Probing turbid medium structure using ultra low coherence enhanced backscattering spectroscopy

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ABSTRACT

We report on experimental results and theoretical investigation on probing the structure of turbid medium using ultra low coherence enhanced backscattering spectroscopy where the spatial coherence length of the incident line light is not greater than 25 µm. The periodic structure contained in the low coherence enhanced backscattering spectroscopy is found to decrease with the dominant scatterer size. A theoretical model is proposed to explain the observations and is verified by Monte Carlo simulations.

Keywords: reflectance spectroscopy, coherent backscattering, turbid medium, low coherence backscattering

1. INTRODUCTION

Backscattering of light has been widely used in optical probing of tissue. To probe the superficial layer of tissue which is of most interest in, for example, sensing the epithelium for potential pathological changes, the detector must be placed close to the source. To the same end, spatially low coherence light may be used to limit the penetration depth via detecting enhanced backscattering light. Enhanced backscattering is the phenomenon that the intensity of backscattered light is found to enhance around the exact backscattering direction, originating from the constructive interference between the light waves propagating along a pair of time-reversal trajectories.[1–5] When illuminated by a low coherence source with the spatial coherent length, L_c, much less than the transport mean free path, l_t, of light in the medium, only light remitting within the coherence area $\sim L_c^2$, much smaller than the illuminated area, participates in enhanced backscattering and diffuse light which travels much deeper into the medium is greatly rejected.[6–8] The enhancement factor approaches two in the limit of a long spatial coherent length and decreases proportional to L_C/l_t in the limit of a small spatial coherent length ($l_s < L_C \ll l_t$ where l_s is the scattering mean free path).[8]

We have implemented an ultra low coherence enhanced backscattering spectroscopy (ULEBS) system using a line source generated by a Xenon lamp. The spatial coherence length of the incident beam is not greater than 25 µm, much smaller than either scattering or transport mean path in typical biological tissue. ULEBS has been used to exam enhanced backscattering from tissue phantoms and *ex vivo* tissue samples. Both intralipid-20% suspensions and a set of suspensions of polystyrene spheres with diameters ranging from 0.19 µm to 8.31 µm were investigated. A periodic structure is found to be contained in the low coherence enhanced backscattering spectrum whose period decreases with the scatterer size.

In this brief report, we first present the ultra low coherence enhanced backscattering spectroscopy system and the experimental findings on the low coherence enhanced backscattering spectrum obtained from intralipid and polystyrene sphere suspensions. We then present a theoretical model to explain the experimental observations and verify that by electric field Monte Carlo simulations.

2. EXPERIMENTS

The schematic diagram of the low coherence enhanced backscattering spectroscopy system is shown in Fig. 1. The light source is a Xenon lamp (Newport, 75W). The lens L1 and L2 form a $4f$ system and a slit of variable width is placed on the Fourier plane. The width of the slit controls the spatial coherence length of the beam incident upon the sample. The two polarizers P1 and P2 are oriented in either horizontal or vertical direction and hence four different pairs of linear polarization (ss, sp, ps, and pp) of the incident and scattering light can be detected. The entrance slit of the imaging spectrograph is positioned at the focal plane of the lens L3. The spectrograph disperses light in the direction perpendicular to the entrance slit according to the wavelength. As a result, backscattered light by the sample at different scattering angles and of different wavelengths (350 - 650 nm) is recorded at different pixels on the CCD (CoolSnap HQ2, Photometrics). The specular reflected light by the sample will not be detected by the camera through setting the angle of the specular reflectance of the incident beam outside the detectable scattering angular range.

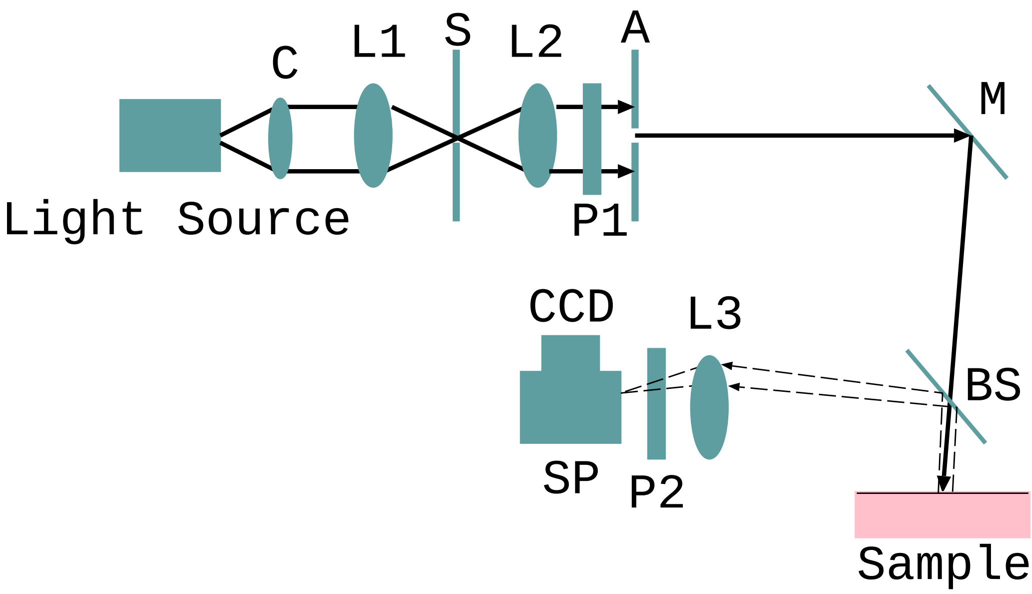

Figure 1. The schematic diagram of the low coherence enhanced backscattering spectroscopy system. C: condenser, L1, L2, L3: lenses, S: slit, A: aperture, P1, P2: polarizers, BS: beamsplitter, M: mirror, SP: spectrograph. The CCD camera images the focal plane of lens L3. It records a 2D image of the intensity of backscattered light versus the scattering angle and the wavelength of reflected light.

We used the low coherence enhanced backscattering spectroscopy system to investigate enhanced backscattering of light by intralipid-20% suspensions and a set of suspensions of polystyrene spheres with diameters ranging from 0.19 µm to 8.31 µm. These suspensions were diluted by de-ion water before measurements to reach the transport mean free path of $1-2\mathrm{mm}$ at the wavelength of $500\mathrm{nm}$ of the incident beam.

Fig. 2 displays the spectra of backscattering light from suspensions of a set of polystyrene spheres of diameters $0.95\mu m$, $2.06\mu m$, $4.19\mu m$, and $8.31\mu m$. These spectra were normalized by the spectrum measured for diluted intralipid-20% suspension using the same system. The purpose of the normalization is to remove the effect of variations in the spectrum of the incident light source and the spectral response of the optical imaging system. It is clear the spectra exhibit an oscillatory pattern whose period depends on the size of the scatterer, particularly for polystyrene spheres of size $2.06\mu m$ and $4.19\mu m$. The period (in wavelength) of the oscillatory pattern decreases with the increase of the size of the scatterer.

3. THEORY

When illuminated by a low coherence source, the intensity of the low coherence backscattering light is expressed for a collimated low coherence beam with near normal incidence as[8,9]:

$$I_{\mathrm{CBS}}(\mathbf{q}_\perp) = \frac{1}{A}\int d\boldsymbol{\rho}_1 \int d\boldsymbol{\rho}_2 I(\boldsymbol{\rho}_2-\boldsymbol{\rho}_1)\exp\left[i\mathbf{q}_\perp\cdot(\boldsymbol{\rho}_2-\boldsymbol{\rho}_1)\right] J(\boldsymbol{\rho}_1,\boldsymbol{\rho}_2) \tag{1}$$

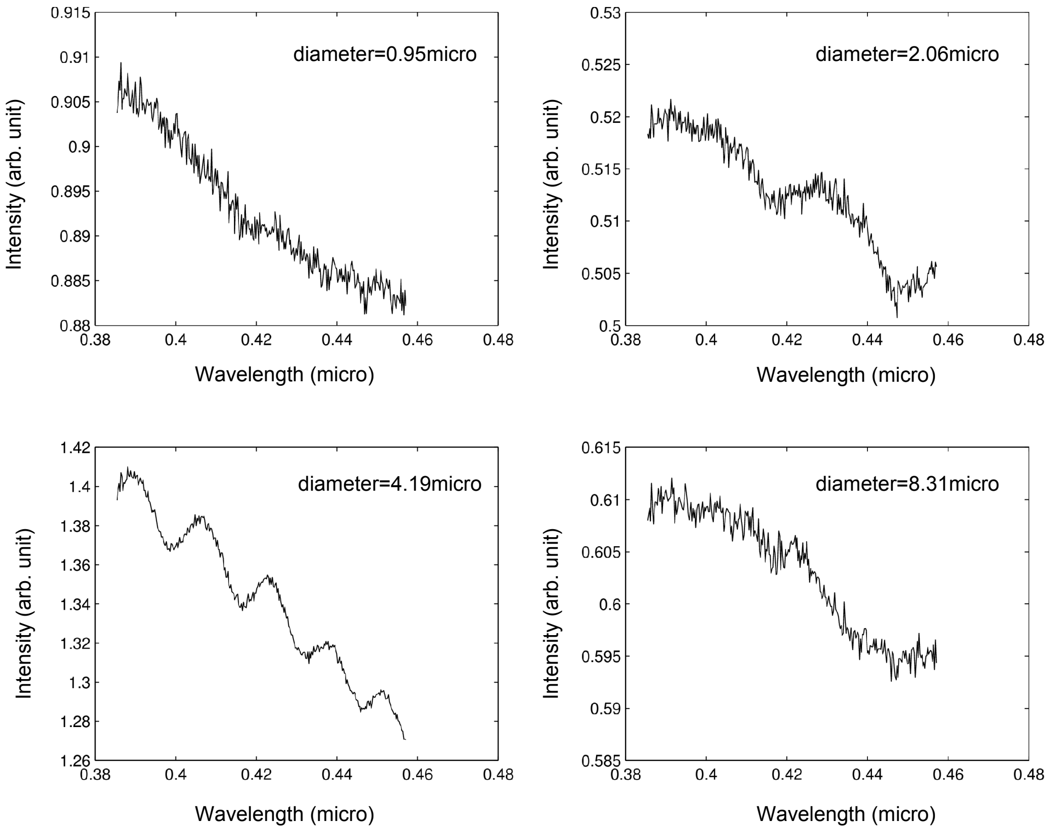

Figure 2. The normalized spectra of backscattering light from suspensions of a set of polystyrene spheres of diameters $0.95\mu m$, $2.06\mu m$, $4.19\mu m$, and $8.31\mu m$.

where $\boldsymbol{\rho}_{1,2}$ is the incident point of light on the surface of the sample ($z = 0$), the integrations of $\boldsymbol{\rho}_{1,2}$ are over the illumination area A, $I(\boldsymbol{\rho})$ is the intensity of incoherent backscattered light for a beam incident upon the medium at the origin and escaping the medium at $\boldsymbol{\rho}$, $q_\perp \simeq k\theta_b$ with $k = 2\pi/\lambda$ the wave number of light in the air and θ_b the angle between the incident and outgoing directions, $\mathbf{q}_\perp \cdot (\boldsymbol{\rho}_2 - \boldsymbol{\rho}_1)$ is the phase delay due to the longer time-reversed path, and $J(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2)$ is the complex degree of coherence of fields which is given by[10]

$$J(\boldsymbol{\rho}_1, \boldsymbol{\rho}_2) = \mathrm{sinc}(kp_x w/2)\,\mathrm{sinc}(kp_y L/2) \tag{2}$$

for illuminating light when a slit of width w in the x direction and height L in the y direction is placed on the Fourier plane S where $p_x = (x_1 - x_2)/f$, $p_y = (y_1 - y_2)/f$, f is the focal length of the lens L2, and $\mathrm{sinc}(x) = \sin(x)/x$ is the sinc function. The intensity of incoherent backscattered light is proportional to the backscattering efficiency of the scatterer. For the scatterers investigated in the experiments, the backscattering efficiency contains a component proportional to $\cos\left[\pi(m^2+1)n_{\mathrm{water}}d/\lambda\right]$ where d is the diameter of the polystyrene sphere, n_{water} is the refractive index of water, and $m = n_{\mathrm{polystyrene}}/n_{\mathrm{water}}$ is the relative refractive index of the polystyrene sphere. This component in I gives rise to the periodic structure observed in Fig. 2 and predicts that the period of the periodic structure contained in the low coherence enhanced backscattering spectrum decreases with the scatterer size.

Electric field Monte Carlo simulations were performed for low coherence backscattering of light from a semi-infinite medium of water solutions of Mie scatterers.[11, 12] The Mie scatterers are polystyrene spheres of diameter $4.19\mu m$. In simulation, a matched refractive index boundary is assumed. The backscattered light intensity $I(\rho)$ in the exact backscattering direction at a distance ρ away from the incidence point is simulated for a pencil beam normally incident upon the surface. A similar trend was observed in the results of Monte Carlo simulations.

4. CONCLUSION

In summary, we have developed an ultra low coherence enhanced backscattering spectroscopy system using a line source generated by a Xenon lamp. We observed a periodic structure contained in the low coherence enhanced backscattering spectrum whose period decreases with the size of the scatterer. We attributed the oscillatory pattern in the low coherence enhanced backscattering spectrum to the wavelength dependence in the backscattering efficiency of the scatterer.

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