonlinear least-squares fitting algorithm to solve the diffuse equation.

In this paper we propose an alternative method using an oblique incidence for measuring tissue optical properties. Our method uses the Monte Carlo light propagation model rather than the diffusion equation. Because we do not use the diffusion approximation, we can measure a wider range of tissue optical properties. Monte Carlo simulation causes a computational burden, and we overcome this by a look-up-table based approach. Feature extraction from the diffuse reflectance is also a key technique in this method.

2. Method

In this paper we assume that the tissue is a semi-infinite homogeneous medium with absorption coefficient μ_a, reduced scattering coefficient μ_s' and refractive index *n*. We also assume that a laser beam is incident on the medium surface obliquely and the diffuse reflectance on the medium surface is detected by a CCD area sensor. We define Cartesian coordinate, x, y, z as shown in Fig. 1 where the origin is the beam entry point, the x-y plane represents the medium surface and the projection of the obliquely incident beam onto the medium surface matches the x axis. To estimate two optical properties, μ_a , μ_s' from the diffuse reflectance, we extract two features from the reflectance measured: one is the shift of the center line from the entry point in the diffuse reflectance profile, and the other is the amount representing the degree of asymmetry of the diffuse reflectance distribution on the x-y plane. Details of these two features are described below.

2.1 Center of the Diffuse Reflectance Profile

In this section, we briefly review the method utilizing the center of the diffuse reflectance profile conceived by Wang and Jacques [8)]. When a narrow laser beam is normally injected into a semi-infinite homogeneous turbid medium, the reflection intensity distribution on the medium surface can be approximately represented by the intensity distribution that a buried isotropic-scattering point source generates. This scattering point source is located at a depth equal to one transport mean free path mfp' which is defined by

$$mfp' = 1/(\mu_a + \mu_s') . \tag{1}$$

Similarly, the reflection intensity distribution by a laser beam with oblique incidence is also approximated by an isotropic point source located at mfp' away from the beam entry point along the unscattered-light transmission path. Schematic illustration of this phenomenon is shown in Fig. 1. Due to oblique incidence, the isotropic point source horizontally shifts a certain amount away from the beam entry point. This amount, dx, is given by

$$dx = \frac{\sin\theta_{in}}{n_{rel} \cdot (\mu_a + \mu_s')} , \tag{2}$$

where θ_{in} is the incident angle and n_{rel} is the relative refractive index of turbid medium to the ambient medium. In this paper, we assumed that $\theta_{in} = \pi/4$ and $n_{rel} = 1.4$. The latter is based on the assumption that the refractive indices of the ambient layer (air) and the tissue are 1.0 and 1.4, respectively. Equation (2) is rewritten as

$$\mu_s' = -\mu_a + \frac{\sin\theta_{in}}{n_{rel} \cdot dx} . \tag{3}$$

Note that Eq. (3) provides a relationship between μ_a and μ_s', and that if a graph is plotted as μ_s' (vertical) vs. μ_a (horizontal), the function is a linearly decreasing one.

The shift dx can be obtained by the following procedure. A one-dimensional profile of diffuse reflectance along with the x axis is extracted. By finding the midpoint at each reflectance level and connecting them, one can draw a curve giving the center line of the reflectance profile as shown in Fig. 2. While the curve is gradually away from the entry point ($x = 0$) in the high reflectance region, it becomes almost parallel to the vertical axis in the low reflectance region. The shift of the vertical part from the origin corresponds to the distance *dx*.

In fact, however, the validity of Eq. (2) needs to be reconsidered. Wang and Jacques[8] conducted Monte Carlo simulations and concluded that Eq. (2) is not accurate, especially for relatively high μ_a values. They found from the simulation results that the buried scattering point source site is actually at a depth equal to $1/(0.35\mu_a + \mu_s')$ rather than mfp'. Their corrected equation is given as

$$dx = \frac{\sin\theta_{in}}{n \cdot (0.35\mu_a + \mu_s')}, \tag{4}$$

where the factor 0.35 is significant for a turbid medium which has moderately high absorption relative to scattering.

We compared Eqs. (2) and (4) for many combinations of μ_a and μ_s' by Monte Carlo simulations, and confirmed that Eq. (4) is more accurate than Eq. (2) as Wang and Jacques insisted. The results described below were all obtained using Eq. (4).

2.2 Asymmetry of Reflection Intensity

In the above subsection, we presented a linear equation, Eq. (4), relating two optical properties given the shift amount dx. To determine the optical properties (μ_a, μ_s') uniquely, another relationship between μ_a and μ_s' is needed. Moreover, this second relationship must touch or cross at one point with Eq. (4). Lin *et al.* deduced the former function by employing the diffusion theory [9]. The second relationship they used was with the effective attenuation coefficient and given as

$$\mu_{eff} = \sqrt{3\mu_a(\mu_a + \mu_s')}. \tag{5}$$

The value, μ_{eff}, is a parameter in the diffuse equation and obtained by the least squares fitting with the measured diffuse reflectance.

Our method provides a second relationship by extracting a proper feature from the measured reflectance, looking up a predetermined table of the feature, and interpolating it. The feature extracted is the degree of asymmetry of the diffuse reflectance and is defined as follows. First, the two-dimensional reflectance distribution is divided into two regions: forward and backward region for incident beam direction, then the integration of each distribution is calculated. Finally, the ratio is calculated by their difference normalized by their sum.

Figure 3 shows a schematic illustration for calculation of the ratio. In this figure $V_{forward}$ and $V_{backward}$ are the integration of reflection intensity in the forward area and that in the backward area, respectively. Using these values, the ratio is defined by

$$K = (V_{forward} - V_{backward}) / (V_{forward} + V_{backward}) . \quad (6)$$

In this paper, we call this ratio K-value. Prior to measurement, K-value is calculated using Monte Carlo simulations for many combinations of μ_a and μ_s' selected so that they cover the possible range of biological tissue sufficiently. We then put the all ratio data in an array whose horizontal axis is μ_a and vertical axis is μ_s'. We call such an array K-map.

As shown in the next section, we found through computer simulation that the K-value has the convenient property that the contour giving the same K-value is a right-up curve. This suggests that the combination of such a curve together with the decreasing function, Eq. (4), yields a unique solution stably.

Given a measured diffuse reflectance, the relationship between μ_a and μ_s' is obtained by the following procedure (see Fig. 4).

1. Calculate the ratio, $K_{measured}$, of the turbid medium by applying Eq. (6).
2. On each horizontal line, $\mu_s' = \mu_{s,j}'$, find the range of μ_a, $[\mu_{a,i}, \mu_{a,i+1}]$, which satisfies $K(\mu_{a,i}, \mu_{s,j}') \le K_{measured} \le K(\mu_{a,i+1}, \mu_{s,j}')$. Then determine μ_a corresponding to $K_{measured}$ by linear interpolation of $K(\mu_{a,i}, \mu_{s,j}')$ and $K(\mu_{a,i+1}, \mu_{s,j}')$.
3. Connect these points with lines. The connected line gives the second relationship between μ_a and μ_s'.

3. Simulation experiments

3.1 Preparation of K-Map

The K-map was first prepared by Monte Carlo simulations. The number of photons N launched in each Monte Carlo simulation is based on the following empirical formula,

$$N = \sqrt[4]{\mu_a/(\mu_a + \mu_s')} \cdot 5 \cdot 10^4. \quad (7)$$

This formula is based on the report by Kienle *et al.* [7].

In the simulation, the two-dimensional reflectance intensity is represented discretely as $P_{i,j}$ where (i, j) are integers denoting the location of the pixel. $V_{forward}$ and $V_{backward}$ are expressed by

$$V_{forward} = \sum_{(i,j)\in R_{forward}} P_{i,j}$$
$$V_{backward} = \sum_{(i,j)\in R_{backward}} P_{i,j} \quad . \quad (8)$$

Here the forward and backward area were respectively defined by,

$$R_{forward} = \{(\mathrm{i}, \mathrm{j}) \mid -120 \le \mathrm{i} \le -10, -120 \le \mathrm{j} \le 120\}$$

$$R_{backward} = \{(\mathrm{i}, \mathrm{j}) \mid 10 \le \mathrm{i} \le 120, -120 \le \mathrm{j} \le 120\},$$

where a pixel size is $0.01[cm] \times 0.01[cm]$. The center space including an incident point is not used because such treatment allows easy finding of the forward and backward area in a practical experiment. Note that as long as the investigation uses computer simulation, one can add the center space as well.

Figure 5 shows a part of the obtained K-map in forms of mesh (top) and contour image (bottom). It should be noted that the K-value gradually decreases from high μ_a and low μ_s' to low μ_a and high μ_s'. The contour map in this figure clearly shows that for any given K, μ_s' increases with μ_a monotonically.

Though we showed a part of the K-map whose range covers $0 \le \mu_a \le 1[cm^{-1}]$ and $2 \le \mu_s' \le 25[cm^{-1}]$ sampled at an interval of $0.1[cm^{-1}]$ for μ_a and $1.0[cm^{-1}]$ for μ_s', ultimately we prepared a K-map that covered a wider range. We found that a sparse K-map did not degrade the estimation accuracy very much because of the smooth variation of the value. Thus, in our ultimate K-map, the range of absorption and reduced scattering coefficients covered is $0 \le \mu_a \le 5[cm^{-1}]$ and $2 \le \mu_s' \le 25[cm^{-1}]$. This range is sparsely sampled at the $\mu_a =$ 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 2.0, 3.0, 4.0, 5.0 and $\mu_s' =$ 2, 3, 4 , 5, 10, 15, 20, 25.

3.2 Validation

To confirm the validity of the proposed method, we performed computer simulations. The confirmation procedure is as follows:

(1) Give some specific optical properties (μ_a, μ_s') to the Monte Carlo simulations and determine the reflection intensity distribution.

(2) Apply the proposed method to the generated reflection intensity distribution to obtain the estimated optical properties, denoted by $(\hat{\mu}_a, \hat{\mu}_s')$.

(3) Calculate the relative error by

$$E_a = |\hat{\mu}_a - \mu_a| / \mu_a, \quad E_s = |\hat{\mu}_s' - \mu_s'| / \mu_s',$$

and evaluate the method.

Table 1 shows the results of estimation for semi-infinite homogeneous medium with 18 different combinations of (μ_a, μ_s'). It includes the center of diffuse reflectance curves and K-value. The mean relative error in shift dx is 3.0%. The relative error for the absorption coefficient μ_a is 3.6% on average and mostly within 6%. The relative error for reduced-scattering coefficient μ_s' is 3.1% on average, which is very close to the error in dx. Figure 6 shows the error in μ_s' against the error in dx. The graph clearly shows the strong correlation between these two errors. This suggests that the accuracy in estimation of μ_s' is mainly subject to the accuracy in estimation of dx. No such a remarkable correlation was found between the error of μ_a and dx.

We briefly discuss here the accuracy in practical measurement of dx. With a sufficiently large number of photons, the diffuse reflectance profile as shown in Fig. 2 gives a stable center line, and therefore a stable value of dx. Practically, however, there is a limitation in the number of photons, which leads to the fluctuation of light intensity in the region far from the beam entry point and therefore causes an error in determination of dx. We actually performed Monte Carlo simulations in which the fluctuation of measured dx against the number of incident photons was examined and confirmed that the mean error of dx increases as the number of photons decreases. The number of photons required to obtain an accurate dx in actual measurement depends on the characteristics of the imaging system such as quantum efficiency and performance of the AD converter, as well as the optical properties of the medium under test. More detailed investigation considering practical experiments is required on this issue hereafter. As another possible factor which might affect the accuracy of dx, the size of the incident beam should be addressed as well. Theoretically, however, it was shown by Wang and Jacques [8)] that the shift value is independent of the size of the incident laser beam if the beam has a mirror symmetry about the y axis and if the size of the laser beam is smaller than the distance between the observation points and the incident point. We believe that under a normal measurement situation these conditions hold, therefore the error due to the size of incident beam can be ignored.

Figure 7 shows the relative error in absorption and reduced scattering coefficient estimation against the parameters μ_a given to the Monte Carlo simulation. It is seen that, over the wide range of μ_a, the amount of the error is stable. The proposed method achieves good accuracy for a wide range of (μ_a, μ_s'). This is due to not using the diffusion approximation. In Lin's paper[9)], only the narrow range of $0.2 \le \mu_a \le 0.6\,[cm^{-1}]$ and $4 \le \mu_s' \le 10\,[cm^{-1}]$ was presented, where the error of μ_a was 2.1% on average and the error of μ_s' was 1.2% on average. This accuracy is better than ours. However, since their method is based on the diffusion approximation in determining the effective attenuation coefficient, its accuracy would be poorer in the range of higher absorption coefficient. We will demonstrate this problem due to the diffusion approximation using computer simulations. Assuming normal incidence of a laser beam for simplicity, diffuse reflectance was obtained by both the diffusion theory and Monte Carlo simulation for two cases of optical properties:(1) $\mu_a = 0.5[cm^{-1}], \mu_s' = 10[cm^{-1}]$, (2) $\mu_a = 4[cm^{-1}], \mu_s' = 5[cm^{-1}]$. The latter is a case where the absorption coefficient is relatively large. The results are shown in Fig. 8. The discrepancy between the diffusion theory and the Monte Carlo simulation is especially remarkable in the region near the beam entry point in case (2). This discrepancy is even more serious because the region far from the beam entry point cannot be used because of the extremely weak intensity of reflection. It is widely recognized that Monte Carlo simulation provides a good prediction of real light propagation. From this example, the superiority of the proposed method using Monte Carlo simulation would be obvious.

The method presented requires a considerably long time for preparation of the K-map. Actually, it took about 20 minutes on average to calculate one K-value with a 450MHz Pentium-II PC. Calculation time is highly dependent on the optical coefficients, however, this is not a serious problem because the calculation is required only once.

4. Conclusions

We have proposed an alternative method to estimate the absorption and reduced scattering coefficients. In our method a Monte Carlo light propagation model rather than the diffusion equation is used. Using this approach, a wide range of optical properties can be estimated with high accuracy. Moreover, our method does not employ a nonlinear regression algorithm. Thus the correct solution is stably obtained without falling at any unwanted local solutions. The validity of our approach was confirmed by computer simulations. As a next step we are currently preparing a phantom experiment to make sure of the effectiveness of the described method.

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Figure caption

Fig. 1. Schematic illustration of oblique incidence and coordinate definition.

Fig. 2. Diffuse reflectance profile along with x axis and calculated center line of the profile with symbol □. The profile shown is an example obtained by the Monte Carlo simulation mentioned in section 3.

Fig. 3. Schematic illustration of calculation of the ratio, K.

Fig. 4. Part of the K-map obtained by Monte Carlo simulations and an example of interpolated function giving a specific K-value.

Fig. 5. K-map for the range of $0 \le \mu_a \le 1[cm^{-1}]$ and $2 \le \mu_s' \le 25[cm^{-1}]$.

Fig. 6. Relationship between the estimation error of μ_s' and that of dx. There is a strong correlation between them.

Fig. 7. Relative error in estimation of μ_a and μ_s' against given values of μ_a. ○, Absorption coefficient; ×, Reduced scattering coefficient.

Fig. 8. Comparison in diffuse reflectance between Monte Carlo simulation and the diffuse equation. Normal incident beam is assumed for simplicity. (a) Case that $\mu_a = 0.5[cm^{-1}], \mu_s' = 10[cm^{-1}]$,(b) Case that $\mu_a = 4[cm^{-1}], \mu_s' = 5[cm^{-1}]$, (c) Relative error of reflectance with the diffuse equation to Monte Carlo simulation in two cases.

Table 1 Result of estimation for 18 specific media. The 'expected values' of μ_a and μ_s' refers to the parameters given to the Monte Carlo simulations for diffuse reflectance generation. The expected values of dx refers to those calculated by Eq. (4) given by the μ_a and μ_s' parameters.

Table 1

Expected values [cm^{-1}]		dx [cm]		K [AU]	Estimated values [cm^{-1}]		Relative error Ea[%]	Es[%]
μ_a	μ_s'	Measured values	Expected values	Measured values	μ_a	μ_s'	μ_a	μ_s'
0.2	6.0	0.0854	0.0832	0.297	0.198	5.844	1.0	2.7
0.8	6.0	0.0789	0.0804	0.397	0.816	6.115	1.9	1.9
1.5	6.0	0.0776	0.0774	0.465	1.541	5.972	2.7	0.5
2.3	6.0	0.0740	0.0742	0.522	2.321	6.014	0.9	0.2
3.2	6.0	0.0709	0.0673	0.568	3.500	6.277	9.4	4.6
4.2	6.0	0.0676	0.0676	0.603	4.335	5.949	3.2	0.9
0.2	12.0	0.0418	0.0424	0.251	0.214	11.834	6.7	1.4
0.8	12.0	0.0411	0.0398	0.333	0.787	12.411	1.6	3.3
1.5	12.0	0.0403	0.0395	0.393	1.571	12.221	4.8	1.8
2.3	12.0	0.0394	0.0396	0.440	2.341	11.947	1.8	0.4
3.2	12.0	0.0385	0.0377	0.480	3.161	12.197	1.2	1.6
4.2	12.0	0.0375	0.0358	0.518	4.325	12.585	0.6	4.9
0.2	18.0	0.0280	0.0304	0.222	0.187	16.565	6.9	8.7
0.8	18.0	0.0276	0.0286	0.297	0.824	17.378	2.9	3.6
1.5	18.0	0.0273	0.0281	0.348	1.475	17.439	1.7	3.1
2.3	18.0	0.0269	0.0251	0.391	2.487	19.285	8.1	7.1
3.2	18.0	0.0264	0.0246	0.431	3.516	19.303	9.9	7.2
4.2	18.0	0.0255	0.0259	0.463	4.192	18.325	0.2	1.8