POLARIZATION MEASUREMENT OF BACKSCATTERING FROM TURBID MEDIA FOR TISSUE CHARACTERIZATION

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Abstract: We present a newly developed system for 2D angular pattern of the backscattering light from turbid media and also propose a Monte Carlo method for backscattering of polarized light in sphere suspension. This system can detect the specific angular distribution by backscattering from highly scattering materials. The experimental results of polystyrene sphere suspension coincide well with the simulation results. Proposed method has potential to be an in vivo monitoring system for tissue characterization.

Introduction

Scattering properties of tissue depend on cell size, cell constituents and cell structure, therefore the measurement of scattering light has potential to be an useful tool for tissue characterization and metabolism monitoring and so on. Especially backscattering is very sensitive to size of sub cellular structure, and also to polarization state.

Several researchers have been studied about the backscattered polarized from turbid media [1]-[5]. Those study intend to observe the surface of sample with imaging optics. When the sample has very low scattering coefficient, those systems provide good results and are able to obtain backscattering pattern images, which contain information about optical parameters of scattering substances. Basically those optical systems are not different from photographic cameras'. But actual biological material does not form characteristic pattern because mean free path is too short and multiple scattering is too strong. Mechanism of the formation of backscattering pattern on surface of scattering materials was discussed in literature [2].

Conventional method to study scattering of biological material is goniophotometric measurement, however this method need to prepare sample as thin slice.

In this paper we propose an experimental system to measure the 2D (2-dimensional) angular pattern of polarized backscattering light from turbid media, to derive single scattering component which has specific angular distribution pattern depending on the constituent and structure of scattering substance. We do not aim to observe surface image of the scattering materials illuminated by polarized light but attempt to detect the angular distribution of back scattered light using 2D imaging sensor. We also demonstrate a Monte Carlo simulation to estimate the photon propagation behavior of our experimental system.

Methods

We are concerned with the 2D pattern, which can be observed by the system shown in Fig.1. In our study polarized laser beam was led into the samples through a pinhole plate placed on a sample container. The incident beam was scattered and spread in the sample, however only backscattered light which could passed through the pinhole radiated outward like point light source.

Thus by placing 2D photon sensor above the sample container as shown in fig.1, backscattered light in the direction of scattering angle θ and azimuthal angle φ from the pinhole projected on the 2D sensor at the corresponding XY position.

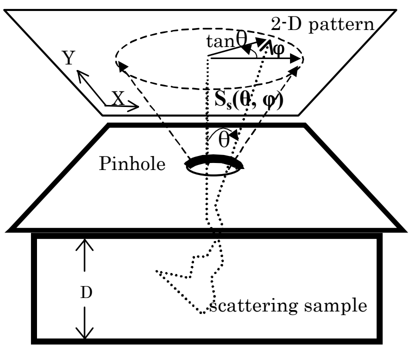

Figure 1 Explanatory graphics for 2D angular pattern of the backscattering

Figure 2 shows the actual experimental system. For the experiment we used a He-Ne laser (wavelength of λ=633nm, beam diameter 1.5mm) as a light source. Polarized laser beam through the first linear polarizer LP1 was introduced onto the sample by small mirror M1. The sample was covered with optical glass window and black pinhole plate. The backscattered light from the sample through the pin-hole was projected on a imaging plate of C-MOS imaging sensor (49.8mm x 49.8mm). A detecting linear polarizer LP2 was placed in front of the C-MOS imaging sensor to chose the polarization direction. A strong specular reflection from the optical glass window was ejected by the mirror M1. The sample cuivette was plased on a magnetic stirrer to prevent particle sedimentation.

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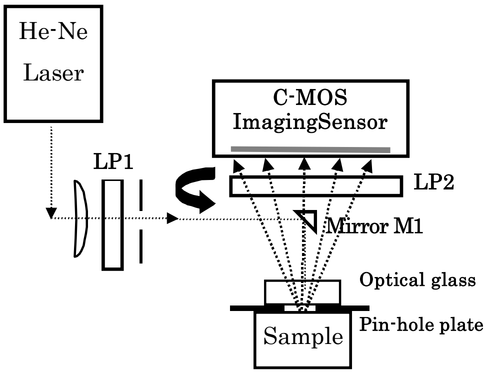

Figure 2 Experimental System for 2D angular pattern of the backscattering

Simulation

To validate our experiment and to expect the 2D projection image, we performed Monte Carlo simulation by using the coordinate as illustrated in Figure 1. As shown in this figure, backscatterd light which has the scattering direction to the angle of θ and φ is projected at the corresponding pixel on X-Y plane of imaging sensor. Thus our simulation results are 2D photon density distribution of angular pattern. The scattering of the polarized light from turbid media can be conveniently simulated using Monte Carlo method incorporating with the Stokes vector representation of polarized light. By one scattering event an incident Stokes vector Si is modified to an outgoing scattered Stokes vector Ss which has scattering direction in azimuthal angle φ and scattering angle θ, as

$$\mathbf{S}_{\mathrm{s}} = \mathbf{M}(\theta)\mathbf{R}(\varphi)\mathbf{S}_{\mathrm{i}} \qquad (1)$$

written in formula (1) with Rotation vector $\mathbf{R}(\varphi)$ and Mueller matrix $\mathbf{M}(\theta)$, where

$$\mathbf{R}(\phi) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\phi & \sin 2\phi & 0 \\ 0 & -\sin 2\phi & \cos 2\phi & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \qquad (2)$$

$$\mathbf{M}(\theta) = \begin{bmatrix} m_{11}(\theta) & m_{12}(\theta) & 0 & 0 \\ m_{12}(\theta) & m_{11}(\theta) & 0 & 0 \\ 0 & 0 & m_{33}(\theta) & m_{34}(\theta) \\ 0 & 0 & -m_{34}(\theta) & m_{33}(\theta) \end{bmatrix}. \qquad (3)$$

Muller matrix $\mathbf{M}(\theta)$ can be determined if we know the value of refractive index of suspending medium and susupended shere, diameter of the sphere and light wave length by Mei theory. To use Mie distribution for photon traces in Monte Carlo method is time-consuming. So that we applied the time reduction technique to angle sampling of light direction proposed by Frank Jaillon et. al [5].

Results

Simulations

Prior to the experiment we performed simulations to predict 2D angular pattern of backscattered light and to prepare for adequate experimental set up. First of all we demonstrate simulation results of 2D backscattering patterns by different size of scattering particle in water. In Figure 3 the patterns (a) are results for suspension of polystyrene spherer of 3.5 μm in diameter, and the patterns (b) are those of polystyrene spherer of 5.0 μm in diameter respectively. Each scattering sample shows specific scattering pattern and it is recognized that patterns are very sensitive to the size change of particle. The reduced scattering coefficient (μs') of the simulation models (a) and (b) are 1mm^{-1} and 4mm^{-1} respectively, and scattering coefficient (μs') of those are 7.36mm^{-1} and 26.6mm^{-1} respectively.

Figure 4 shows the 3D graphics of angular distribution pattern to esimate the effect of pinhole size on the angular distribution of backscattered light. Radius of the circular view plane in these graphs corresponds to the scattering angle of 25°. The Z axis in these graphs represent the photon density ratio to the unit power of incident light intensity. The scattering material was spherical particles suspension in water illuminated by 633nm porlarized beam. The scattering particle was polystrrene sphere(refractive index of the particles:1.59) of 3.5μm in diameter, and its concentration in water was set to redused scattering coefficient μs'=1.0mm. In this case scattering coeffcinet becomes 7.37mm^{-1} and mean free path length is 0.136mm.

As shown in the Figure 4 the smaller pinhole provided the more clear scattering pattern, the pinhole only surpress the magnitude of background component due to multiple scattering and does not affect the magnitude of ripples on the characteristic scattering pattern. Therefore it is obvious that the characteristic patterns which have information about scattering particle and medium result from the scattering phenomenon occured at only very small volume around incident point. In our actual experiment, 2mm pinhole plate was mainly used, because positioning of the laser beam was moderate.

Consecutively we estimated how large volume contributed to the detected 2D image. Figure 5 shows the 3D graphics of angular distribution pattern of the same scattering materials with various sample thicknesses. In all calculations aperture of pinhole was fixed to 2mm. In Figure 5 the patterns on the upper row are parallel polarization and those on the lower row are cross polarization. As shown here, characteristic scattering patterns were recognized in both parallel and cross polarization in all cases.

The patterns (a) for 0.1mm slab thickness showed the most clear angular distribution pattern. The patterns (b) for 1.0mm slab thickness, the patterns (c) for 2.0mm slab thickness and the patterns (d) for 10.0mm slab thickness showed almost same distribution pattern.

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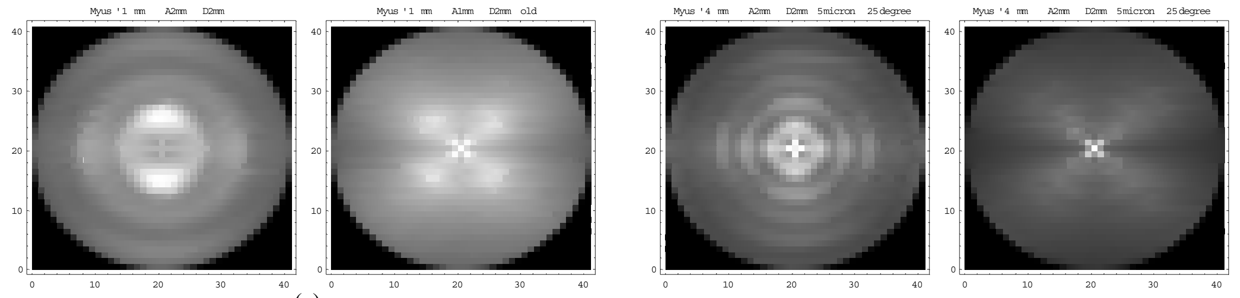


(a) (b)

Figure 3 Comparison of 2D patterns by polarized backscattered light for particle suspension of different particle in size. (a) Polystyrene sphere (refractive index n=1.59), particle diameter d=3.5µm. (b) Polystyrene sphere (refractive index n=1.59), particle diameter d=5.0µm. Left panel is parallel polarization, that is incident beam is horizontally polarized and detecting polarizer is oriented horizontally. Right panel is cross polarization that is incident beam is horizontally polarized and detecting polarizer is set vertically. Aperture of pinhole is 2mm and scattering angle of view plane is 25 degrees. Size difference was clearly appeared on the patterns. Scattering angle of view plane is 25 degree.

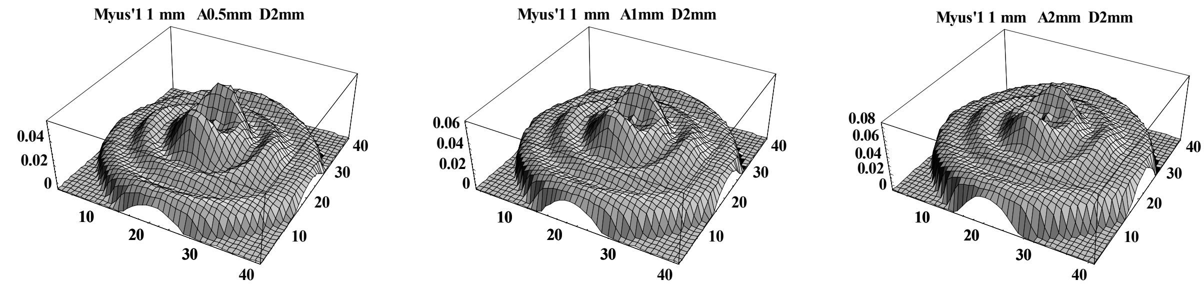
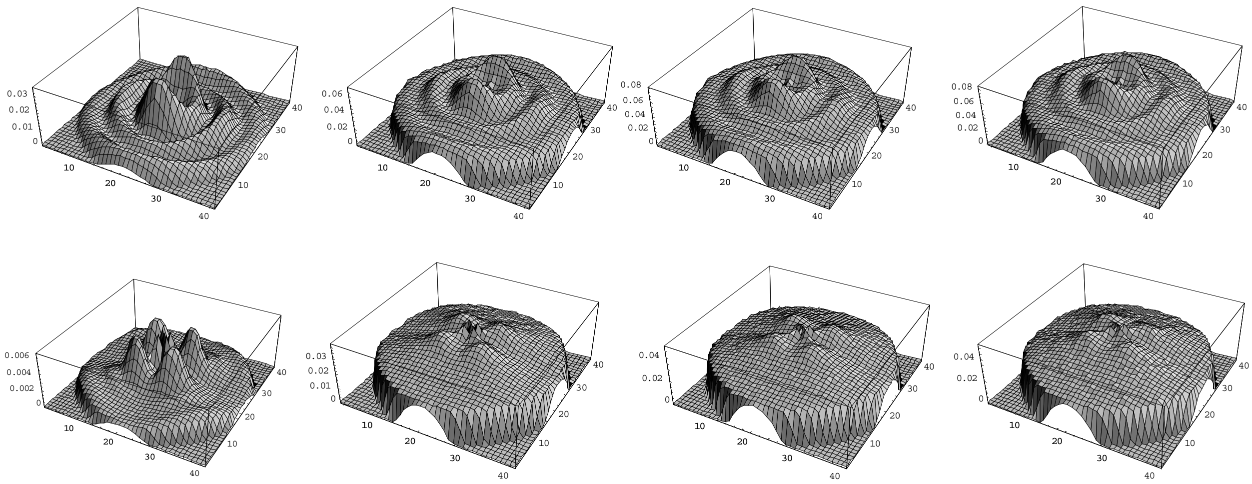


Figure 4 Comparison of 2D angular distribution pattern by polarized backscattered.
All results are by parallel polarization. (a): Aperture of pinhole is 0.5mm in diameter. (b) Aperture of pinhole is 1mm in diameter. (c) Aperture of pinhole is 2mm in diameter.
Model sample is polystyrene suspension in water (refractive index of particle n=1.59, particle diameter d=3.5µm, reduced scattering coefficient $\mu s' = 1.0mm^{-1}$). Scattering angle of view plane is 25 degree.



(a) D=0.1mm (b) D=1.0mm (c) D=2.0mm (d) D=10mm

Figure 5 Sample depth dependency of simulation results of 2D backscattering pattern.
Geometrical condition: pinhole aperture:2mm, Slab thickness; (a)D=0.1mm, (b)D=1.0mm, (c)D=2.0mm, (d)D=10mm. Sample: particle diameter:3.5µm, refractive index of particle:1.59, refractive index of suspending medium:1.333, wavelength: 633nm, scattering coefficient μs:$7.37mm^{-1}$, reduced scattering coefficient $\mu s'$:$1.0mm^{-1}$.

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Especially patterns (c) for 2mm slab thicness are identical with patterns (d) for 10mm slab thicness. This result is quite reasonable from the value of μs' (1.0mm) so that over 1mm distance from the incident position, photon start to propagate diffusively. From this rerult, we estimated that 2 times of the inverse of reduced scattering coeficient was enough depth for sample in simulation when pinhole aperture was 2.0mm in diameter.

Besides when sample depth is thinner than the inverse of scattering coeficient (mean free path length) like Figure 5 (a), multiple scatttering component decreases, so that clear specific angular pattern is ovserved, .but unignorable number of incident photons are to extinct without scattering. In case of Figure 5 (a) the sample thickess was only 0.1mm, and this slab thickness was insufficient to collect total number of backscattered photons by single scattering.

Experiment

We used polystyrene sphere powder (SX300, Soken Chemical & Engineering Co.) which was industrial grade, having average diameter 3.6mm, and mixed it into deionized water with small quantities of detergent.

Figure 6 is 2D backscattering pattern by this sample adjusted to have reduced scattering coefficient μs'=1mm^{-1}. Aperture of pinhole was 2mm. Left panel is parallel polarized pattern and right panel is cross polarized pattern respectively. The radius of view plane corresponds to the scattering angle of ±17°.

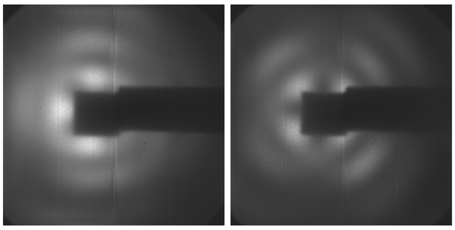

Figure 6 2D image of the backscattered light by the C-MOS imaging sensor.
Incident beam was fixed to horizontal polarization.
(a) Detecting polarizer LP2; horizontal,
(b) Detecting polarizer LP2; vertical.
Sample; 3.5μm polystyrene sphere suspension in water μs'=1.0mm$^{-1,}$ μs=7.3mm^{-1}. Diameter of pinhole was 2mm. The black shadow from right to the center is by a mirror holder for the mirror M2 in the Figure 2.

As shown in this figure the scattering pattern of parallel polarization showed concentric ring patterns and that of cross polarization showed high intensity areas in the diagonal directions. The experimental patterns were blurred by background light or some other fluctuations, however showed similar pattern to the simulation results shown in the Figure3 (a).

Conclusions

We proposed a newly experimental system which was able to obtain 2D angular pattern of backscattering from turbid medium. We also presented simulation results applied for our system. The simulation results showed that the characteristic patterns which have information about scattering particle and medium result from the scattering phenomenon occured at only very small volume around incident point, and reduced scattering coefficient μs' became good index for estimating the influence of diffusive multiple scattering on the 2D angular pattern. For our system with 2mm aperture pinhole it was enough to take into account the space volume with the scale of 2 times of the inverse of reduced scattering coefficient μs'.

Small pinhole system suppresses the diffusive multiple scattering, so that angular distribution of informative single scattering component can be observed by our system as 2D image. Theoretically it is suggested that the pinhole size can be reduced to the scale of mean free path length, however that of submillimeter is too small and unrealistic for actual experimental system. Therefore 2mm diameter pinhole plates were used

We verified that the proposed system could obtain 2D angular pattern of backscattered polarized light from even high scattering materials which had μs'=1mm^{-1} and was equivalent to biological materials. To apply our method for tissure characterization, further improvement of experimental system and new approaches to interpret the 2D patterns of angular distribution to tissure structure and constituents are needed.

Acknowledgement

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