The Specular Reflection Problem with a Single Fiber for Emission and Collection.

T. P. Moffitt and S. A. Prahl

ECE Dept., Oregon Health & Science University, Portland, OR

ABSTRACT

A single fiber may be employed to emit and collect light from a optically diffusing medium such as biological tissues. However, the light collected by the fiber consists of two components: diffusely scattered light from within the tissue and specularly reflected light from the surfaces. Only the diffuse reflection contains the desired information regarding the optical absorption and scattering properties of the tissue, but the specular component is comparable in magnitude to the diffuse reflection with visible light. The refractive index mismatch between the fiber and tissue account for a portion of the specular reflection. However, imperfect contact of the fiber with the surface of tissue creates additional boundaries and thus additional specular reflections. Experiments are performed with a 200 micron diameter fiber and a 632.8 nm He-Ne source to characterize the specular reflection collected through the same fiber using water as a coupling medium. The angular collection efficiency is measured for a fiber in contact with the surface on a glass substrate (specular reflection only) and an epoxy resin tissue phantom (specular and diffuse reflection components). Next, the collection efficiency is measured for a separation between the fiber and the samples for perpendicular illumination to the surface, 14 degrees, and 25 degrees from the normal. Imperfect contact is demonstrated to vary the amount of specular reflection collected using a single fiber where changes in angle greater than 4 degrees or a separation between the fiber and the surface in excess of 400 micron caused a minimum of 7 percent reduction of the collected specular reflection.

keywords: tissue, reflectance, scattering, absorption, sized-fiber.

1. INTRODUCTION

Determining the optical scattering and absorption properties of tissue for diagnostic and therapeutic applications is of interest in medicine. Most reflectance techniques rely on light distribution information over a large area ($>1\,\text{cm}^2$) having separate illumination and collection fibers with a separation distance on the order of several millimeters[1] or have mixed fiber bundles with source and emission fibers randomly arranged from 0.1-1 mm from each other.[2]

Two studies on devices with separate source and detector fibers show that the mean photon penetration depth increases as the square root of the separation between source and detector fibers either spatially[3] or temporally.[4] Source-detector fiber devices sample relatively large volumes, because of the separation between the fibers.[3, 4] Though effort has been made to minimize the sampling volume using small source-detector separations,[5] little work has been done on photon penetration depths when the source fiber is also used to collect backscattered photons.[6] Since large sampling volumes are less likely to be homogenous, we are developing a device that acquires information from small volumes of tissue ($< 1\,\text{mm}^3$) by using the same fiber for both source and detector.

We are developing a technique and device, which we call sized-fiber reflectometry, for measuring absorption and reduced scattering of tissue using optical fibers with different diameters. The device consists of two fibers with diameters of 200 and 1000 micron. Each fiber emits and collects its own backscattered light but the larger fiber collects light that on average travels deeper into the tissue.[7] The absorption and reduced scattering properties can be determined using a lookup table based on Monte Carlo simulations of the diffuse reflectance collected by these fiber sizes.

Further author information: (Send correspondence to S.A.P.)

S.A.P.: E-mail: prahl@ece.ogi.edu, Telephone: (503) 216-2197, 9205 SW Barnes Rd., Portland, OR 97006, USA
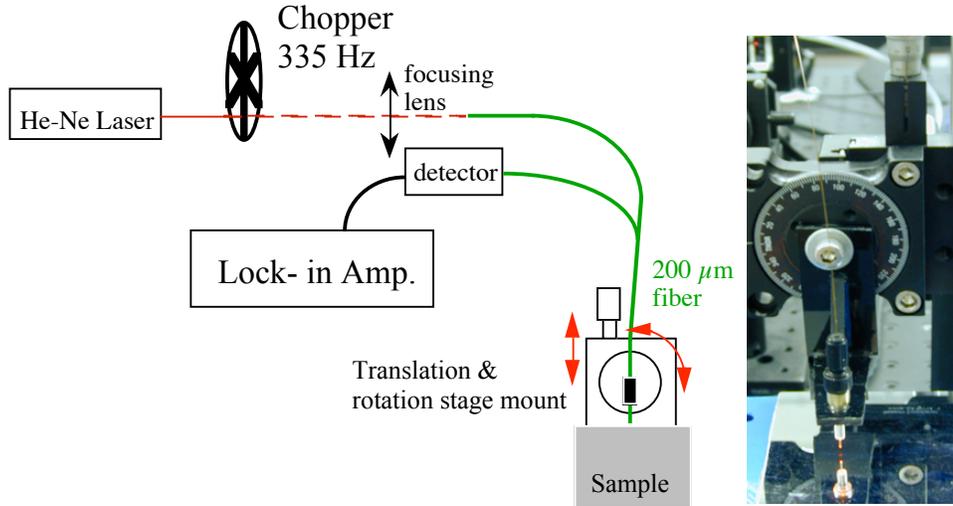
Figure 1. The experimental set-up consists of two 100 micron fibers that are end coupled into a 200 micron fiber to separate illumination from collection light. The photo on the right shows the fiber mounted in the positioning stages over a first surface mirror.

However, single emission and collection fiber measurements suffer from measurement variability, which in turn leads to large variation in the predicted optical properties. The collected light consists of two components, diffuse and specularly reflected light. When measuring tissue, both components are comparable in magnitude. Information regarding the absorption and reduced scattering properties is only contained in the diffuse reflection and the specular reflection changes effectively act as a noise source.

The goal of this study was to determine the contribution of the specular reflection in variations between measurements. We examine the effect of contact of a fiber with the surface of a sample to elucidate the influence on the specular reflectance collected by the fiber. Measurements of pure specular reflection are measured by independently varying the angle of contact a fiber makes with the surface of a mirror. Next, the fiber was positioned normal to the surface of the mirror to measure the effect of displacement between fiber face and the surface. These two experiments were then repeated on a epoxy resin block with diffuse scattering properties.

2. MATERIALS AND METHODS

To perform the experiments, a single fiber is bifurcated to separate the illumination light from the back-scattered light.[7] A 200 micron fiber is used for emission and collection by being end coupled to a pair of 100 micron fibers mounted together in an SMA connector. The light source consists of a 632.8 nm He-Ne laser that is chopped (MC1000, Thorlabs Inc., Newton, NJ) at 335 Hz then focused into one 100 micron fiber. The back-scattered light is channeled through the other 100 micron fiber to a UDT silicon photodiode. A lock-in amplifier (SR830, Stanford Research Systems, Sunyvale, CA) is used to display the voltage produced by the photodiode. All fibers are fused silica glass/glass from Polymicro Technologies LLC, Phoenix, AZ. The manufacturer cites a numerical aperture of 0.22 which corresponds to a maximum exit angle of 12.7 degrees in air. We measured 13 ± 1 degrees for the 200 micron fiber for the maximum acceptance angle in air. All fibers are encased in Teflon tubing and polished flush in SMA connectors.

Fiber positioning relative to the sample surface is achieved by mounting the 200 micron fiber simultaneously to both a rotation and a translation stage. The sample is set onto a lab-jack to allow coarse movement of the sample relative to the fiber. To test angular effects, the angle is set with the rotation stage then the fiber is lowered until the fiber just touches the sample surface using a vernier translator (figure 2 left). To test displacement, the fiber angle is aligned perpendicular to the sample and the fiber is brought into contact with

Rotational Experiment   **Displacement Experiment**
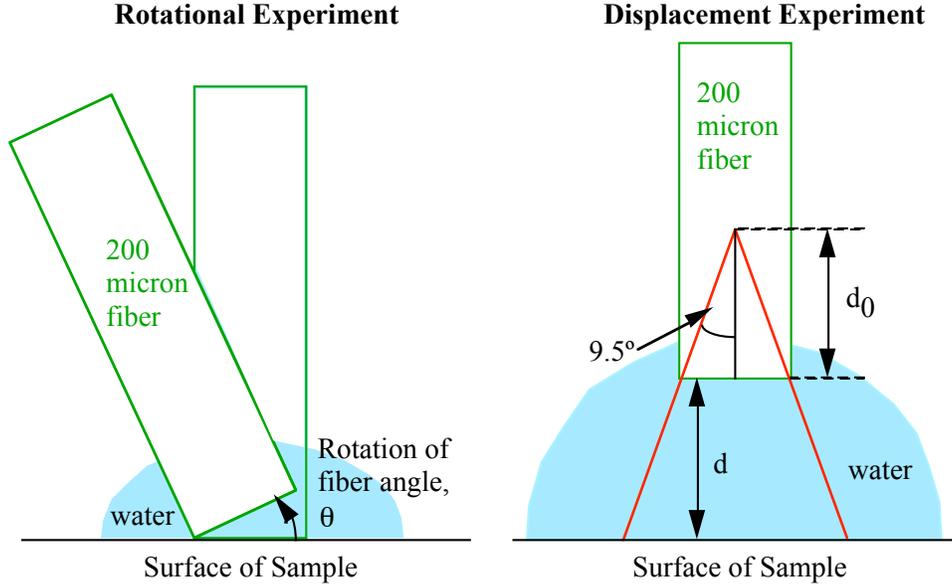
Figure 2. Diagrams of the geometry used for the angular rotation of the fiber (left) and the displacement of a fiber form the surface (right).

the surface using the vernier translator (figure 2 right). In all measurements, a drop of water is placed on the sample to act as a coupling agent between the fiber and the surface of the sample.

Two different samples were used for all measurements: a first surface mirror and an epoxy resin block. The mirror acted as a sample that returns only specular reflection. The resin block is a solid sample with added absorber (India ink) and a scattering agent (Titanium dioxide). The resin block has a large area flat surface smoothed with 400 grit sandpaper. Thus the block has some specular reflection in addition to a diffusely reflected light. The optical properties of the block are similar to those found in tissue: $\mu'_s \approx 15\,\text{cm}^{-1}$ and $\mu_a \approx 1.0\,\text{cm}^{-1}$.

All data points are normalized using Fresnel reflection from the fiber face in air and water. The voltage returned from the photodiode is converted by

$$\text{Total Reflectance} = \frac{V_{sample} - V_{water}}{V_{air} - V_{water}}[R_{air} - R_{water}] + R_{water}$$

where $R_{air} = 0.03465$ is the Fresnel reflectance for the fiber core/air junction, $R_{water} = 0.00204$ is the Fresnel reflectance for the fiber core/water junction at normal incidence. V_{sample}, V_{water}, and V_{air} are the measured voltages for the fiber incident upon the sample, water, and air respectively. The fiber core has an index of refraction of 1.457 at the 632.8 nm wavelength. Measurements of the air and water Fresnel reflectance are taken periodically throughout the experiments to correct for any variations in light output.

3. RESULTS

Measurement to measurement variation is demonstrated in figure 3 showing the distribution of the total reflectance measured on a epoxy resin standard when the fiber is held by hand and when the fiber is mounted stationary. Typical measurement variation is shown in figure 4 on the forearm. The fiber had to be mounted in some sort of holder (we used and SMA connector) to achieve measurement consistency. Direct pressure from a bare fiber caused the signal to increase steadily in excess of 200 percent of the initial value over a period 30 seconds.
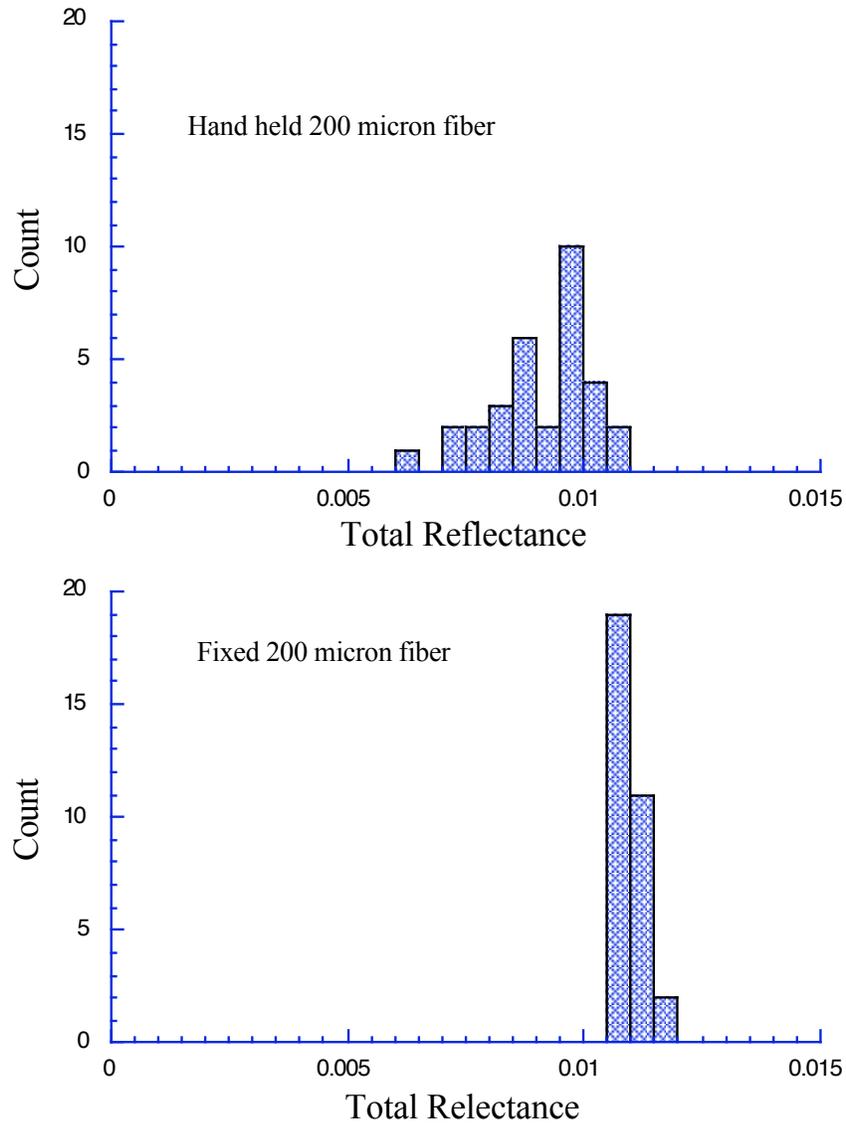
Figure 3. Typical distributions of 32 measurement of a diffusely scattering epoxy resin block with a 200 micron fiber when the fiber is held by hand (Top) and when the fiber is mounted to a translation stage and positioned in contact with the block (bottom). The fiber is lifted from the surface of the block between every measurement.
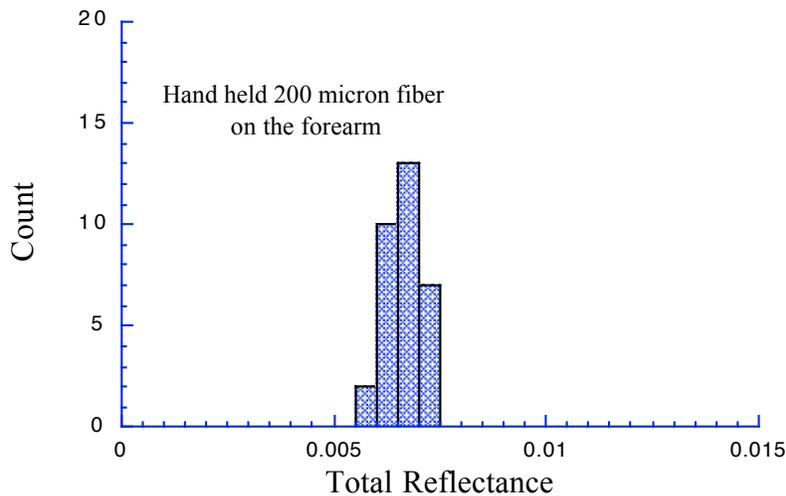
Figure 4. Typical distributions of 32 measurement on a forearm with a 200 micron fiber mounted flush in an SMA connector that is held by hand. The fiber is lifted from the arm between every measurement.

Figure 5 shows the contribution due to specular reflection when the central-axis of the 200 micron fiber is not normal to a first surface mirror while the fiber maintains contact with the mirror. Figure 6 shows contributions due to the specular reflection when the fiber is displaced from the surface while remaining normal to the surface.

Figure 7 shows the deviation in total reflectance when the central-axis of a 200 micron fiber is not normal to a surface on a epoxy resin block, but the fiber still maintains contact to the surface of the block. Figure 8 shows the effect of the specular reflection change to a displace of the fiber from the surface on an epoxy resin block while the fiber is normal to the surface, at 14, and 25 degrees from the normal to the surface.

4. DISCUSSION

When making any type of measurement, the resulting measurement must be reproducible to give reliability to the acquired information. Single fiber reflectance measurements are prone to great variability if fiber placement on the material is not carefully controlled. Figure 3 exemplifies this point. When a fiber is carefully and precisely aligned (figure 3 bottom), the standard deviation is less than 2 percent; while less precise measurements (figure 3 top) had a standard deviation of 12 percent and a mean that was 83 percent less than the more precise method. The solid block has a more pronounced effect than soft tissue (comparing figure 3(upper) to figure 4), simply because the soft tissue will naturally deform to give a more complete contact with the fiber. Tissue deformation is also a hindrance. Pressure induced by the contact of the optical fiber causes skin to visibly blanch by driving the blood out of the immediate tissue. We were unable to achieve a steady signal with a bare 200 micron fiber on skin unless the fiber was mounted so that a larger area ($\approx 7\,\mathrm{mm}^2$) of support was given around the face of the fiber.

Ideally, a fiber may be positioned such that the fiber face will be in perfect contact with negligible pressure and that any deviation will have minimal effect. In less than ideal circumstances, two problems affect measurements; displacement of the fiber from the surface and a non-normal fiber angle to the surface. By using a first surface mirror, these two effects can be described for the extreme case of pure specular reflection. First, a small change in the angle less than 2 degrees from the normal causes a 2 percent or less drop in collected light. At 4 degrees the signal drops by 6.5 percent and at 6 degrees the signal drops to 83 percent of the value at normal incidence.
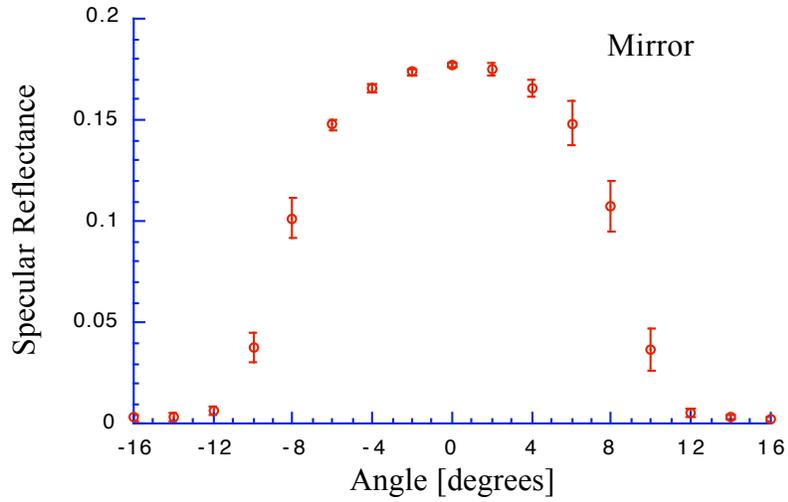
Figure 5. The specular reflectance collected from a 200 micron fiber in contact with a first surface mirror where 0 degrees corresponds to the fiber's optical axis normal to the mirror.
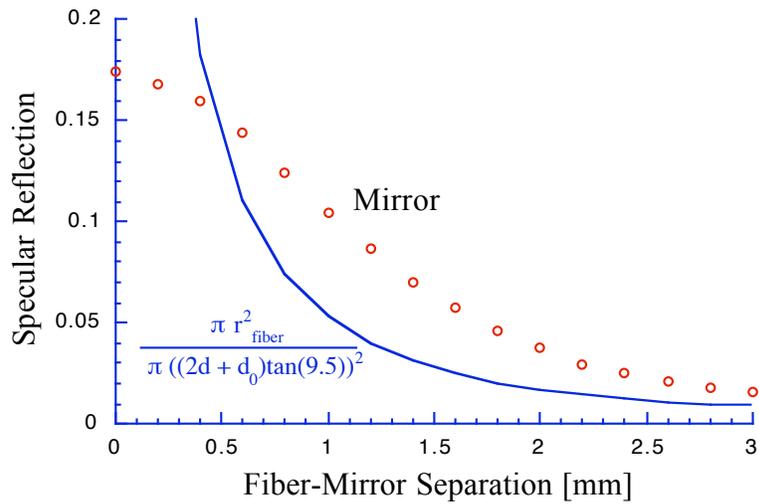
Figure 6. The specular reflectance collected with a 200 micron fiber displaced from the surface of a first surface mirror(points) and the expected geometric result (curve).
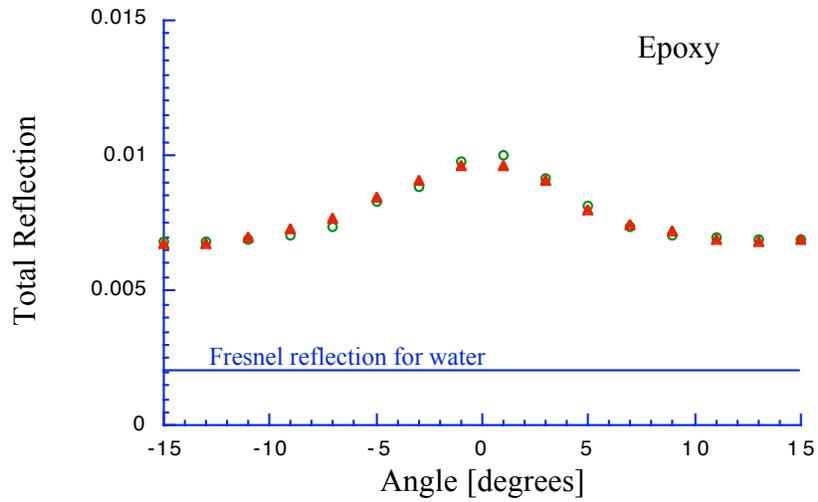
Figure 7: The specular reflection collected by a 200 micron fiber in contact with an optically diffusing epoxy block.
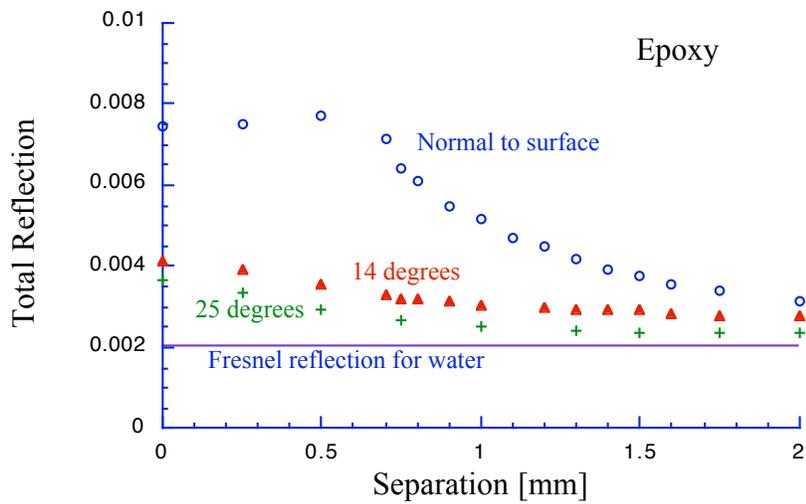
Figure 8. The specular reflectance collected with a 200 micron fiber displaced from the surface of a first surface mirror.

Beyond 10 degrees, the reflected light incident upon the fiber is outside the numerical aperture (0.22) of the fiber and the collected signal is nearly equal to the Fresnel reflection due to the index mismatch at the fiber face.

Displacement between the fiber and the surface of the sample has a similar effect. A 200 micron displacement causes a 3 percent loss in signal, 400 micron an 8 percent loss, and 600 micron a 17 percent loss of signal. However, the signal does not drop off as rapidly as a pure geometric solution would suggest. In a first approximation that assumes that all modes are evenly filled (the modes were not perfectly even), the collected specular reflection can be described by the ratio of the area of the fiber face relative to the spot size reflected back in the plane of the fiber face (figure 2 right) giving the equation

$$\mathrm{SpecularReflection} = \frac{C \pi r_{\mathrm{fiber}}^2}{\pi((2\mathrm{d} + \mathrm{d}_0)\tan 9.5)^2}$$

where C is the maximal reflection from the mirror ($C = 1$), r_{fiber} is the radius of the fiber, d is the distance between the fiber face and the surface of the sample, and d_0 is the height of the triangle (600 micron) that forms the cone of light emitted from the fiber (figure 2 right). In water, the maximum half angle of emission of the fiber would be 9.5 degrees. The discrepancy may be due to additional reflections off the meniscus of water back onto the mirror being captured by the fiber. Uneven annular modes of propagation through the fiber may also attribute to the discrepancy especially if the central modes carries substantially less light than outer annular modes. Under-filling of modes will change the fiber exit angle (to less than 9.5 degrees) and not change the general shape of the curve and so can not be the sole explanation of the difference between the experiment and the geometric model.

On measurements of the epoxy resin block, the results are similar to the mirror though the deviations were not as pronounced. This was the expected result since the block produces much less specular reflection than a mirror. The collected reflectance did not drop to the Fresnel reflection of the index mismatch due to the presence of diffuse reflection. Figure 7 show that the influence of the specular reflection is about the same magnitude as the diffuse reflection. In figure 8, at normal incidence the change in specular reflection almost equally offsets any changes in the collected diffuse reflection for separations less than 400 microns . At large fiber angles (≥ 14 degrees), the specular reflection is not collected and the diffuse reflection collected slowly decreases with increasing separation between the fiber and the surface of the epoxy block.

In this study, we examined the effect of fiber contact on the collection of specular reflection. When fiber contact is imperfect between the face of the fiber and the surface of the sample, the collected specular reflection decreases. Changes in angle greater than 4 degrees or a separation between the fiber and the surface in excess of 400 micron caused at least a 7 percent attenuation of the collected specular reflection. On diffusely scattering media, the change in the specular reflection is nearly identical to the change in diffusely collected light for fiber separations less than 400 micron. Any change in the fiber's optical axis from normal to the surface caused signals to decrease. Imperfect contact of any sort between a fiber and the material caused the light collected to decrease. And so, reproducible measurements using a fiber in this manner requires that conscientious control of fiber placement to avoid artificially low signals that may be falsely attributed to increased absorption or a decrease in scattering.

Acknowledgements

REFERENCES

1. M. G. Nichols, E. L. Hull, and T. H. Foster, "Design and testing of a white-light, steady-state diffuse reflectance spectrometer for determination of optical properties in highly scattering systems," *Appl. Opt.*, **vol. 36**, pp. 93–104, 1997.
2. N. Kollias95, "The physical basis of skin color and its evaluation," *Clinics in dermatology*, **vol. 13**, pp. 361–367, 1995.

3. G. H. Weiss, R. Nossal, and W. F. Bonner, "Statistics of penetration depth of photons re-emitted from irradiated tissue," *J. Modern Optics*, **vol. 36**, pp. 349–359, 1989.

4. M. S. Patterson, S. Anderson-Engels, B. C. Wilson, and E. K. Osei, "Absorption spectroscopy in tissue-simulating materials: a theoretical and experimental study of photon paths," *Appl. Opt.*, **vol. 34**, pp. 22–30, 1995.

5. F. Bevilacqua, D. Piquet, P. Marquet, J. D. Gross, B. J. Tromberg, and C. Despeursinge, "*In vivo* local determination of tissue optical properties: applications to the human brain," *Appl. Opt.*, **vol. 38**, pp. 4939–4950, 1999.

6. S. A. Prahl and S. L. Jacques, "Sized-fiber spectroscopy," in *SPIE Proceedings of Laser Tissue Interaction IX*, S. L. Jacques, Ed., vol. 3254, pp. 348–352, SPIE, Bellingham, 1998.

7. T. P. Moffitt and S. A. Prahl, "Sized-fiber reflectometry for measuring local optical properties," *IEEE J.S.T.Q.E.*, **vol. 7**, pp. 952–958, 2001.