Noninvasive measurement of scattering anisotropy in turbid materials by nonnormal incident illumination

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Many existing methods for the recovery of optical parameters from turbid materials rely on the diffusion approximation, which does not permit the recovery of the degree of anisotropy in the scattering phase function. These methods also make the explicit assumption that light is normally incident at the top surface of the material. We demonstrate a steady-state imaging technique that uses nonnormally incident light to determine anisotropy parameter g by fitting Monte Carlo simulation results to high dynamic range images of the intensity profiles of samples. The proposed method is simpler than existing methods and does not rely on thin samples to produce reasonable results. © 2006 Optical Society of America

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Noninvasive methods for determining the optical properties of biological materials are useful for diagnostic and therapeutic medicine. Optical parameters of these turbid materials are commonly recovered by obtaining reflectance measurements from a normally illuminated turbid sample and fitting those measurements to the results of a numerical simulation or analytical model. The optical properties of turbid materials are characterized by absorption coefficient μ_a, scattering coefficient μ_s, and the phase function. The phase function is typically modeled by use of a Henyey–Greenstein phase function, which is accurate for forward scattering materials such as biological tissue[1] and is characterized by scattering anisotropy parameter g. Measuring g usually requires *in vitro* time-domain measurements from optically thin tissue slices[2]; it can be difficult to make such measurements of sensitive tissue, such as tissue from the brain.[3] Other methods, such as the $\delta-P_1$ approximation, require *a priori* knowledge of the range of the g parameter.[4]

Monte Carlo numerical methods for comparing measured data with a computer model[5] are accurate but require long computation times to achieve reasonable results. The diffusion approximation combined with the method of images is a popular approximation to radiative transfer that yields accurate parameter estimation for highly scattering materials.[6,7] Diffusion-based methods make the explicit assumption that scattering within the material is isotropic (i.e., $g=0$), and they cannot be used to recover the parameters of the phase function. For materials with anisotropic scattering, diffusion-based methods use similarity theory[8] to combine g and μ_s into a reduced scattering coefficient, $\mu_s'=(1-g)\mu_s$, and effectively assume that the material exhibits isotropic scattering. Another limitation of diffusion-based methods is that they fail to predict the reflectance profile when the material is nonnormally illuminated.

Our goal is to determine *in vivo* the optical properties μ_a, μ_s, and g by utilizing a simple, steady-state domain imaging technique. Using nonnormally incident illumination and Monte Carlo numerical simulations, we have found that a few measurements are sufficient to determine all three optical properties. Although nonnormally incident illumination was used previously to measure μ_a and μ_s',[9,10] to the best of our knowledge this is the first time that it has been applied to the recovery of the g parameter.

We measured the optical properties of commercially available skim milk held at room temperature. This material has characteristics similar to those of many biological materials: It is strongly forward scattering, with scattering dominating absorption.

Our experimental setup consists of a container for holding the liquid measurement sample, a camera for imaging the surface of the liquid, and a white point-light source with focusing lenses to illuminate a single point on the surface of the liquid (Fig. 1). The container is large enough that we may assume that the liquid is semi-infinite and that no light reflects at the edges. The light source can be positioned to illuminate the liquid with a focused beam of light from a variety of angles. Similarly, the camera can be posi-

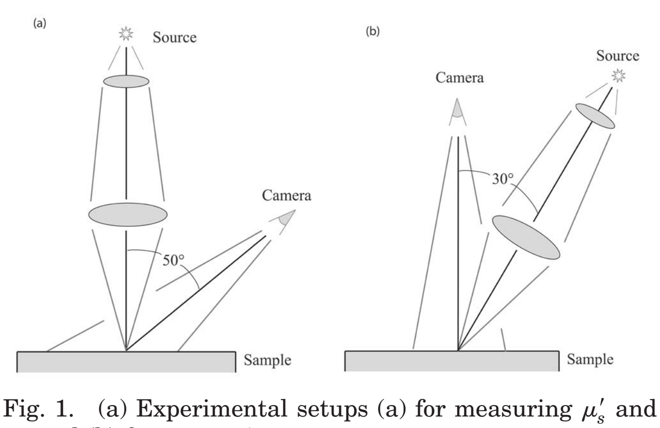

Fig. 1. (a) Experimental setups (a) for measuring μ_s' and μ_a and (b) for measuring g.

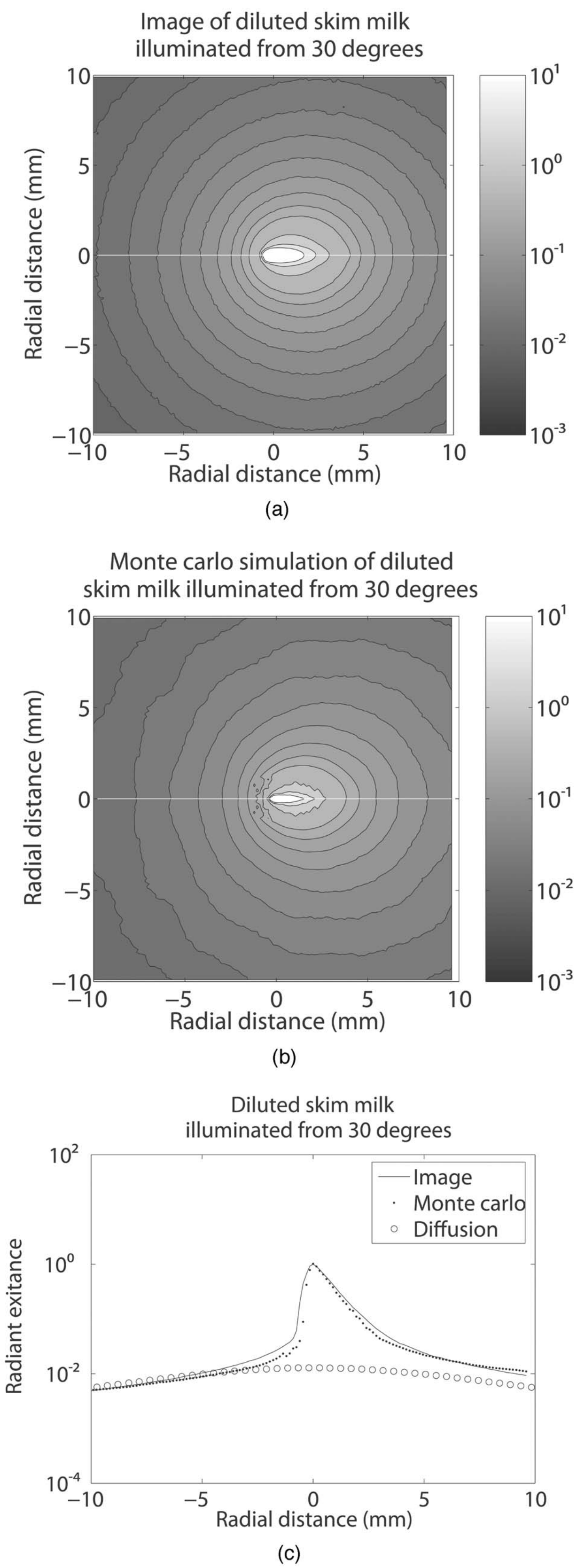

Fig. 2. (a) Radiant exitance for the green color channel data from our skim milk measurement. (b) Results of fitting by a Monte Carlo simulation with $g=0.7$. (c) Intensity profiles for the central scan lines indicated by white lines in (a) and (b) and the result predicted by dipole diffusion.

tioned to image the liquid from different viewing angles.

The measurement process consists of two steps. First, using the configuration shown in Fig. 1(a), we illuminate a sample of the liquid with a narrow beam of light normally incident onto its surface and measure the radiant emittance as a function of distance to the point of illumination. For this purpose we use a high dynamic range image constructed from multiple exposures of the sample.[11]

We calculate the absorption and reduced scattering coefficients by fitting this measurement, using a Levenberg–Marquardt algorithm, to the radiant emittance predicted by the dipole diffusion model.[7] The fitting is done independently for each color channel and can conceivably be performed for a single wavelength of incident light. Assuming that the container is semi-infinite, we can use the dipole diffusion model to predict the shape of the reflectance profile, R, at the surface.

To obtain reflectance from our measurement we divide the radiant emittance by a calibrated scale factor corresponding to the intensity of our light source and fit it to the following expression for R (Ref. 7):

$$R(r) = \frac{\alpha'}{4\pi}\left[\frac{z_p(1+r_p\mu_{\text{eff}})\exp(-r_p\mu_{\text{eff}})}{{r_p}^3} + \frac{z_n(1+r_n\mu_{\text{eff}})\exp(-r_n\mu_{\text{eff}})}{{r_n}^3}\right], \qquad (1)$$

where r is the distance to the point of illumination; $r_p=(r^2+{z_p}^2)^{1/2}$ and $r_n=(r^2+{z_n}^2)^{1/2}$ are the distances to the dipole sources; $z_p=1/({\mu_s}'+\mu_a)$ and $z_n=z_p+4AD$ are the distances above and below the surface of the positive and negative sources, respectively; $\mu_{\text{eff}}=(\mu_a/D)^{1/2}$ is the effective transport coefficient; $\alpha'={\mu_s}'/({\mu_s}'+\mu_a)$ is the reduced albedo; $D=[3({\mu_s}'+\mu_a)]^{-1}$ is the diffusion constant; and $A=[1+\rho_d(\eta)]/[1-\rho_d(\eta)]$ takes into account diffuse internal reflectance owing to a mismatch in index of refraction at the surface.[12] Internal diffuse reflectance ρ_d is

$$\rho_d(\eta) = -0.4399 + 0.7099\eta^{-1} - 0.3319\eta^{-2} + 0.0636\eta^{-3} \qquad (2)$$

and depends only on the ratio of indices of refraction η. For our experiments we use existing measurements of the index of refraction.

We then dilute the sample with purified water to a 1:12 concentration and take measurements for recovering the anisotropy parameter and scattering coefficient. Although dilution is not strictly necessary for the successful application of our method, by increasing the relative contribution of single scattering we reduce the sensitivity of our method to measurement noise.

To measure anisotropy parameter g we illuminate the sample from a nonnormal angle; we used 30° for our experiments, as shown in Fig. 1(b). High dynamic range images of the diluted sample are taken with the camera placed directly above the incident location of the beam of light. (The viewing angle is 0°.) As

Table 1. Recovered Optical Parameters

	Parameter		
Color of Skim Milk	g	μ_s	μ_a
Red	0.7	2.33	0.0014
Green	0.7	3.596	0.0015
Blue	0.6	4.75	0.0142

there is a large contribution from single scattering, the measured intensity profile deviates significantly from the result predicted by diffusion theory [Fig. 2(c)].

Since the nonnormal angle of illumination emphasizes the effects of anisotropic scattering, the g parameter for the material can be recovered. To accomplish this, we perform a parameter search over the range of valid g values ($-1<g<1$), using several Monte Carlo simulations. Each Monte Carlo simulation traces photons from the virtual light source into the material; the photons are scattered inside the material according to given optical parameters, and the photons that reach a virtual detector are recorded by a method similar to that used by Wang *et al.*[5] Each individual simulation runs for approximately 1 h on a cluster of 60 CPUs. The simulation parameters (incident light angle, camera location, aperture size, etc.) are calibrated to match the actual experimental setup. The optical parameters used in the simulation are the absorption and reduced scattering coefficients computed from the dipole model fit, scaled according to the dilution of the sample.

After several runs of the Monte Carlo simulation, we select the value of g that gives the lowest error fit, in the least-squares sense, between the Monte Carlo simulation and the captured high dynamic range image. Using this value of g, we compute the scattering coefficient from the reduced scattering coefficient, using similarity theory[8]:

$$\mu_s = \frac{\mu_s'}{1-g}. \tag{3}$$

Using the above technique, we calculated $g \approx 0.7$ for skim milk, which matches well the values reported in the literature.[13] Figure 2 shows the measurement and fitting result for skim milk illuminated from 30°. For the skim milk we used $\eta = 1.3485$.[14] Table 1 summarizes our measurement results.

In conclusion, we have developed a simple noninvasive method for measuring the full optical parameters of a turbid material sample. We plan to measure more materials, and we are interested in how our method works with materials that cannot be diluted, particularly human skin. We plan to improve our experimental setup to increase the accuracy of our measurements and are looking into improving the fitting by incorporating multiple measurements taken with more illumination and camera angles. We believe that the extra measurements will enable us to estimate the index of refraction as well. Finally, we are investigating whether analytical methods can be adapted to model the effects of nonnormal incident light. This would remove the need for costly Monte Carlo simulation and greatly improve the speed of fitting.

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