MULTIPLE SCATTERING OF POLARIZED LIGHT IN BIREFRENGENT TURBID MEDIA: A MONTE CARLO SIMULATION

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Abstract: Non-invasive optical methods for inspection of biological tissues are of growing interest, mainly in medicine and food control. Biological tissue represents a complex turbid material in which multiple scattering randomizes incident polarization states. Modeling photon propagation with one of Monte Carlo methods is a flexible yet rigorous approach to simulate photon transport. In the method, photon transport is expressed as probability distributions which describe the step size of photon movement between sites of photon-tissue interaction and the angles of deflection in a photon trajectory when a scattering event occurs. The paper deals with major steps in this investigation.

Keywords: biological tissue, anisotropy, polarization, scattering, Monte Carlo

1. INTRODUCTION

Biological tissue is turbid optically very complex material due to its inhomogeneity, anisotropy, and nonlinearity. Therefore optical measurement methods used in noninvasive processing of tissues in medicine and in food engineering could not extract all essential data information on their structure [1,2,3].

However, the properties of foods are important in the process design and manufacture of food products. Most of these properties indicate changes in the chemical composition and structural organization of foods ranging from the molecular to the macroscopic level.

A non-destructive optical study of material characteristics in processed meat needs a complex approach involving both scattering and polarization as well as mathematical simulations. Monte Carlo simulation is an effective method for the investigation of light propagation in turbid media, such as biological tissues. The source code of a Monte Carlo program for simulating the behavior of photon transport in multilayered turbid media was made public [4]. The first Monte Carlo models were developed for intensity calculations only and neglected polarization. More recently, a number of implementations have incorporated polarization into their Monte Carlo models. [5,6]

2. MONTE CARLO ANALYSIS OF MULTISCATTERED LIGHT

The proposed Monte Carlo analysis of multiple scattering events of light in turbid media is based on the radiative theory. It is assumed that the scattering event of light is independent and has no coherence effects. In addition, we assume that all of the linearly birefringent tissue can be looked on as a uniaxial material with the slow axis (the orientation with higher refractive index) along the direction of the collagen fibers and the fast axis (the orientation with lower refractive index) along the cross section. Scattering is assumed to be caused by the spherical particles that randomly suspend among the birefringent media. The birefringent effect of the considered medium is homoge-

neous everywhere in the sample, which means that, for different positions in the sample, the birefringent orientation and the birefringent value are the same. The geometry of a multiple scattering event is shown in Figure 2. In this figure, we assume that the direction of the slow axis of the linear birefringence is along the *x* axis. Photons are scattered in the medium by spherical particles, therefore Mie theory can be used to describe the scattering events. Diffusely backscattered photons are recorded as a function of (x',y') on the upper surface of the medium.

Simulation of the photon trajectories in Monte Carlo method consists of the following key stages:
- injection of the photon in the medium, generation of the photon path-length,
- generation of a scattering event,
- definition of reflection/refraction at the medium boundaries,
- definition of detection and
- accounting for the absorption.

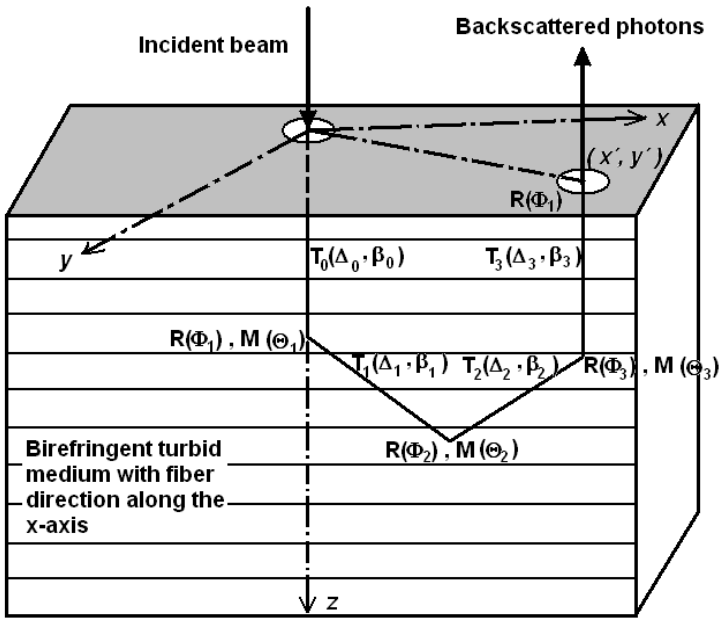

Figure. 2. Geometry of a multiple scattering event in a linearly birefringent turbid medium.

A Stokes vector $\mathbf{S}_0$ describes the polarization state of the incident photon packet. An individual photon packet propagates in the turbid medium until it is scattered by a spherical particle.

The transport path length *s* between two adjacent scatters is randomly sampled according to $s = - \ln(\xi)/\mu_T$, where ξ is the random number between 0 and 1, and $\mu_T = \mu_a + \mu_s$ is the interaction coefficient. At each scattering point, an individual photon packet will drop part of its energy and the loss is represented by $\Delta w = w\mu_a / \mu_T$, where *w* is the weight of the photon packet before the scattering event. In a scattering event, the photon packet will select a polar angle θ and an azimuthal angle ϕ to decide the orientation of the next step. The angle ϕ is positive for a counterclockwise rotation.

Once the polar angle θ and the azimuthal angle ϕ are known, the Stokes vector of the photon packet in the new local coordinate system is given by

$$\mathbf{S}'' = \mathbf{M}(\theta)\mathbf{R}(\phi)\mathbf{S}', \tag{1}$$

where

$$\mathbf{R}(\phi)=\begin{bmatrix}1 & 0 & 0 & 0\\ 0 & \cos(2\phi) & -\sin(2\phi) & 0\\ 0 & \sin(2\phi) & \cos(2\phi) & 0\\ 0 & 0 & 0 & 1\end{bmatrix},\quad \mathbf{M}(\theta)=\begin{bmatrix}a(\theta) & b(\theta) & 0 & 0\\ b(\theta) & a(\theta) & 0 & 0\\ 0 & 0 & d(\theta) & -e(\theta)\\ 0 & 0 & e(\theta) & d(\theta)\end{bmatrix}. \qquad (2)$$

are Mueller matrices.

S'' and **S'** are the Stokes vectors before and after the scattering event, respectively. **R** is the rotation matrix that connects the two Stokes vectors that express the same polarization state of the photon packet in two different reference planes. One reference plane coincides with another after it rotates an angle f around the propagation direction of the photon packet. **M** is the single scattering matrix deduced from Mie theory.

The polar angle θ and the azimuthal angle ϕ are not uniformly distributed between [0,π] and [0,2π]. Sampling of θ and ϕ depends on the probability density function (PDF) of θ and ϕ that is a function of the incident Stokes vector. Figure 3 shows the difference between Standard Monte Carlo program [4] and program involving polarized light.

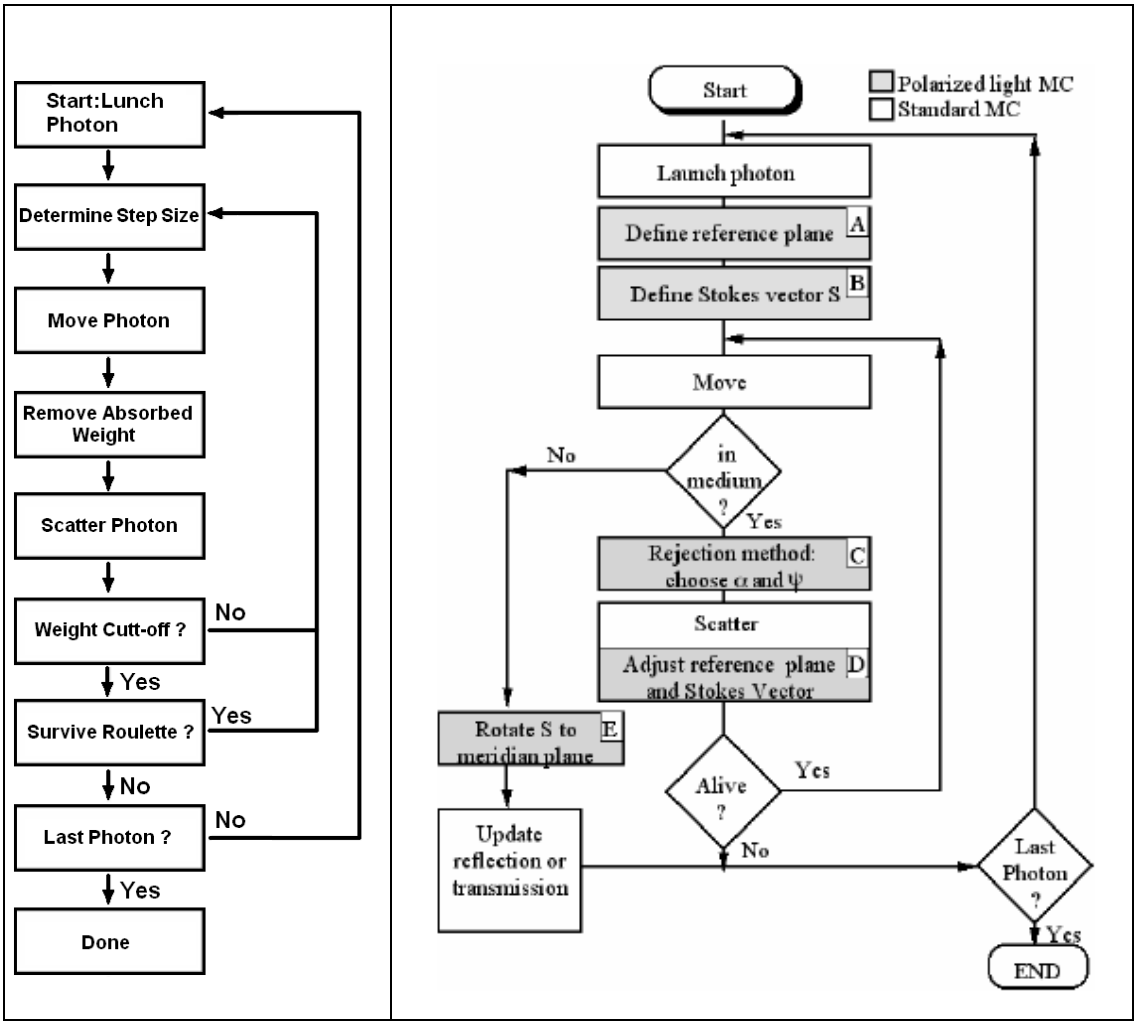

Figure 3. Flow chart of Standard Monte Carlo program (left) [4] and proposed Polarized Light Monte Carlo program (right). The white cells are used in Standard Monte Carlo programs, while the gray cells are specific of Polarized Light Monte Carlo programs.

4. RESULTS

The experimental system used in our experiments is drawn schematically in Fig. 4 [7]. We used a focused He–Ne laser (λ = 632.8 nm) whose beam diameter d = 1.5 μm is normally incident onto the medium (meat tissue). The emerging light within an area of (2 × 2) cm^2 around the point of incident was reflected onto a photomultiplier tube replaced here by 14-bit CCD camera.

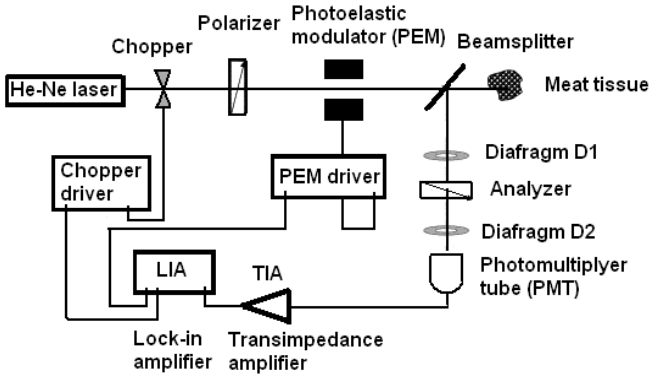

Figure 4: Schematic of the experimental system for measuring polarization properties of back-scattered diffusely reflected light from a turbid biological sample.

The photoelastic modulator (oriented at 6° off normal incidence with respect to the incident beam direction, to negate the effects of modulated specular interference) oscillates in the plane of the optical table. The polarizer is at 0° and 90° with respect to the plane of the optical table, and the orientation of analyzer is set to rotate in the 0–360° range. D_1 and D_2 are pinhole diaphragms.

Three kinds of chicken breasts were investigated: frozen (-18°C), cooled (+4°C), and fresh (+20°C) [8]. The skin and fat were removed, and the chicken breasts were cut so as to have only one muscle fiber orientation.

We have considered the meat sample as a linearly birefringent turbid medium consisting of a stack of horizontal fibers with diameter of 2 μm.

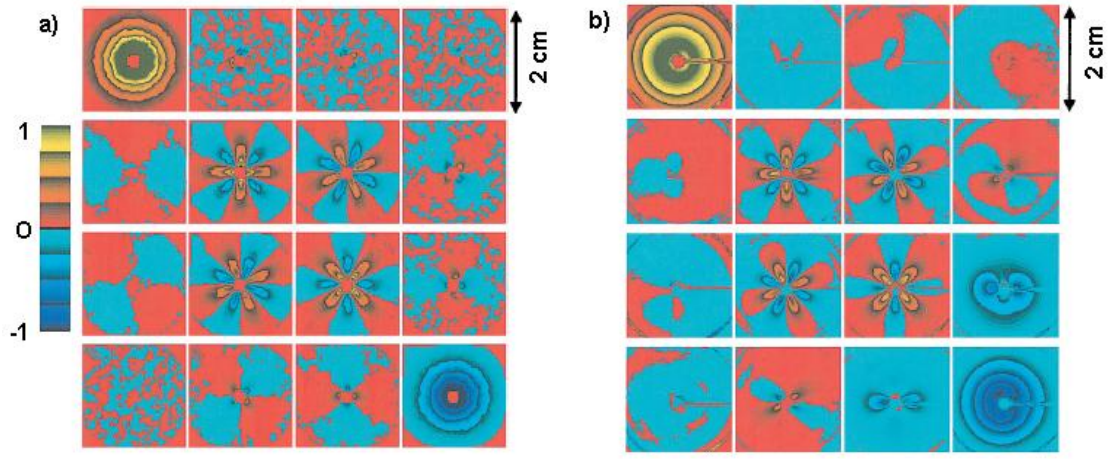

Figure 5. a) Simulated back-scattering Mueller matrix for suspension of linear fiber with diameter of 2 μm. Each image displays a (2 × 2) cm^2 area of the surface. b) Experimental back-scattering Mueller matrix for fresh chicken breast fibers. Each image displays a (2 × 2) cm^2 area of the surface.

5. CONLUSIONS

Precise knowledge of biological tissues optical properties are essential for medical and food quality control investigations. Therefore a modeling photon propagation with one of various Monte Carlo methods is a flexible yet rigorous approach to simulate photon transport. In this method, photon transport is expressed as probability distributions which describe the step size of photon movement between sites of photon-tissue interaction and the angles of deflection in a photon trajectory when a scattering event occurs. We have experimentally found that the diffused light has the depolarization state depends on the direction of muscle fiber.

The presented results show that the Monte-Carlo method, which incorporates a polarization of back-scattered light into its model is a versatile technique allowing to solve the Radiative Transfer Equation and simulate photon transport in turbid biological media over the whole range of material properties. On the other side this method is time-consuming with normal PC processing.

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