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A Monte Carlo study of penetration depth and sampling volume of polarized light in turbid media

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Abstract

Detection depth and sampling volume of polarized light in highly turbid, cylindrically-shaped samples are estimated using pathlength distributions calculated from a polarization-sensitive Monte Carlo model. Due to defined ranges of the polarized light pathlength distribution, the estimated penetration depth and the interrogated volume of the polarization-maintaining photon subpopulation are smaller than those of the whole collected photon population, the latter exhibiting a wider pathlength distribution resulting from multiple scattering. It is also demonstrated that the spatial interrogation extent of polarized light in turbid media is greatly affected by the experimental detection geometry.
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1. Introduction

There has been increasing interest in applying light for medical diagnostics and therapeutics. In these applications, it is important to ensure that the light reaches a particular target within the tissue. However, determination of the light penetration depth and interrogated volume is difficult because biological tissue is highly scattering, causing the photons to travel in a complicated non-unique zigzag fashion way, thus exhibiting a statistical distribution of possible paths. Nevertheless, the estimation of these parameters may be achieved by investigating the pathlength distributions of photons migrating in, and escaping from, turbid media.

So far, great effort has been put into the investigation of light distribution and penetration depth in the scattering media experimentally and numerically [1–12]. These studies have mostly dealt with semi-infinite or slab planar geometries. A less explored geometry is cylindrical [13–17], which may be of special importance in biomedicine, for example in noninvasive blood glucose monitoring for diabetics. These optical blood glucose measurements are often performed on fingers or lips, whose curved surfaces may be well represented by cylinders of varying dimensions. The cylindrical geometry may also provide additional experimental flexibility (0° to 360° detection directions), permitting detection of angle-dependent (goniometric) signals with potentially valuable information content; it may also prove clinically convenient. Therefore better understanding of photon migration in cylindrical turbid samples is needed.

Some of the optical investigations have suggested the use of polarized light for studying highly turbid media [2,4,13–25]. For example, the change in the photon's polarization

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state, quantified by metrics such as the optical rotation α of the linear polarization fraction [2,4,15–24] and surviving linear (circular) polarization fraction β_L (β_C) [15–19,24,25], provides valuable insight into the scattering and depolarization processes, and may yield useful measures for characterizing turbid media. In addition to the glucose problem, other emerging applications of turbid polarimetry in which the developed formalism (including its cylindrical embodiment) may play a role include birefringence mapping for quantifying tissue collagen anisotropy [24,26], and polarization gating for enhanced optical tissue imaging [20,27–30]. Here we present an approach to estimate the penetration depth and sampling volume of linearly polarized light in highly scattering cylindrical samples, using Monte Carlo-modeled pathlength distribution statistics [17]. This paper is a continuation of our previous work of determining the pathlength distributions in turbid media [17], in that the pathlength distributions are used in the developed formalism for penetration depth/sampling volume estimation. An elliptically shaped detection depth distribution and ellipsoidal shaped sampling volume are derived, and their dependence on pathlengths, polarization state, and detection geometry are investigated. The details of polarized and depolarized pathlength distribution derivations were investigated in a previous paper [17] using a polarization-sensitive Monte Carlo (MC) model developed in our group [18,19], where additional modeling information pertinent to the current study may be found.

2. Geometry of the polarization-sensitive Monte Carlo simulation

Fig. 1 is a schematic of the cylindrical geometry used in our ongoing experimental studies [17] and in the Monte Carlo simulations that follow, from which the pathlength distributions were calculated. A 632.8 nm horizontally linearly polarized beam of 1 mm diameter is incident on a vertically oriented cylindrical sample of 0.8 cm diameter and 4 cm height. Linearly polarized light may be particularly pertinent for the glucose monitoring application, because the glucose-induced optical rotation, if measurable in turbid media, can be linked to its concentration. The scattered photons that exit at point $P(z, \theta)$, within a 14° acceptance angle ψ are collected by a detector of 1 mm diameter circular active area. The detection direction angle θ, varying from 0° to 180°, is between the incident forward direction and the normal of the interface at point P. "z" is the vertical position of point P with respect to the horizontal incident plane. The sample is a water suspension of 4.1 μm diameter polystyrene microspheres, with a scattering coefficient $\mu_s = 100\ \text{cm}^{-1}$, close to the turbidity of biological tissue. Calculated from Mie theory [31], the scattering anisotropy g (a measure of the amount of forward direction retained after a single scattering event) is 0.884. The absorption coefficient is $0.00326\ \text{cm}^{-1}$ to account for the contribution from water. This study deals with achiral (glucose-free) media; ongoing and future work will concentrate on the polarization effects of glucose, and will be reported separately.

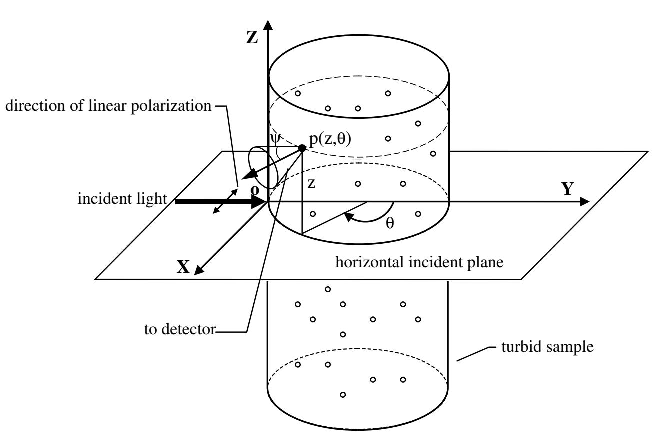

Fig. 1. Cylindrical geometry used in the MC simulations. Linearly polarized light incidents at O on a vertically oriented cylindrical sample. The scattered light is collected by a small detector element at $P(z, \theta)$ on the surface of the cylinder with an acceptance angle ψ. Z is the distance of the detector off the horizontal incident plane and θ is the detection direction (the angle between the forward direction y and the normal to the detector element).

The boundary of the cylinder in the Monte Carlo simulations is defined as an interface between the turbid suspension and the air surrounding the cylinder. This differs slightly from the experimental situation in that the thin glass walls of the cuvette are neglected. This is done to reduce the complexity and the computational requirements; future Monte Carlo simulations will incorporate its effects and an experimental study will examine its importance. The boundary conditions at the sample/air interface are that a photon is either reflected or transmitted. The probability of reflection or transmission is calculated from the polarization-dependent Fresnel coefficient and the polarization state of the incident photon at that point. The photon's Stokes vector and propagation direction are modified according to whether a reflection or a transmission event occurs. If the photon is reflected, the propagation inside the sample continues; if transmitted, its experimentally observable Stokes vector is computed [19].

3. Theoretical analysis

3.1. Estimation of detection depth using MC-derived pathlength distribution

Due to the multiply scattering nature of turbid media, it is challenging to estimate a unique penetration (detection) depth of the photons, either experimentally or theoretically. The resulting distribution of photon paths precludes a single value description, yielding instead a statistical distribution of photon travel histories. The situation may appear even more complex if one considers polarization effects. However, the detection depth might be estimated

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