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Characterization of human scalp hairs by optical low-coherence reflectometry

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Optical low-coherence reflectometry is used to investigate the internal structure and optical properties of human scalp hair. Regardless of hair color, the refractive index of the cortical region remains within the range of 1.56–1.59. The amplitude of the backscattered infrared light coupled into different-colored hair confirms the relative melanin content. Discontinuities in the refractive index permit identification of distinct structural layers within the hair shaft.

Photonics industries today use optical low-coherence reflectometry (OLCR) to characterize various materials. Recently OLCR has been applied to characterize biological materials,¹ including the human eye² and skin.³ We have found that this method also can be useful for investigating biological fibers. Previous research into the optical properties of human hair used external probes to detect scattered light.^{4,5} When OLCR is used, however, light propagates within the shaft, permitting noninvasive characterization of internal structure.

The internal structure of most human scalp hairs is dominated by the presence of three distinct layers⁶: the cuticle, the cortex, and the medulla. The cuticle is the outermost portion of the shaft and makes a coat of thin, overlapping scales inclined at an angle of approximately 5° toward the central axis of the shaft.⁴ The cortex, immediately beneath the cuticle, consists of tightly packed, rodlike cells that contain melanin granules that pigment the shaft. The innermost portion of the shaft, the medulla, is a core of loosely packed, cubelike cells with small packets of air between them. The width of each layer, as well as that of the entire shaft, can vary significantly even along the same hair. In some shafts, the medulla may be discontinuous or entirely absent.^{6,7}

Melanin granules in the cortical layer have a substantial effect on the optical properties of hair. The perceived color of hair depends not only on the type of melanin but also on the quantity, location, and shape of the granules in the cortex. Two types of melanin are found in hair—eumelanin and pheomelanin; each produces a distinct pigmentation.⁸ Eumelanin, responsible for black and brown pigment, predomi-

nates in dark-colored hair. Pheomelanin pigment is dominant in lighter-colored hair, particularly red and blond shades.⁹ A relative deficiency of melanin granules results in light colors such as blond and gray. White hair is believed to be unpigmented.⁹

In our study, near-infrared light in one arm of a fiber-optic interferometer is coupled into the shaft of an individual human scalp hair (Fig. 1). Continuous near-infrared light ($\lambda = 850$ nm), emitted by a superluminescent diode (SLD), is coupled into a fiber-optic Michelson interferometer and split into two beams by a 2×2 fiber coupler. We use near-infrared light because absorption by melanin and water is reduced in this spectral region.¹⁰ With a 2×1 coupler, light from a He–Ne laser ($\lambda = 632.8$ nm) is coupled into the interferometer and serves as an aiming beam.

Fig. 1. Apparatus for OLCR scans of human hair.

The SLD power output from the coupler is set at 1 mW. Light intensity in the reference arm is attenuated to 2 μ W to yield a higher signal-to-noise ratio.¹¹ The optical phase in the reference and test arms is modulated by means of piezoelectric cylinders driven by a serrodyne (i.e., ramp) waveform. Light beams backscattered from the shaft and the reference mirror recombine within the 2×2 coupler and interfere only when the path-length difference is less than or equal to the coherence length of the SLD source light. Stress birefringence is used to match the polarity of the beams and optimize fringe contrast. Optical interference fringe intensity is measured by a photoreceiver in combination with a spectrum analyzer. An OLCR recording is a plot of electrical power contained in the measured interference fringe intensity (in decibels) versus reference mirror position (in micrometers). Because the coherence envelope of the SLD source light yields rapid phase decorrelation of the beams for path-length differences greater than the coherence length,¹² high spatial resolution ($<10 \mu\text{m}$) is achieved.

To ensure the removal of contaminants (e.g., dirt, spray-on chemicals, and oil deposited by handling), we wipe the hair shaft clean with lens paper and ethanol before scanning. All shafts are of natural color and are harvested from scalps with no history of chemical treatment. Shafts are scanned both longitudinally (length) and cross-sectionally (width). Samples being scanned longitudinally are cleaved to a desired length with a blade anchored to a high-resolution ($1\text{-}\mu\text{m}$) positioning stage. Cleaving can play a significant role in longitudinal OLCR scans. If shafts are not cleaved properly, the resulting angular edge leads to greater measurement error. Although it is possible to measure length and group index simultaneously,¹³ the small size of our samples facilitates use of a light microscope to measure the length of cleaved shafts.

A thin metal wire wrapped with doubled-sided tape holds the hair sample in position approximately 3.5 mm from an $f/1.5$ fiber lens that terminates the test arm. The lens is positioned to create a spot size of $5\text{-}\mu\text{m}$ (FWHM) diameter on the front end face. In both longitudinal and cross-sectional scans light is focused at a position on the shaft surface that gives the greatest reflected intensity. A personal computer synchronizes the depth, speed, and time of each scan.

Longitudinal OLCR plots of blond and black shafts are shown in Figs. 2 and 3, respectively. The two large peaks in the OLCR recording of blond hair represent reflection from the front and back end faces and indicate propagation of the incident light along the entire length of the shaft. Initial scans of black shafts of the same length (1 mm) show significant attenuation within 300 μm following the initial peak, and no second peak is observed. When the black hair is cleaved to shorter lengths (200 μm), reflection from the back end face is observed. We believe that attenuation in black hair is caused by absorption and scattering of light by large quantities of dark eumelanin pigment granules located in the cortex.

A cross-sectional scan of red scalp hair is shown in Fig. 4. Peaks in the measured interference fringe intensity indicate distinct structural layers. The initial peak signifies light reflected from the air-cuticle interface, the second peak denotes light from the cortex-medulla interface, and the third represents light from within the medulla. Similar readings are seen from hairs of darker color such as black and brown. However, a multiplicity of peaks is observed in cross scans of lighter color hairs.

Longitudinal scans of the shaft are used to estimate the refractive index of the cortical region. Our measurement technique is actually a procedure for determining the group index of the test material. The refractive index (n) is deduced¹⁴ from the group index (n_g) and the optical dispersion ($dn/d\lambda$):

$$n = n_g \left(1 + \frac{\lambda}{n} \frac{dn}{d\lambda} \right). \quad (1)$$

Fig. 2. Longitudinal scan of blond hair.

Fig. 3. Longitudinal scan of black hair.

Fig. 4. Cross-sectional scan of red hair.

Table 1. Hair Shaft Refractive Indices

Color	Refractive Index	Error
Black	1.59	0.08
Brown	1.58	0.06
Red	1.56	0.01
Blond	1.57	0.01
Gray	1.58	0.01
White	1.58	0.01

At $\lambda = 850$ nm, dispersion in hair is small and the group index is nearly equal to the refractive index. Because the group velocity of the incident light in air is proportional to that within the shaft, we deduce that

$$n \approx n_g = \frac{L_s}{L_h}. \quad (2)$$

Here L_s is the scan length of the reference mirror in the OLCR recording and L_h is the physical length of the shaft. Table 1 shows the refractive index for different-colored hair, as calculated by Eq. (2). The refractive-index measurement error (Δn) is computed according to

$$\frac{\Delta n}{n} = \left[\left(\frac{\Delta L_s}{L_s} \right)^2 + \left(\frac{\Delta L_h}{L_h} \right)^2 \right]^{1/2}. \quad (3)$$

The uncertainty (ΔL_s) is primarily from human error associated with estimation of scanning depth. Although a mathematical algorithm could be applied for best results, we take $\Delta L_s \approx 15$ μ m. Light microscope measurement gives a ΔL_h of approximately 5 μ m.

Because the medulla contains a significant quantity of air, light in this region often couples into the surrounding cortex. Because the cortex is the densest portion of the shaft and substantially larger than the spot size of the beam, we conclude that light is coupled into, and primarily propagates through, this layer. Our results suggest that, regardless of shaft color, the refractive index of the cortical region remains within the range of 1.56–1.59.

In longitudinal scans, the relative decrease in the magnitude of the second peak versus the first suggests that human hair is a lossy optical fiber. Measured interference fringe intensity from the back end face of the shaft does not end abruptly but gradually declines. This feature is due to higher-order optical modes that propagate with longer path lengths and undergo multiple reflections within the shaft. In lighter-colored hair, infrared light contained in higher-order modes is prone to escape along the shaft, whereas in darker-colored hair it is more readily absorbed by melanin granules. We have found that shafts of successively lighter color more readily propagate near-infrared light over longer distances.

In scans of blond shafts, interference fringe intensity between end face peaks is close to the noise level, so that reflections from air–material interfaces

within the cortex must be infrequent and of small amplitude. The small quantity of backscattered energy that is observed may be due to the presence of delicate air pockets called fusi⁶ that are interspersed between cortical cells. The absence of this phenomenon in black hair is explained by greater melanin absorption.

Cross-sectional scanning of blond and white hair often result in many peaks, which may be due to multiple reflections from the interfaces between three main structural layers. Multiple peaks are not observed in cross scans of progressively darker shafts in which attenuation is greater.

This preliminary investigation provides a basis for further research on the use of OLCR in characterizing biological fibers. Our purpose has been to introduce OLCR as a noninvasive diagnostic method that if combined with other techniques can provide useful data for the future characterization of biological fibers.

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References

1. X. Clivaz, F. Marquis-Weible, R. P. Salathé, R. P. Novák, and H. H. Gilgen, *Opt. Lett.* **17**, 4 (1992).
2. D. Huang, E. A. Swanson, C. P. Lin, J. S. Schuman, W. G. Stinson, W. Chang, M. R. Hee, T. Flotte, K. Gregory, C. Puliafato, and J. G. Fujimoto, *Science* **254**, 1178 (1991).
3. J. M. Schmitt, A. Knüttel, and R. F. Bonner, *App. Opt.* **32**, 6032 (1992).
4. H. Bustard and R. Smith, *Appl. Opt.* **30**, 3485 (1991).
5. R. F. Stamm, M. L. Garcia, and J. J. Fuchs, *J. Soc. Cosmet. Chem.* **28**, 571 (1977).
6. V. Valkovic, *Human Hair* (CRC, Orlando, Fla., 1988), Vol. 1, p. 41.
7. W. Montagna and K. S. Carlisle, in *Hair Research: Status and Future Aspects*, C. E. Orfanos, W. Montagna, and G. Stuttgen, eds. (Springer-Verlag, Berlin, 1981), p. 7.
8. C. Zviak and R. Dawber, in *The Science of Hair Care*, C. Zviak, ed. (Dekker, New York, 1986), p. 23.
9. J. Ortonne and G. Prota, *J. Invest. Dermatol.* **101**, 82S (1993).
10. J. Parrish, R. Anderson, T. Harrist, B. Paul, and G. Murphy, *J. Invest. Dermatol.* **80**, 75 (1983).
11. W. V. Sorin and D. M. Baney, *IEEE Photon. Technol. Lett.* **4**, 1404 (1992).
12. J. Goodman, *Statistical Optics* (Wiley, New York, 1985), p. 157.
13. W. V. Sorin and D. F. Gray, *IEEE Photon. Technol. Lett.* **4**, 105 (1992).
14. E. Hecht, *Optics* (Addison-Wesley, Reading, Mass., 1987), p. 252.