Anisotropy of light propagation in biological tissue

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We investigated the propagation of light in biological tissues that have aligned cylindrical microstructures (e.g., muscle, skin, bone, tooth). Because of pronounced anisotropic light scattering by cylindrical structures (e.g., myofibrils and collagen fibers) the spatially resolved reflectance exhibits a directional dependence that is different close to and far from the incident source. We applied Monte Carlo simulations, using the phase function of an infinitely long cylinder, to explain quantitatively the experimental results. These observations have consequences for noninvasive determination of the optical properties of tissue as well as for the diagnosis of early tissue alterations. © 2004 Optical Society of America

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Knowledge of the dependence of the propagation of light in biological tissue on the microstructure of the tissue is important for applications in the early diagnosis of diseases. Many tissue types have aligned cylindrical microstructures caused, for example, by myofibrils, axons, or collagen fibers. The scattering by these cylindrical structures results in anisotropic light propagation, which one can study by measuring the spatially resolved reflectance $R(x,y)$. In this method the tissue is perpendicularly illuminated (in the z direction) by a small light beam, and the spatially resolved remission from the tissue surface is detected with a CCD camera.[1] If the propagation of light is isotropic, the isointensity contours of $R(x,y)$ are circles; however, in tissue that has an aligned cylindrical structure, such is not the case. Figure 1 shows the spatially resolved reflectance obtained from an experiment with a porcine artery. Here the isointensity contours of $R(x,y)$ are ellipses. The main axes are perpendicular to the cylindrical scatterers (myofibrils from the media layer of the artery, whose axes are oriented in the direction indicated in Fig. 1) of the tissue at small distances (<1 mm). In contrast, at large distances (>1.5 mm) the main axes of the ellipses are parallel to the cylindrical structures. In this Letter we explain, for the first time to our knowledge, the full anisotropic pattern of $R(x,y)$.

In the literature it has almost always been assumed that the propagation of light in tissue is isotropic. Only a few authors have reported on anisotropic propagation of light in tissue. Marquez *et al.* stated that determination of the optical properties in muscle depends on the direction of the myofibrils.[2] This was also found true for skin and, in addition, the elliptical contours of $R(x,y)$ at large distances (>1 mm) were measured.[3] We found indications of different orientations of the ellipses at different distances for measurements of dentin[4] and, recently, also for bone and skin.[5]

A theoretical model to describe anisotropic light scattering was introduced by Nickell *et al.*, who applied Monte Carlo simulations by using a direction-dependent scattering coefficient.[3] With this model the $R(x,y)$ ellipses at large distances could be approximately obtained. Recently an anisotropic random-walk theory was reported,[6] and an anisotropic diffusion equation was derived from the radiation transport equation.[7] However, these models are capable of describing the anisotropy only for large distances.

For the explanation of the $R(x,y)$ pattern we consider both scattering by a single cylinder and multiscattering by many cylinders. The scattering of a plane wave by an infinitely long cylinder can be described by analytical solution of Maxwell's equations (Mie theory for a cylinder).[8] If the angle between the incident direction of the photon and the direction of the cylinder is termed ξ, the calculations show that the photons are scattered only in certain directions, namely, in a cone with the cylinder as the axis of the cone that has half-angle ξ.[9] Thus, if the incident direction is perpendicular to the cylinder ($\xi = 90°$), the cone turns into a plane perpendicular to the direction of the cylinder. Another result from this theory is that the scattering coefficient for $\xi \approx 90°$ is much larger than that for $\xi \approx 0°$. To calculate the propagation of light through a turbid medium that has many cylinders we used the Monte Carlo method.[10] In detail,

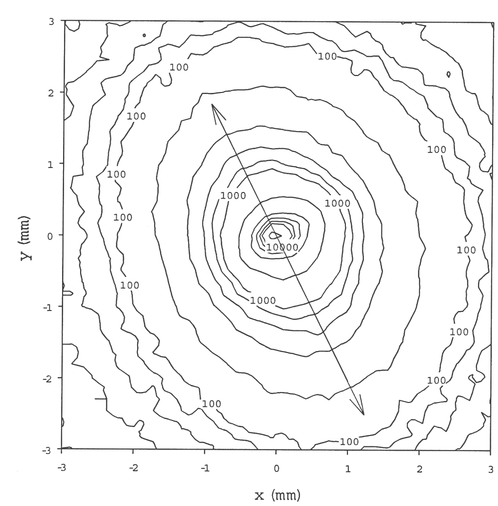

Fig. 1. $R(x,y)$ pattern (in arbitrary units) of a porcine artery. An unpolarized He–Ne laser at $\lambda = 633$ nm served as the source, and the reemitted light was imaged onto a CCD camera.

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the photons are incident at $x = y = 0$ perpendicular to the xy plane onto the surface of a semi-infinite turbid medium. We assumed that the incident beam is unpolarized, as was the case in the experiment shown in Fig. 1. The directions of the cylinders are approximately parallel to the surface, as is found in many tissue types. More precisely, it is assumed that the cylinders are distributed along the x axis and have a Gaussian distribution with standard deviation $\Delta\eta$. In the Monte Carlo simulation, first, an actual direction from the probability distribution of the cylinder directions is calculated. From this value, ξ is obtained by use of the direction of the incident photon. Then, from Mie theory for a cylinder, the scattering coefficient for this ξ value is computed, from which the length to the next scattering location is deduced. Next, the new scattering direction is determined from the scattering cone mentioned above. This is accomplished by a coordinate transformation and by use of the phase function from Mie theory for a cylinder. Then the next cylinder direction is calculated, and the ξ value relative to the actual direction of the photon is determined. This procedure is continued until the photon is absorbed or remitted, in which case the surface location of the remission is stored by the computer. For the calculations of the scattering coefficient and the phase function of the cylinders we used 2 μm as the thickness of the cylinders and 1.33 and 1.52 as the refractive indices of the cylinders and of the surrounding medium, respectively. These values are those for dentin and for the cylindrical scatterers in dentin, i.e., the tubules.[10] However, using other values for these quantities does not alter the principal results of the simulations. The absorption coefficient of the turbid medium was set to $\mu_a = 0.01\ \text{mm}^{-1}$, a typical value for tissue in the red-wavelength region.

First, $R(x,y)$ was simulated for cylinders lying in the direction parallel to the x axis ($\Delta\eta = 0$). Considering the scattering by a cylinder when the incident light is perpendicular to the cylinder axis, it follows that the scattered light will always stay in the plane perpendicular to the cylinder axis and, therefore, that the light will be remitted in a line parallel to the y axis (not shown). In Fig. 2(a) $R(x,y)$ was calculated for cylinders that were aligned not exactly parallel to the x axis but with $\Delta\eta = 10°$. It can be seen that at small distances the isointensity lines are elongated in the y direction owing to the presence of photons that are remitted after a few scattering interactions. In contrast, at large distances the isointensity lines are elongated in the x direction. Because of the different directions of the cylinders, the photons can propagate in arbitrary directions after many scattering iterations. Therefore the photons will propagate farther along the x axis because the scattering coefficient parallel to the cylinders is much smaller than that which is perpendicular to the cylinders. Similar results are obtained for $\Delta\eta = 20°$ [Fig. 2(b)], but now the isointensity lines are more elongated in the x direction and their shapes are elliptical. This $R(x,y)$ pattern is close to that found in the experiment (Fig. 1). The isointensity lines for an isotropic distribution of the cylinders are circular as expected for an isotropic medium [Fig. 2(c)].

For the simulations in Fig. 2 it was assumed that the cylindrical structures are the only scatterers in tissue. However, there are also structures in biological tissue that scatter light independently of the incoming direction. Figure 3 shows $R(x,y)$ obtained from the Monte Carlo simulation of a turbid medium that contains cylinders along the x axis with $\Delta\eta = 0°$ and, additionally, isotropic scatterers characterized by $\mu_s = 10\ \text{mm}^{-1}$ and $g = 0.9$, assuming a Henyey–Greenstein phase function. The figure shows that the elliptical isointensity lines are perpendicular to the cylinder's axes at short distances and parallel to their axes for large distances. These results are similar to the remission pattern measured experimentally (Fig. 1). Here the isotropic scattering component results in photons that can travel in any direction in space, and thus the protons that are multiscattered and remitted at large distances from the incident beam are influenced mainly by the different scattering coefficients parallel and perpendicular to the axes of the cylinders.

In summary, we have shown that the elliptical isointensity contours of the remitted light observed in many biological media can be explained as being due to scattering by the constituent cylindrical structures. We demonstrated that one can obtain the experimentally determined isointensity curves both by assuming that the scatterers are solely cylinders that have a certain distribution of their directions or by adding isotropic scatterers to the cylindrical scatterers with $\Delta\eta = 0°$.

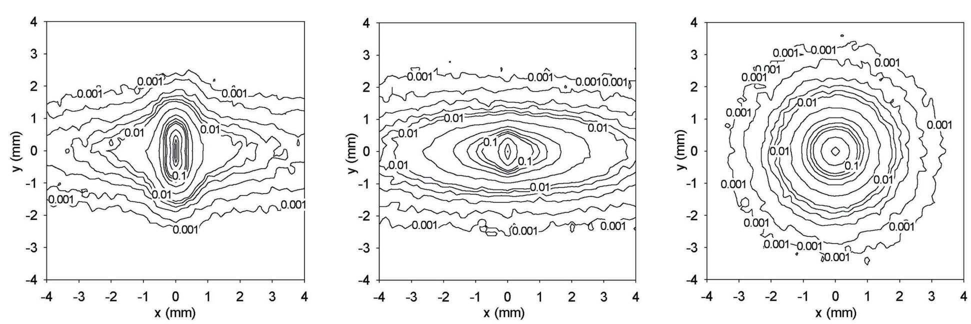

Fig. 2. $R(x,y)$ pattern (mm^{-2}) obtained from Monte Carlo simulations of a semi-infinite turbid medium containing cylinders along the x axis with (a) $\Delta\eta = 10$, (b) $\Delta\eta = 20$, and (c) for an isotropic distribution.

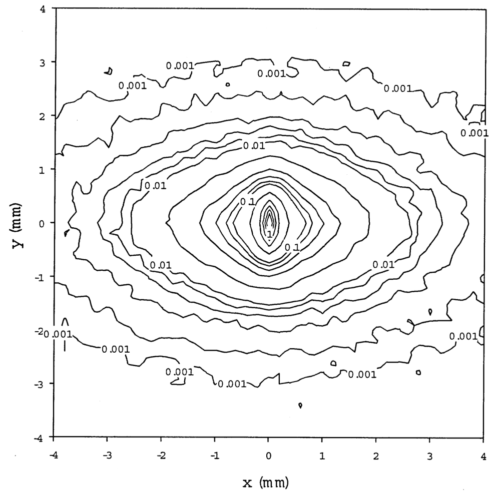

Fig. 3. $R(x, y)$ pattern (mm^{-2}) obtained from Monte Carlo simulations of a semi-infinite turbid medium containing isotropic scatterers and cylinders along the x axis with $\Delta\eta = 0$.

These findings may have an important effect on the diagnosis of early tissue alterations because the elliptical isointensity curves at small distances are highly sensitive to local alterations of the superficial cylindrical structures.

In addition, we found that, if isotropic models are used to determine the optical coefficients of anisotropic tissue, values with large errors may be derived. For example, the optical coefficients derived from the spatially resolved reflectance for an isotropic distribution of cylinders [Fig. 2(c)] by use of a standard isotropic model of the diffusion theory have errors of $\sim$10%, which are typically due to the diffusion approximation. However, if the optical coefficients are derived for the anisotropic cases shown in Figs. 2(a) and 2(b), the derived values for the absorption coefficient are completely wrong as a result of applying the isotropic model.

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