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Measurement and Modeling of Light Transmission through Turbid Media

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The use of visible radiation to characterize materials and elucidate structural details comparable to the wavelength of light (400-700 nm) is well established (van de Hulst 1957). Within the current research areas of nanoscience and nanoparticles, optical techniques are proving useful as probes of structure (Shalish et al. 2004). One area that is currently receiving much attention these days is the propagation of light in biological tissue (Cheong et al. 1990; Bearden et al. 2001). Much progress has been made in understanding the mechanisms for light absorption and scattering in highly complex biological structures and elaborate modeling schemes for simulating light propagation are continually being developed and refined (Turchin 2000). Elaborate methods for monitoring light propagation have been devised as have modeling methods for predicting the propagation properties of the light. The full potential of optical probes will, however, only be achieved only when the properties of light propagation in complex biological tissue are completely characterized and adequately modeled for the full variety of biological structures.

We have previously carried out studies dealing with light reflectance and propagation in plant leaves and its possible implications for monitoring the general health of the plant (Nicoletti and Adams 2000, Adams and Herden 1998). And, in a recent report, we have evaluated the safety aspects of an intense light source that is being used to study fetal retinal development (Adams and Wilson 2006), a technique that relies on the propagation of visible light through human tissue.

A very useful way to model light propagation is with the Monte Carlo simulation technique (Gould et al. 2007). One of the Monte Carlo programs that has been made available online to researchers is that of Wang et al. (1995). Our current interest is the development of a laboratory workstation capable of measuring the optical parameters of turbid materials in order to better characterize and model light propagation in these materials and find optimal values for the optical parameters in the Monte Carlo simulation. Key measurements involve reflectance and transmittance under a variety of illumination and sampling conditions (Cheong et al. 1990). One tissue system that has not received much attention is the highly reflective one and we have chosen to start with this example. The basic Monte Carlo program by Wang et al. (1995) has recently been adapted to model light propagation in phantoms using values for optical properties which had been extracted from diffuse reflectance (Palmer and Ramanujam 2006). The phantoms used is that study were made with a scatterer, polystyrene spheres, and an absorber, hemoglobin in one case and Nigrosin in the second case. One biological system that is of interest to us is the uterus, tissue that is made up primarily of smooth muscle fibers. To model such a fibrous system we have chosen to study 100% cotton paper. Here we report the results of an optical reflectance and transmittance study of 100% cotton paper and the Monte Carlo modeling for light propagation through it.

The light source for the laboratory measurements is a tunable Lexel Ar-ion laser Model 85 with 6 spectral emission lines: 514.7 nm, 501.7 nm, 496.5 nm, 488.0 nm, 476.5 nm, and 459.7 nm. The beam from the laser was expanded using a spatial filter equipped with a 10x microscope objective and a 25-micrometer pinhole. The integrating sphere was purchased from Labsphere Inc. (North Sutton, NJ) and is a 4-port, 15.24-cm sphere coated with Labsphere's proprietary material spectraflect. It was positioned a distance of 1.06 m from the pinhole where the beam was roughly 20 cm in diameter, and the rays of light arrive collimated and at normal incidence to the 2.54-cm entrance port of the integrating sphere. In line with the entrance port is a 3.81-cm port at which either a standard reflector or the sample was placed. The light detection system was an EG&G Electro-Optics Model 550 Radiometer/Photometer system with a fiber optic collection system. The radiometer was set to read irradiance in microwatts/cm^2. The detection port was transverse to the entrance and sample ports. A photograph of the experimental setup is shown in Fig. 1.

In order to measure sample reflectance a standard reflector was prepared. Magnesium oxide powder was pressed into a plastic cap that was sized properly to just fit over the 3.81-cm sample port. The irradiance reading with nothing in the entrance port and the standard MgO reflector in the sample port was taken as 100% reflectance. Then the paper samples were placed over the sample port and the radiometer was read. The ratio of the latter to the former reading is total reflectance. Then the standard reflector was placed at the sample port and the paper samples were placed over the entrance port and the meter was read again. The ratio of this latter reading to the original measurement with only the standard reflector in place gives the transmittance of the paper samples. Six readings for each paper weight were taken at each of the 6 wavelengths.

In order to standardize the sample and its geometry 100% cotton resume paper purchased from Office Depot was used as the turbid media to study and characterize. The paper is marketed under the tradename Worklife®. Two weights of white paper were purchased, 24 lb and 32 lb. The paper thicknesses were measured using a Vernier caliper and found to be that specified by the paper industry: a thickness of 0.012 cm for the 24-lb paper and 0.016 cm for the 32-lb paper. The paper was massed and its mass density determined to be 0.74 g/cm^3. Square sections of paper roughly 10 cm by 10 cm were cut and care was taken not to touch the central portion of the squares, only the regions near

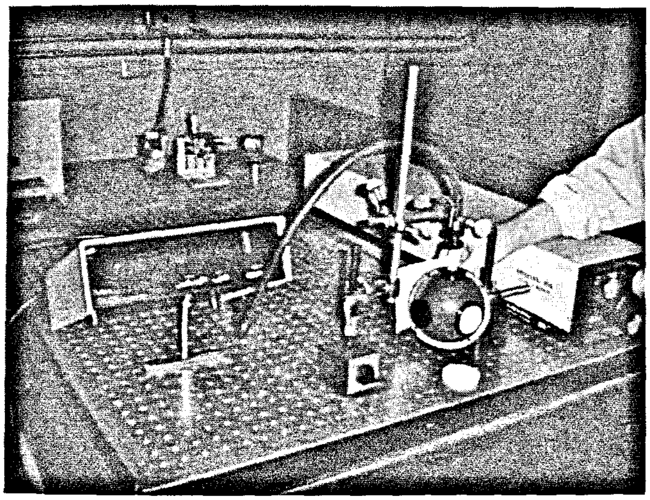

Fig. 1. The experimental setup for the transmittance measurements. The laser beam is expanded using a spatial filter with pinhole and the expanded beam illuminates the integrating sphere at the top of the picture. The fiber bundle collection cable can be seen extending from the right side of the integrating sphere. Samples are held directly in front of the aperture of the integrating sphere that is bathed in green light (wavelength 541.7 nm) in this photograph.

the edges. Measurements of transmittance (ratio of transmitted irradiance to incident irradiance) and reflectance (ratio of total reflected power to incident power) at the 6 wavelengths were made with only 1 layer of paper placed in front of the entrance port of the integrating sphere and also at the sample port; the radiometer was read before and after the paper was placed in front of the port. The readings were recorded by hand and averaged for each paper weight at each of the 6 wavelengths.

Simulations for the various paper geometries were carried out using a Monte Carlo program obtained online. Monte Carlo methods have long been used to model the propagation of electromagnetic radiation through turbid media. The starting point is the program MCML written by Lihong Wang and Steven L Jacques at University of Texas M D Anderson Cancer Center (http://oilab.tamu.edu/mcr5/Mcman.pdf): Monte Carlo simulation of photon distribution in multi-layered turbid media in ANSI Standard C. This program treats a cylinder of light as consisting of individual photons and models the path that a photon might travel along inside the media, based on the probability that it will interact with the tissue in a certain way (be reflected, transmitted or absorbed). After a sufficient number of such simulations of photon paths have been completed, the behavior of the whole light cylinder can be determined statistically using methods of convolution. Also, the program treats the turbid media as composed of multiple homogeneous layers, each having its own absorption and transmission properties.

There are 4 parameters for each layer that must be entered into the program to carry out the simulation. These are 1) the refractive index n, 2) the absorption coefficient μ_a in typical units of cm^{-1}, 3) the scattering coefficient μ_s also in units of cm^{-1}, and 4) the anisotropy factor g that describes the relative probability for the scattering angle. The program calculates the relative reflection due to specular reflection, the reflection due to diffuse reflection, the absorption within the material, and the transmittance. These four values always sum to 1.00. The program assumes a certain minimal weight, at which point one assumes that the photon has been absorbed. For our modeling values of n, μ_s, and μ_a, we carried out a series of measurements with our paper samples as recommended by Dr. Gopal Krishnagopalan of Auburn University's Alabama Center for Paper and Bioresource Engineering. We determined the scattering coefficient to be 217 cm^{-1} and the absorption coefficient to be 1.8 cm^{-1}. We used these values and a standard refractive index of 1.5 in our Monte Carlo simulations.

The results of the reflectance and transmittance studies for the 24-lb paper are presented in Fig. 2. Results were quite repeatable and the standard deviations for 6 measurements did not exceed 5%. We found the reflectance of the 100% cotton paper to be 74% and the transmission to be 22%. The data for the 32-lb paper were similar with reflectance being 78% and transmission 18%. No obvious spectral features were noted, as was expected for white paper.

A series of Monte Carlo simulations was carried out. From previous work we knew that large values of diffuse reflectance were not typical, so we explored the effect of the anisotropy factor, g, on the values for reflectance and transmittance. Using the calculated values of μ_a, μ_s, and a refractive value of 1.5, a thickness of 0.012 cm, and values of g from 0 (scattering at 90° to the incident direction) to 1.0 (perfect forward scattering), the values of reflectance and transmittance and absorption were determined. The results are shown in Fig. 3. We note that for an

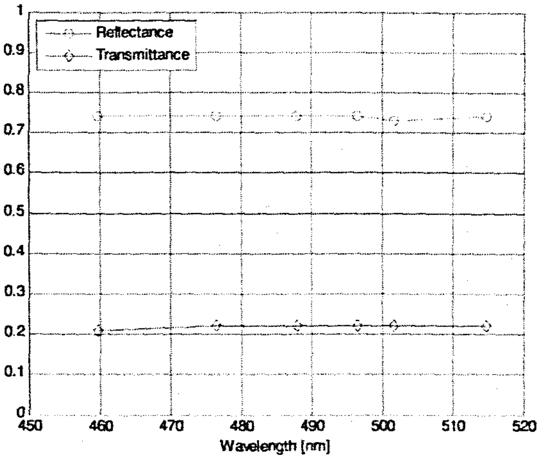

Fig. 2. The measured values for spectral diffuse reflectance and transmittance of 24-lb paper.

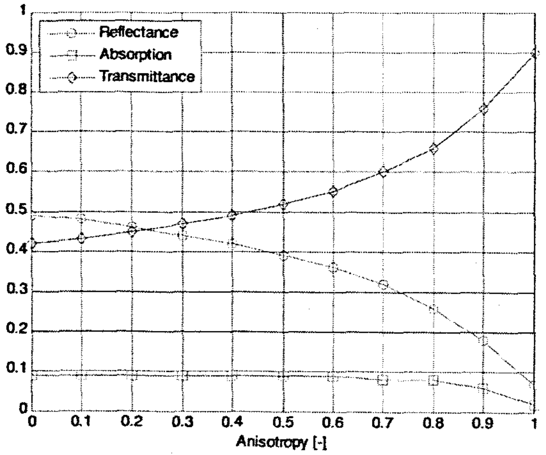

Fig. 3. The results of Monte Carlo simulations for n = 1.5, absorption coefficient of 1.8 cm^{-1}, a scattering coefficient of 217 cm^{-1}, for values of g, the anisotropy factor, ranging from 0 to 1.0.

approximate value of g=0.85, the values of R and T are almost exactly reversed from those actually measured. And even if g is allowed to go to 0, values of R and T approach the same value but do not achieve the measured result.

These results indicate that the Monte Carlo program by Wang et al. (1995) designed primarily for biological tissue is not effective for the highly reflective material found in 100% cotton paper. The scattering properties of cotton fibers apparently do not mimic those of skin or muscle or other tissues that have been modeled by the W-J program and found to be useful. A program that allows for significant backward scattering would seem to be more appropriate for this application. Attempts are now underway to adapt and modify the W-J program to better model light reflectance and transmittance from highly reflective, fibrous media.

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