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Optical properties of hair—Detailed examination of specular reflection patterns in various hair types

R. MCMULLEN and J. JACHOWICZ, *International Specialty Products, International Specialty Products, Wayne, NJ.*

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Synopsis

Details of the specular reflection of curved hair tresses, resulting from illumination with a collimated incident light source, were examined both qualitatively and quantitatively using high-resolution photography and image analysis. The reflections were found to consist of a multitude of light dots aligned with the fibers and typically separated by a distance of 81–145 μm. The contrast between the dots (specular reflection) and the darker regions (diffuse reflection) of the entire reflection band was found to increase with increasing pigmentation of hair. Highly pigmented Oriental hair provided more contrast within the specular reflection band than unpigmented natural white hair. A quantitative description of the light reflection patterns within the specular reflection band included two-dimensional distribution of luminosity, histograms of the frequency of appearance for peak maxima and minima in luminosity distribution plots, and histograms of absolute maxima and minima of luminosity along the length of the fibers.

Specular reflection from African hair, which consists of many curls that provide multiple and randomly distributed reflection centers, have also been investigated. Using microscopy software, Image Tool 2.0, and a method termed *image threshold,* the number of reflection sites and their shapes could be quantified. For example, treatment of African hair with synthetic sebum was shown to significantly affect the reflection patterns, resulting in a decrease in the overall hair luster. Comparison of reflection patterns from Caucasian frizzy, very curly, and curly hair is also discussed.

INTRODUCTION

In a previous report (1), we described the measurements of luster for various types of hair by quantifying the intensity of light reflected from hair fibers spread over a cylindrical surface and illuminated by a collimated beam of light. Such an experimental setup allows one to obtain reflected light distribution curves similar to those typically generated by goniophotometers. By analyzing the shape of the reflection curves and by calculating luster parameters, we were able to investigate the effect of polymer and oil treatments on the luster of hair. While performing this analysis, we took note that the specular reflection band appeared to consist of a series of discrete microreflections arising from individual fibers and corresponding to the structural elements located along the fiber length. Thus, the specular reflection is not a continuous and uniform plane of light but possesses a dot-like or striped appearance. It should be emphasized that this effect is not only detectable by using high-resolution photography but can be easily observed with the naked eye. Consequently, it may play a role in the perception of luster by a consumer and affect his judgment when making a hair treatment selection.

In this paper, we examine the details of the specular reflection of hair by employing macro lenses, close positioning of the camera in relation to the photographed hair samples, and a high-resolution digital camera. Image analysis was employed to investigate the distribution of light intensity and the contrast between the highlights and shadows in the specular reflection area in order to derive a parameter characterizing the luster of hair. We have also employed another image analysis technique to assess the random reflection patterns produced by black, African hair, which cannot be analyzed by methods developed for straight hair of Caucasian or Oriental origin. Finally, we have also applied the same analysis technique for frizzy, very curly, and curly hair of Caucasian origin.

EXPERIMENTAL

METHODS

The luster evaluation apparatus used in this study was described previously (1). An Olympus Camedia E10 digital camera with a front-element auxiliary macro lens was employed to collect images of illuminated hair, typically one tress, from a distance of 5 inches. Previously, we had obtained images that contained two tresses in each photograph and the camera was positioned 10 inches away from the cylinder mount (1). We also utilized a 35-mm single-lens reflex (SLR) Nikon FE 2 camera equipped with an AIS 55-mm macro lens. In our previous study, we scanned the light intensity parallel to the fiber axes of a hair tress by employing image analysis software. In this work, light reflections within the specular reflection band were measured both in perpendicular and parallel directions in relation to the fiber axes. This was accomplished by using image analysis software, Sigma Scan Pro 5.0. As discussed in the Results section of this report, the horizontal and vertical light intensity plots consisted of maxima and minima, which were determined by importing the data into Mathcad 2001 Professional (MathSoft Engineering & Education, Inc.) and utilizing customized programs written within the Mathcad package. In addition to this, we utilized Image Tool 2.0 (University of Texas Health Science Center, San Antonio, TX) to quantify light reflection from curly African hair.

MATERIALS

Luster analysis was performed on natural white, light blonde, medium blonde, dark blonde, light brown, medium brown, and dark brown hair of Caucasian origin purchased from IHI & Products, Inc. (Valhalla, NY). In addition to this, we utilized Oriental hair purchased from DeMeo Brothers (New York) and curly African hair as well as frizzy, curly, and very curly hair of Caucasian origin supplied by IHI & Products, Inc. Hair samples were precleaned with a 3% ALS solution and thoroughly rinsed prior to experimentation. Hair tresses from Caucasian and Oriental hair were obtained by gluing 3 g of fibers to 1.5 × 1.5-in. plexiglass tabs with Duco cement. The length and width of each hair tress were 10 inches and 1.25 inches, respectively. African hair was formed into small 0.5–1.0-gram tresses by tying the upper portions of fibers with a cord. A synthetic sebum formula was prepared as a 5% (w/w) solution in hexane, as described previously (1).

RESULTS AND DISCUSSION

QUALITATIVE DESCRIPTION OF MICROREFLECTION PATTERNS

Figure 1A shows a typical digital image of dark brown hair taken with a macro lens at a distance of 5 inches, illustrating the complexity of the structure of the reflection band. The white outline in the photograph presented in Figure 1A highlights the region of the image that is shown at a higher magnification in Figure 1B. Detailed examination of the pictures presented in Figure 1 reveals a series of light dots aligned with individual fibers. It is important to note that the image shown in Figure 1B is not interpolated in any way and is shown without magnification. On the contrary, the image shown in Figure 1A had to be reduced from its original size in order to fit into its current format. We address this detail since one may conclude that the multiple dot-like reflection patterns in Figure 1B could be attributed to pixelation of the image. In order to further alleviate this concern, we performed similar experiments with a Nikon SLR 35-mm camera equipped with a 55-mm micro lens. Figure 2A provides a non-digital image of hair, obtained by using 100 ASA Kodachrome film, with a field of view similar to that shown in Figure 1A. An enlargement of the inset in Figure 2A results in a more detailed view, which is shown in Figure 2B. The result confirms that the dot-like texture of reflected light is not an artifact of digital imaging. For further illustration, Figure 3 contains digital photographs of a person's head in natural sunlight. The magnified view in Figure 3 is a close-up shot of the specular band located in the crown region of the subject's head. Again, a series of dots corresponding to individual fibers can be observed to pervade the entire reflection band. These photographs, obtained by using natural, solar illumination, suggest that the observed structure of reflected light in the shine apparatus is not an artifact related to the use of the halogen light source.

In our previous publication, we demonstrated the dulling effect produced on hair as a result of treatment with artificial sebum (1). Figure 4B presents a corresponding close-up image obtained for hair treated in the same manner, along with untreated dark brown hair (Figure 4A). While the microreflection patterns are clearly evident in the sebum-treated hair, the contrast between the specular reflection centers and the diffuse reflection (background) is much greater for untreated hair than for sebum-treated hair. As yet another example, natural white hair, is compared with dark brown hair in Figure 5. Similar to sebum-treated hair, micro-reflection patterns are visible for natural white hair, although the contrast between the specular reflection (dots) and the background is much greater for dark brown than for natural white hair.

IMAGE ANALYSIS OF MICROREFLECTION PATTERNS

In order to quantitatively characterize the microcontrast effects arising from the presence of dots (highlights) and neighboring shadows (diffuse reflection areas) in the specular reflection band of hair, we measured the light intensity as a function of distance in the horizontal direction relative to the fiber axis. This is shown pictorially and graphically in Figures 6A and 6B, in which 250 lines (represented by horizontal lines in Figure 6A)

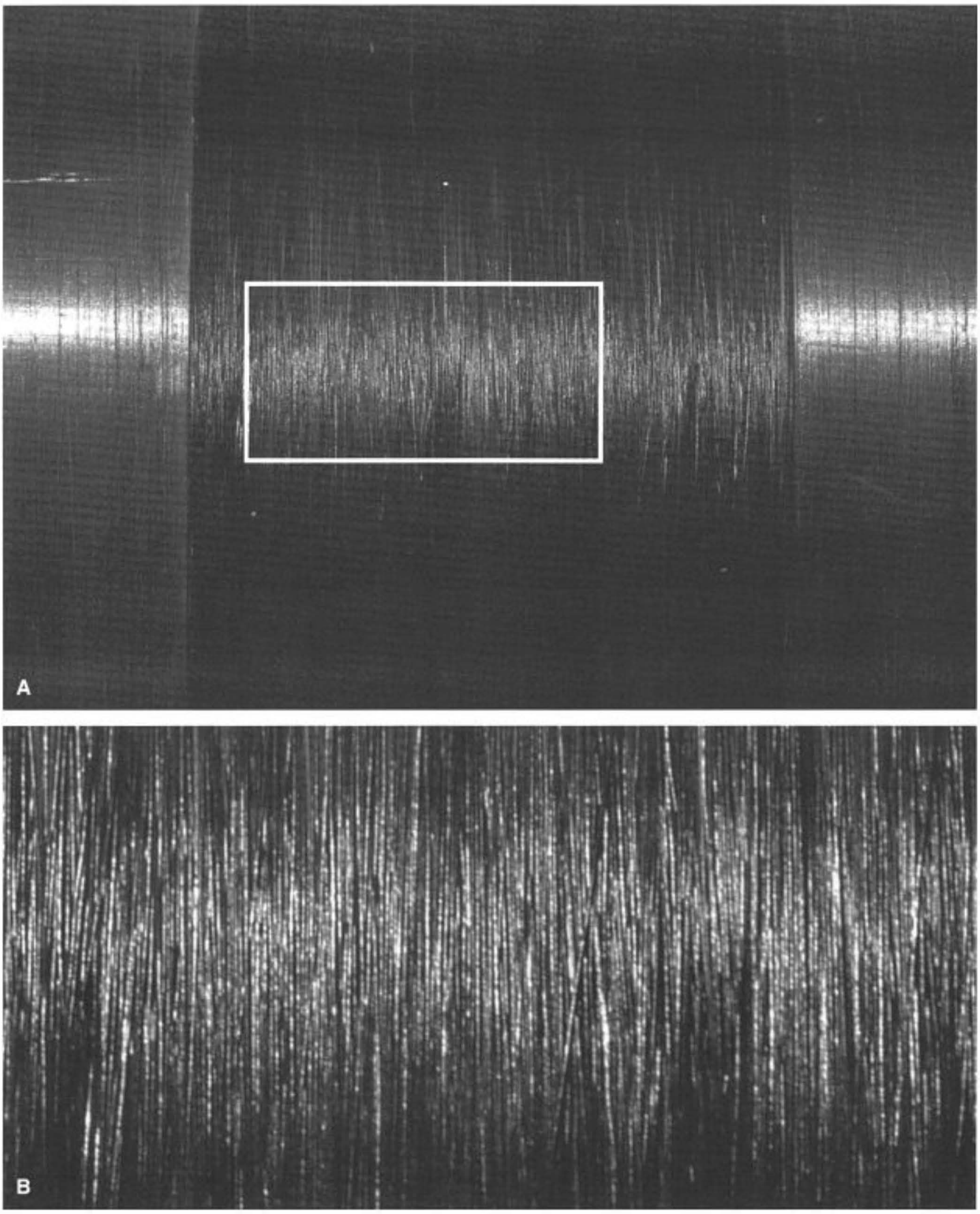


Figure 1. (A) Image of virgin dark brown hair at close proximity with a digital camera. (B) The inset, without interpolation, shown in Part A, providing higher magnification. Exposure settings: f8, 1/13s.

scanned the image and determined light intensity as a function of the horizontal distance. The horizontal lines were one pixel wide and the vertical distance between neighboring lines was four pixels. The graph shown in Figure 6B provides a demonstration of the light intensity profile for one of the lines. As shown in the figure, the plot consists of a complex curve containing a series of peak maxima and minima. The light intensity is measured with the software Sigma Scan Pro 5.0, while the resulting data are

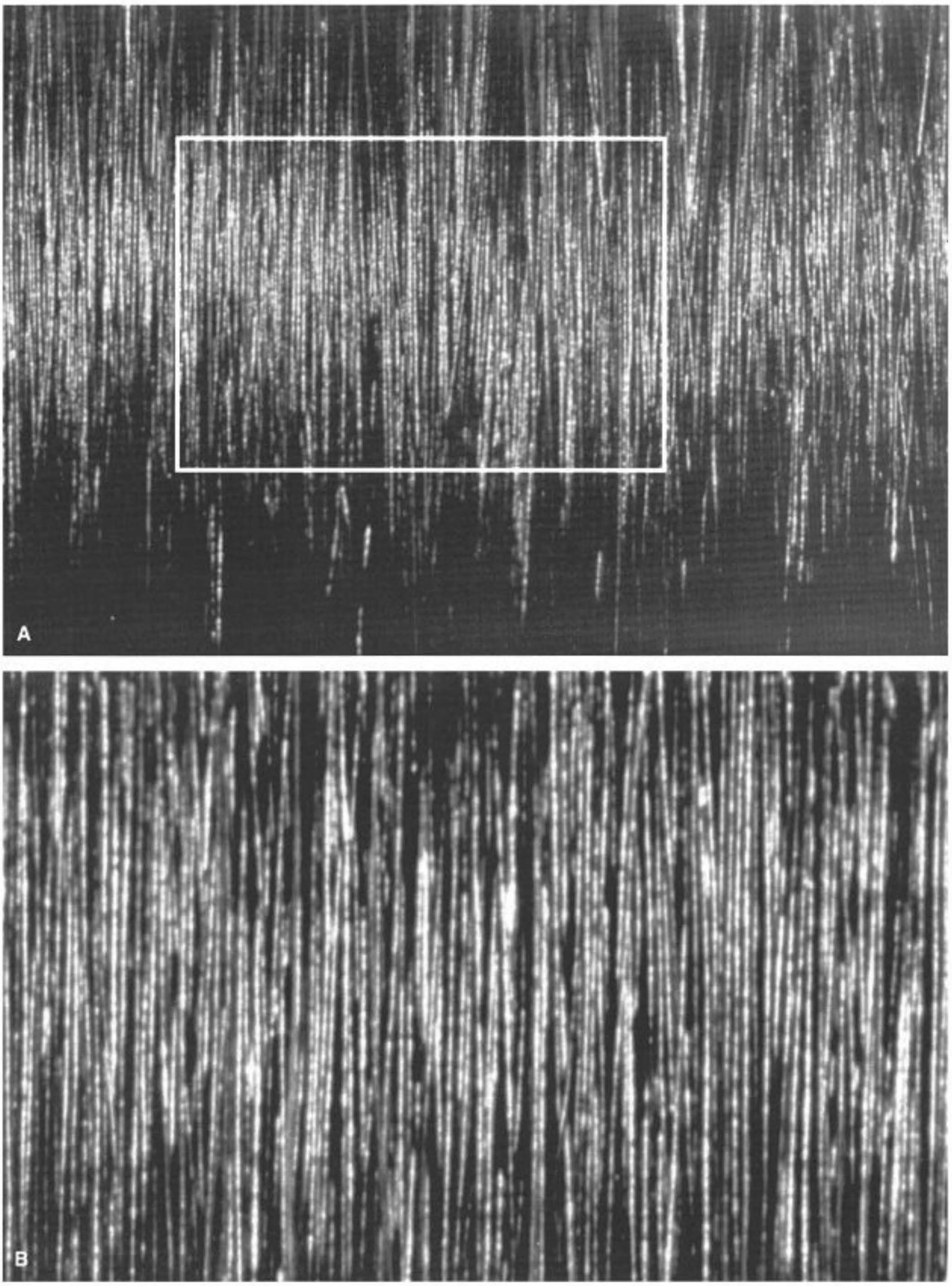


Figure 2. (A) Image of dark brown untreated hair at close range with a Nikon 35-mm SLR camera. (B) Magnification of the inset shown in Part A.

exported to a text file and further analyzed with Mathcad 2001 where the luminance values for the various peak maxima and minima were automatically determined by written macros. Each plot of luminance-vs-distance results in two histograms, showing

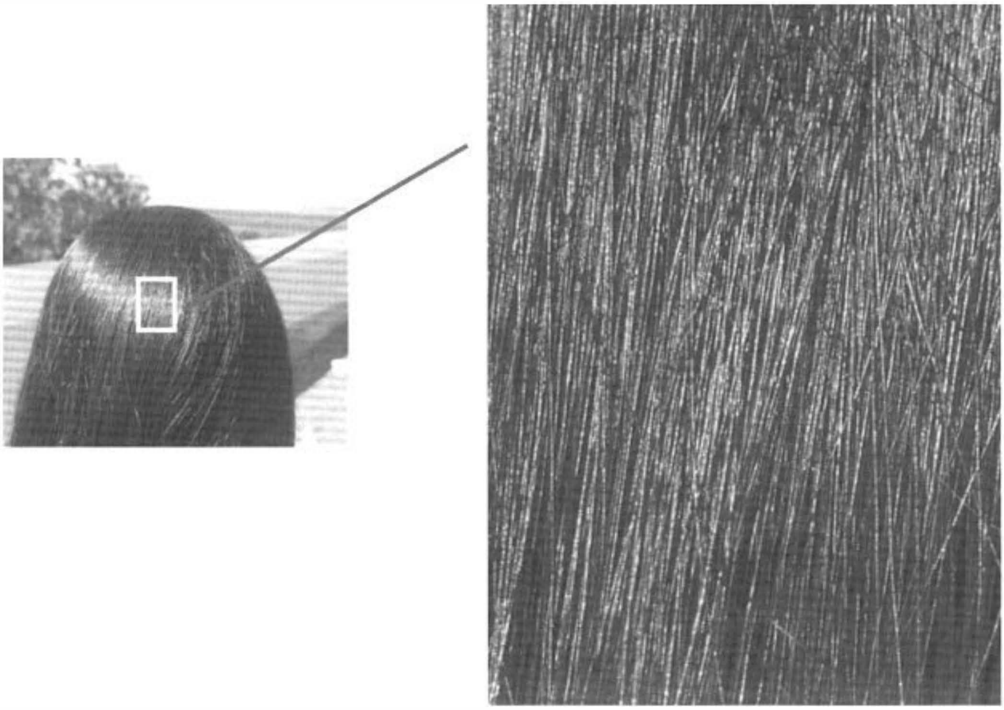


Figure 3. Image of a human subject's hair in which case reflection is a result of incident natural daylight.

the distribution of the peak maxima (Figure 7A) and peak minima (Figure 7B) in which the frequency of occurrence is plotted as a function of luminance. For each of the 250 maxima and minima histograms, we recorded the luminance value that occurs with the highest frequency. Such data can be plotted as a function of the position of a horizontal line along the tress, as shown in Figure 8 for both maxima and minima. As expected, the peak maxima histograms provide larger luminance values than the peak minima. Also, a large peak occurs in the peak maxima curve corresponding to the region of the tress where the highest intensity specular reflection band occurs. A smaller peak is also evident for the peak minima curve. Taking the difference between the peak maxima and peak minima curves provides us with an indication of the microcontrast related to the dot-like appearance of the specular reflection band. Table I lists integrated values for the maximum, minimum, and difference curves for various types of hair.

The integrated luminance parameters collected in Table I show that the microcontrast, based on the values of [Luminance(max) – Luminance(min)], increases for hair with greater amounts of pigmentation. For example, dark brown hair provides greater contrast within the specular reflection band than natural white hair. This is in agreement with previous work, which also reported an increase in hair luster for darker hair (see Table I). This was ascribed primarily to higher contrast between the specular and diffuse reflections, which corresponded to different parts of an illuminated hair tress (1). The data presented in Table I suggest that the contrast calculated for dot-like highlights and shadows within the specular band follows the same trend and could be employed for the assessment of hair luster.

A

B

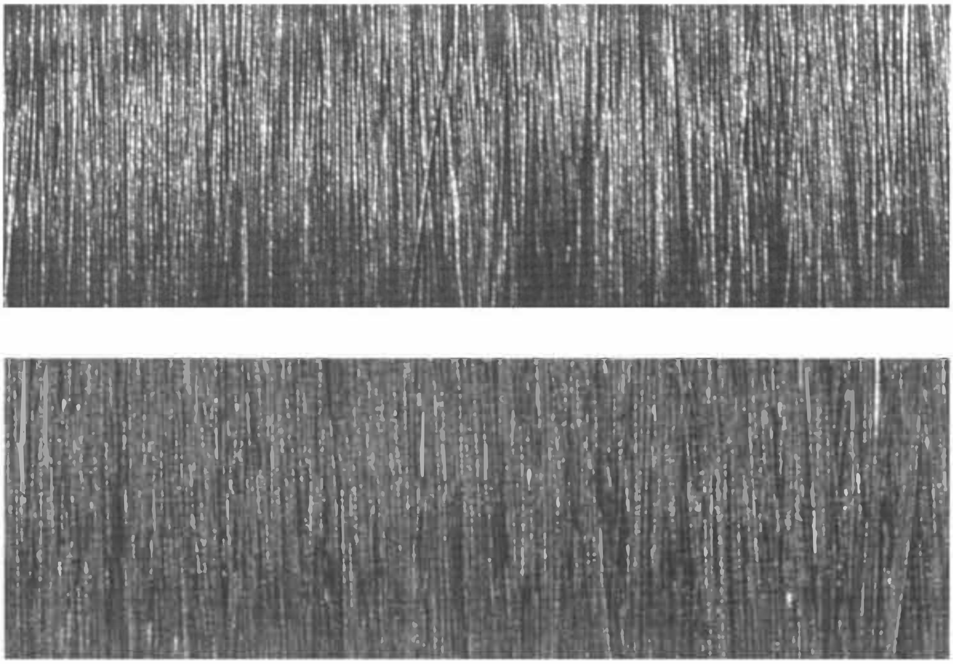


Figure 4. Images of (A) untreated virgin dark brown and (B) sebum-treated dark brown hair at close proximity. Exposure settings: f8, 1/13s.

We also employed image analysis to measure the distances between neighboring microreflection centers along the length of fibers. This was accomplished by scanning an image with vertical lines (in contrast to the analysis above with horizontal lines) that were one pixel wide and whose length depended on the length for a particular vertical series of microreflection patterns. The lines were drawn manually with Sigma Scan Pro 5.0 to ensure that each light intensity plot contained a series of microreflections along a given fiber. After drawing anywhere from 169 to 308 lines, depending on the nature of the image examined, we exported the light intensity data to a text file that could be further analyzed with MathCAD 2001. We then used macros within MathCAD 2001 to determine the distance between neighboring peak maxima for each vertical line in the scanned image. Histograms were then constructed in order to examine the frequency of appearance for the peak maxima data in which a bimodal distribution for each type of hair examined was observed. As an example, Figure 9 contains a histogram for dark brown hair in which the bimodality of the distribution can be observed at distances between peak maxima of 81 μm and 145 μm. Further, Table II provides the frequency of appearance of the peak maxima distances as well as the total sample population of peak maxima distances for various types of hair.

Overall, the data shown in Table II suggest that the distances between the reflection centers fall somewhere in the range of 81–145 μm. In almost all cases, the distance between peak maxima of 81 μm occurs with greater frequency than that of 145 μm. In addition to the data presented above, we also examined untreated dark brown hair and the same hair treated with artificial sebum, as shown in Table III. For both peaks, the effect of sebum treatment on the separation distance appears to be negligible and within the experimental error of the calculated average values.

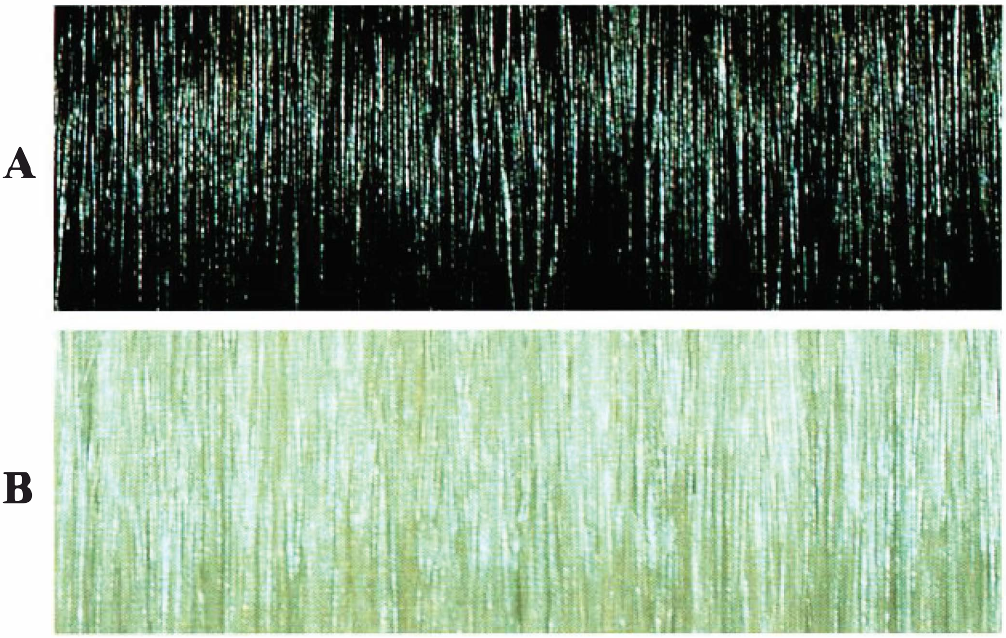


Figure 5. Images of (A) virgin dark brown and (B) natural white hair at close proximity. Exposure settings: f8, 1/13s.

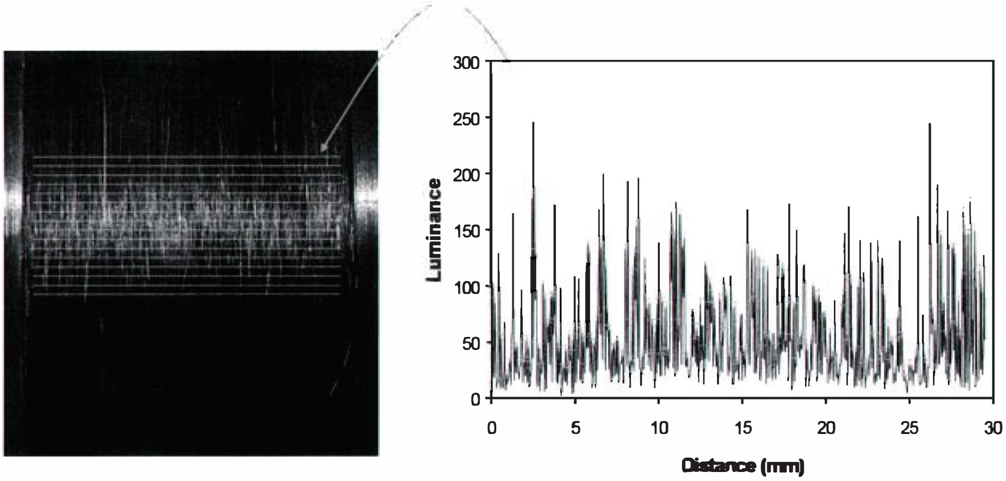
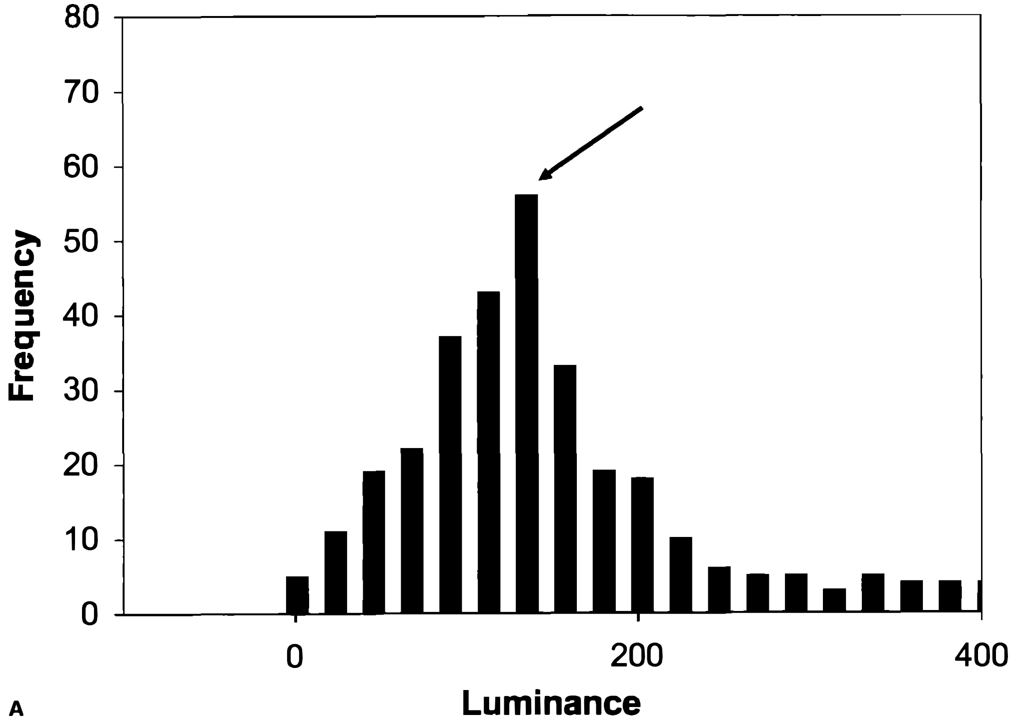
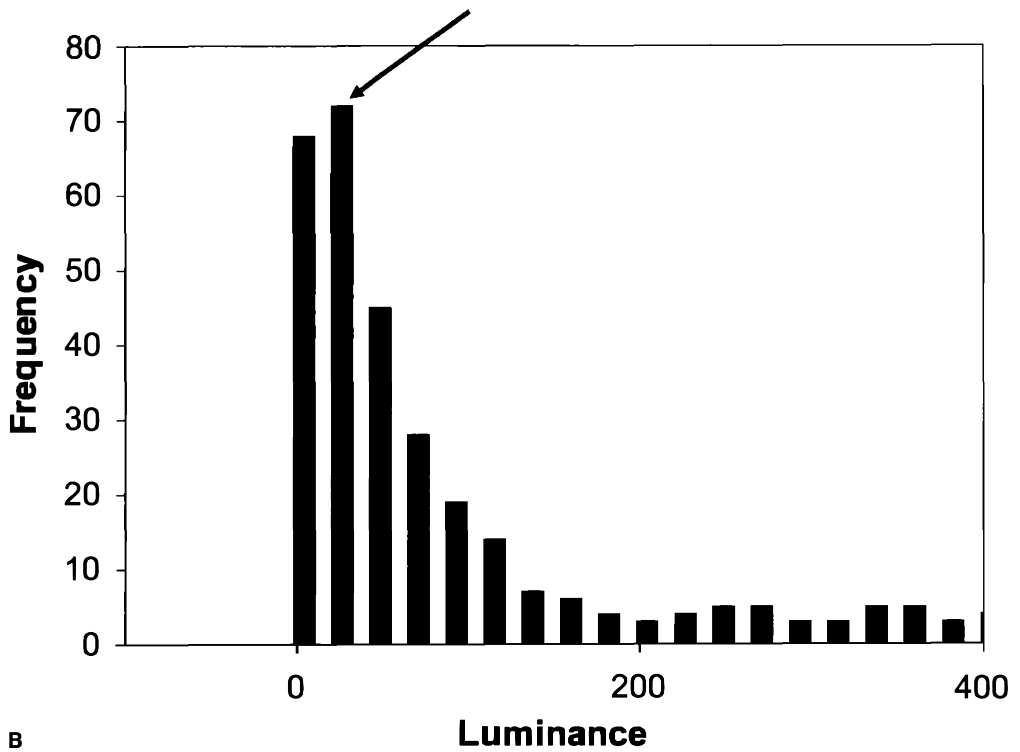


Figure 6. Example of luminosity analysis horizontal to the fiber axes with a plot of luminance-vs-distance for one of the horizontal lines.

Several possibilities exist as to the origin of these reflection patterns. It has been shown by profilometry that the topology of hair along the fiber axis consists of a wave-like structure with alternating maxima and minima (2). Another possible source of the complex reflection pattern may be attributed to the twisting of the fibers. Since the fibers are elliptical, reflection from the larger face may cause greater reflectivity than that



A



B

Figure 7. Example histograms displaying the frequency of appearance for (A) peak maxima and (B) peak minima that occur in one of the horizontal lines in Figure 6.

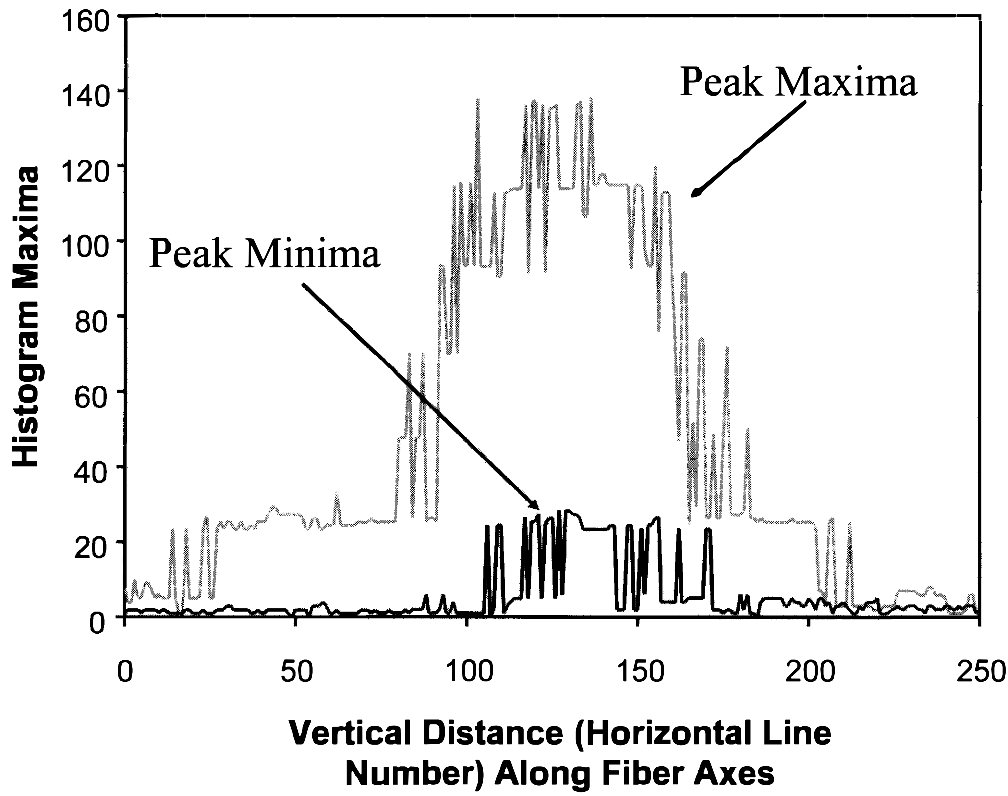


Figure 8. Horizontal luminosity analysis horizontally along a hair tress. The abscissa corresponds to each horizontal line in Figure 6, while each ordinate represents the maximum value obtained from either the maxima histogram (Figure 7A) or the minima histogram (Figure 7B).

Table I
Results of Maxima/Minima Analysis for Various Types of Hair

	Oriental	Medium brown	Light brown	Dark blonde	Medium blonde	Light blonde	Natural white
Maximum area	13,780	15,860	19,020	20,690	24,580	26,140	46,600
Minimum area	428	4,131	7,369	10,200	12,840	17,380	40,020
Maximum - minimum	13,350	11,730	11,650	10,490	11,740	8,765	6,586
L_{Stamm}*		0.72	0.70			0.65	0.32
$L_{Reich\text{-}Robbins}$*		0.67	0.32			0.19	0.06

* From reference (1).

from the smaller face. It has also been suggested that microreflections from hair arise due to the internal porous structure of hair typically found in medullated fibers (3). As a final point, it has been suggested that such light patterns observed on hair may be due to diffraction, with the cuticular structure of hair acting as a diffraction grating (termed *blazed grating*) (4). We are most inclined to concur with the latter explanation, since the reflection patterns we have observed typically represent a spectrum of colors analogous to that observed with a diffraction grating when white light is split into its various wavelength components.

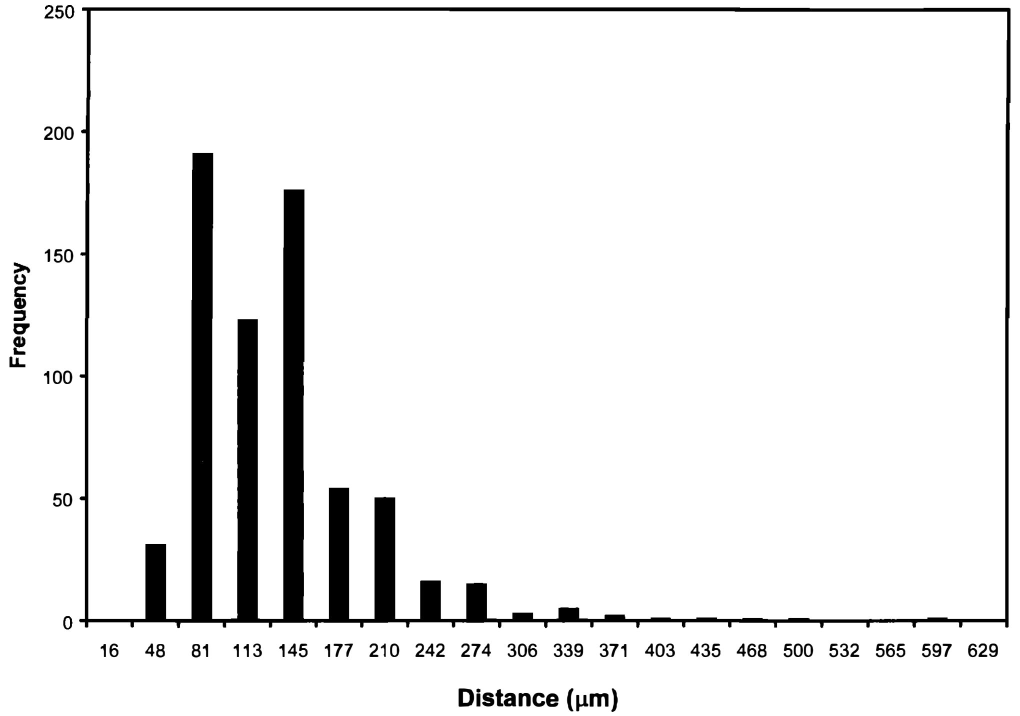


Figure 9. Histogram for the frequency of appearance for distances between peak maxima. A bimodal distribution at 81 μm and 145 μm was observed for all hair types analyzed.

Table II
Frequencies of Appearance for Distances Between Peak Maxima of 81 μm and 145 μm for Various Types of Hair

	Oriental	Medium brown	Light brown	Dark blonde	Medium blonde	Light blonde	Natural white
81 μm	410	332	262	154	234	222	260
145 μm	228	202	171	154	159	160	190
Total population	1007	878	717	560	669	616	769

Table III
Frequencies of Appearance for Distances Between Peak Maxima of 81 μm and 145 μm for Untreated and Sebum-Treated Dark Brown Hair

	Untreated	Sebum-treated
81 μm	191	207
145 μm	176	158
Total population	671	645

ANALYSIS OF REFLECTION PATTERNS FROM AFRICAN HAIR

African hair provides an interesting substrate for optical analysis due to the multiple curls that are naturally present. As shown in Figure 1●, the curls provide multiple

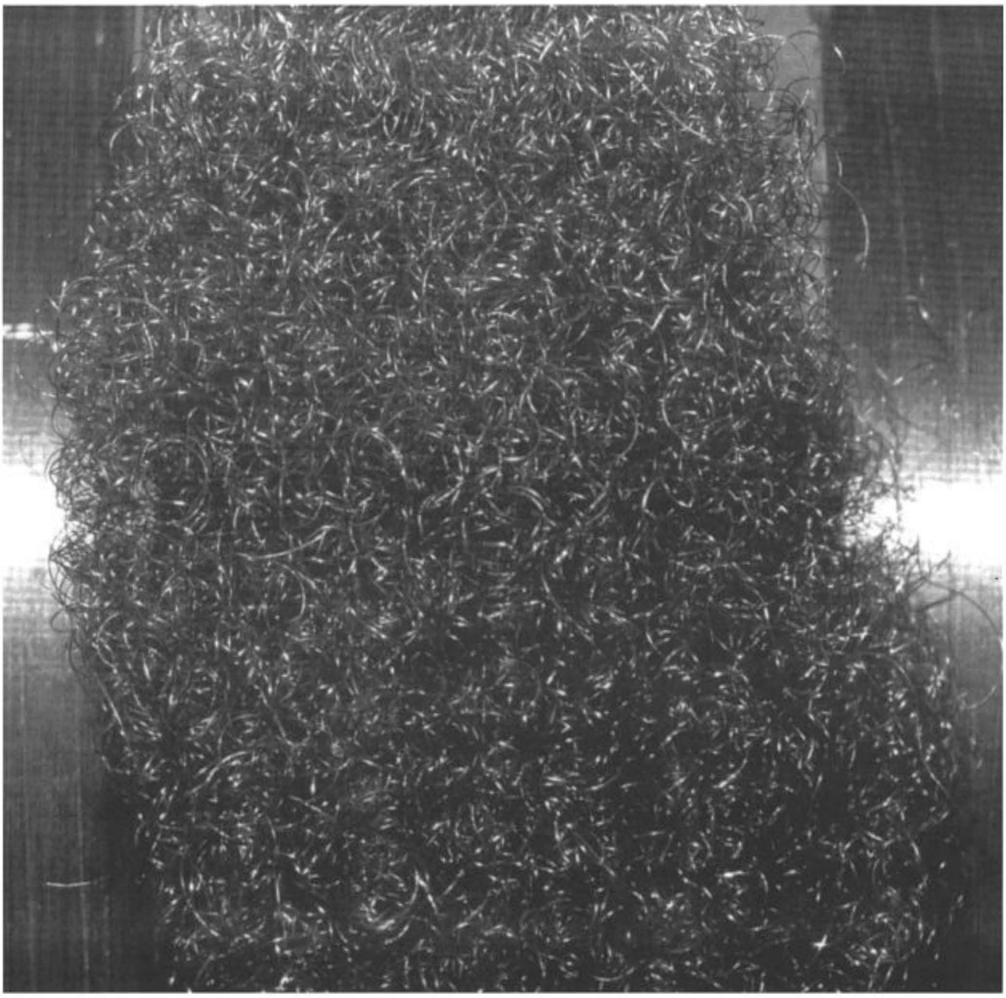
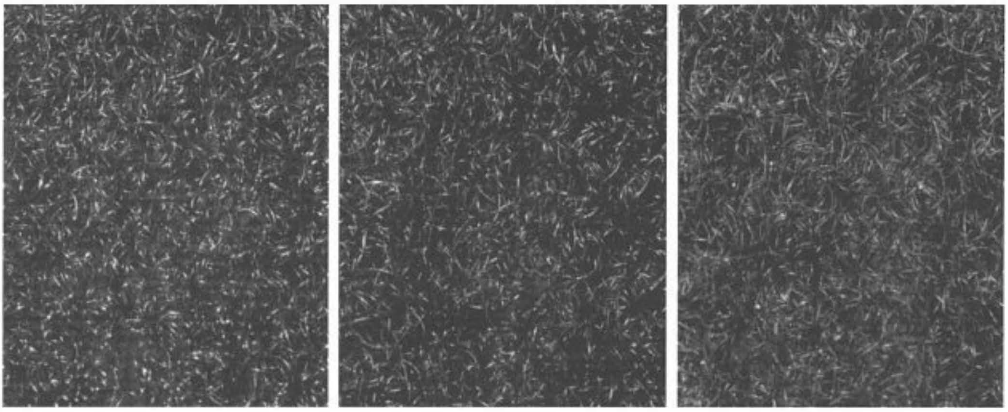


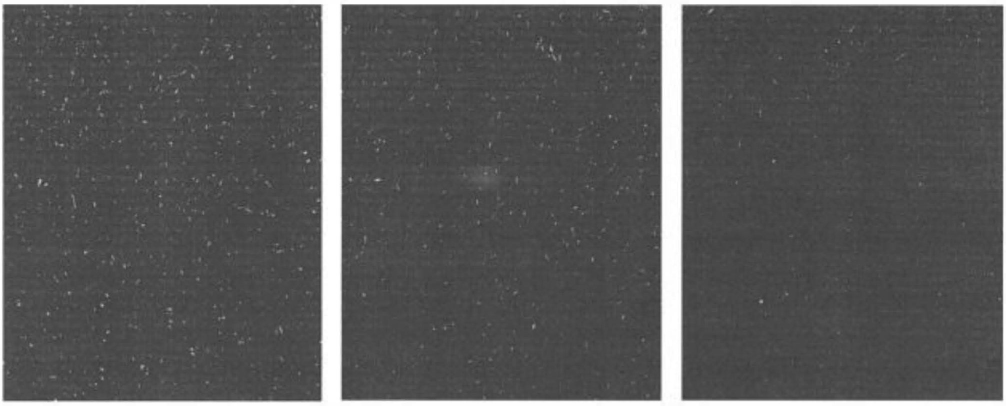
Figure 10. Image of untreated virgin African hair at close proximity. Exposure settings: f8, 1/13s.

reflection patterns in a given African hair sample. It is important to note that unlike straight hair, which exhibits one specular reflection band that coincides with the band on the cylinder mount, homogenous illumination of African hair with a collimated light beam results in multiple reflection centers of equal intensity in all regions of the sample. In order to quantify the multiple reflection patterns, we utilized Image Tool 2.0 software, which allowed us to tally the number of reflection sites as well as to characterize the shape of the reflection. Figure 11 provides images obtained for untreated hair along with hair treated with 17 mg and 61 mg of artificial sebum per gram of hair. Visual inspection of the images reveals a perceived decrease in luster with increasing concentrations of sebum. Further, the decrease in luster is coupled with a decrease in the number of reflection sites. Figure 12 provides images that correspond to the photographs in Figure 11 in which all of the reflection sites have been isolated on a black background using an image threshold technique with Image Tool 2.0. This is accomplished by looking at a histogram corresponding to the colors present in the image and isolating the



untreated 17 mg/g 61mg/g

Figure 11. Images of untreated and sebum-treated African hair. Exposure settings: f8, 1/13s.



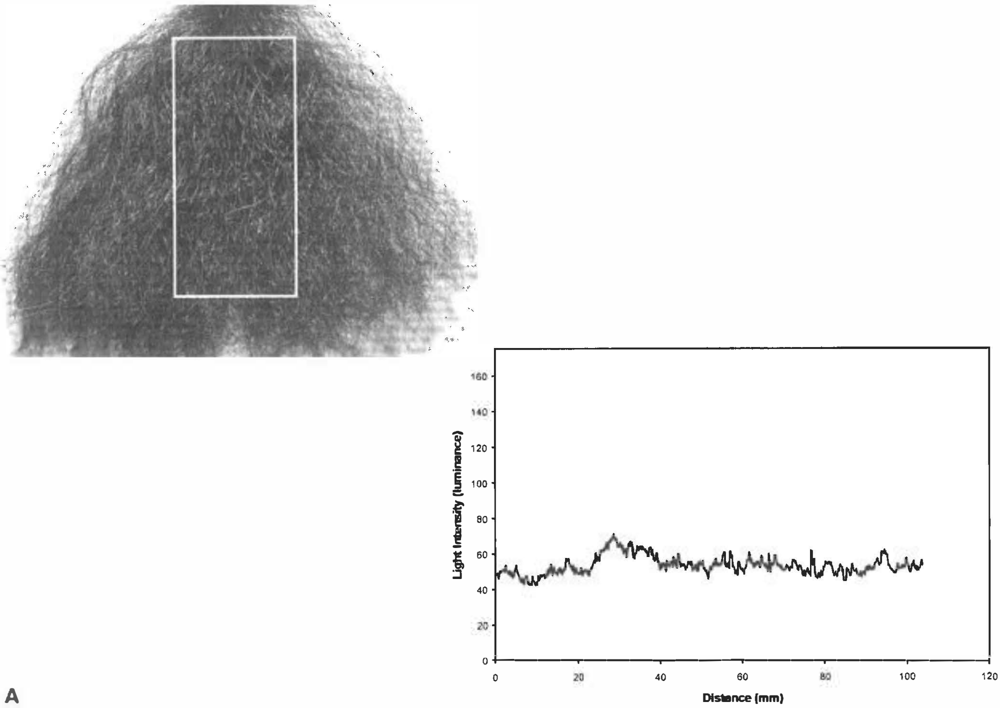
untreated 17 mg/g 61mg/g

Figure 12. Image threshold of the images shown in Figure 11. See text for explanation.

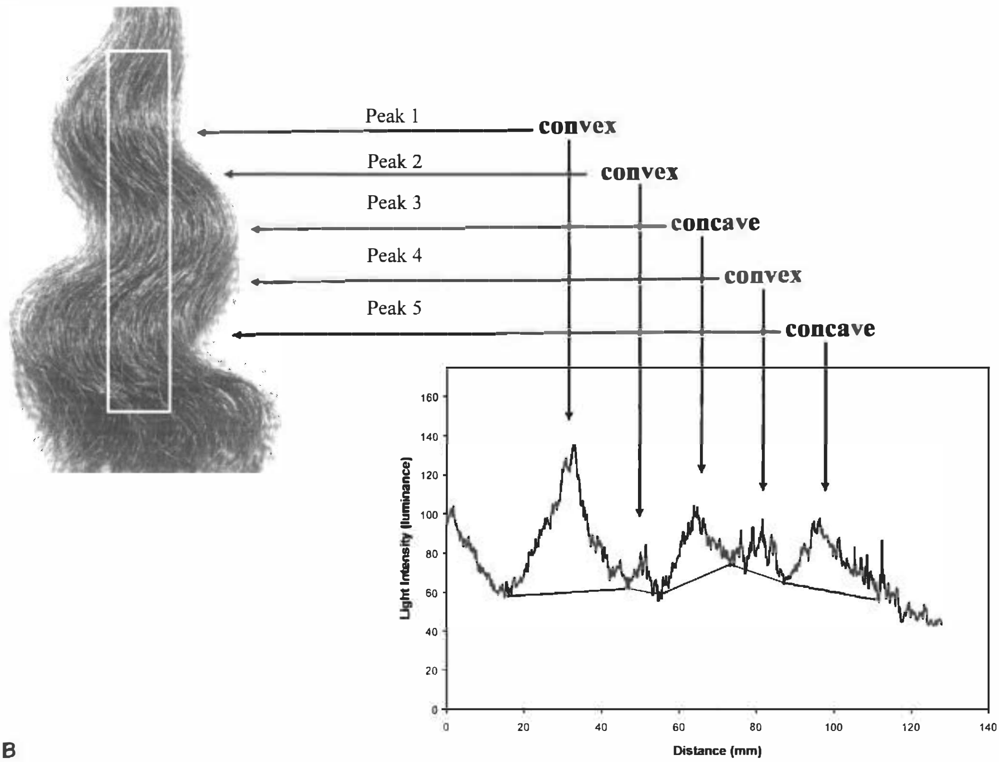
Table IV
Quantification of Reflection Sites on African Hair Treated With Sebum

	Number of reflections	% Black	% White
Untreated	742	98.34	1.66
17 mg/g	536	99.02	0.98
61 mg/g	273	99.67	0.33

bright white light that corresponds to the reflection centers. Image file types usually have a scale from 0 to 255 to represent the colors in the image, with 0 representing the darkest colors (black) and 255 the brightest (white). By isolating values that fall in the range from 225 to 250, we can look at the brightest reflections on an entirely black background (Figure 12), allowing us to count the total number of reflections.



A



B

Figure 13. Examples of hair with various types of curvature: (A) frizzy hair, (B) very curly hair, and (C) curly hair. Plots of luminance as a function of distance are provided for each hair type, where the outlined area in each image was used as the sampling area.

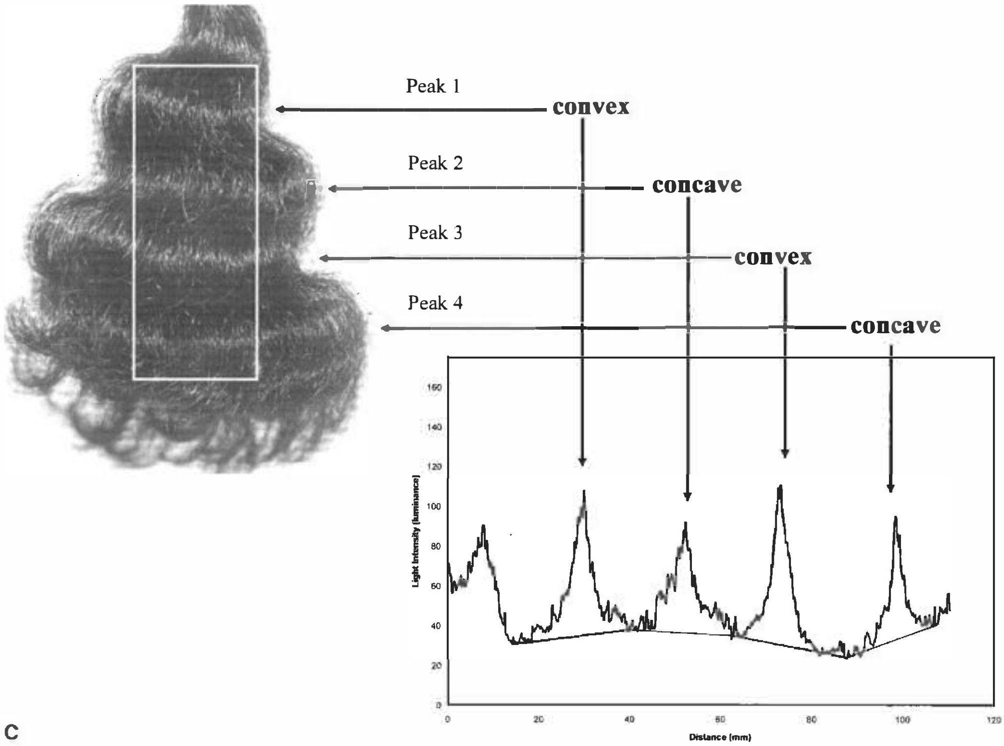


Figure 13. Continued.

Table V
Luster Parameters Calculated From Images of Curly and Very Curly Hair Shown in Figures 13B and 13C

Luster parameter	Peak 1	Peak 2	Peak 3	Peak 4	Peak 5
			Curly hair		
Integrated specular intensity	33010	6653	17768	13283	22234
Integrated diffuse intensity	22579	5926	11544	11544	17508
Stamm's luster	0.32	0.11	0.35	0.13	0.21
			Very curly hair		
Integrated specular intensity	15435	14141	13581	10314	
Integrated diffuse intensity	10270	9742	8749	7345	
Stamm's luster	0.33	0.31	0.36	0.29	

As shown in Table IV, the number of reflections decreases with increasing concentrations of sebum, which was also clearly evident after visual inspection of Figure 12. It should also be added that the reflection shapes could be also characterized in terms of perimeter, roundness, compactness, etc. While we conducted such an analysis in relation to African hair, we did not find any obvious correlations between such parameters and the hair treatments.

ANALYSIS OF REFLECTION PATTERNS FROM FRIZZY, VERY CURLY, AND CURLY HAIR

We also attempted to conduct luster analysis for samples of frizzy, very curly, and curly hair as shown in Figures 13A–13C. Hair was prepared as conventional two-gram tresses, which were hung in the light box and illuminated with a uniform white light at an angle of approximately 45 degrees. In contrast to our previous analysis of straight hair, which was typically spread on a cylinder to impart curvature, and thus produce specular and diffuse reflections, in these experiments we took advantage of the natural (or artificial) curliness of the hair sample to observe and quantify the reflection patterns. As seen in Figure 13A, the reflections in frizzy hair occur at random and correspond to single fibers. At higher magnifications one can see that they consist of sequences of microreflections similar to those presented in Figures 1 and 2. As with African hair, such hair cannot be subjected to conventional goniophotometric analysis as described in our previous paper. On the other hand, the luster of such hair can be studied using the image threshold technique similar to that employed for African hair. In the case of curly and very curly hair (Figures 13B and 13C) there are distinct specular reflection bands, which can be analyzed by measuring light intensity as a function of distance. Four vertical lines, 50 pixels in width, which covered the area of the inset in Figures 13A–13C, were employed to generate a light-scattering curve. Such plots consist of several peaks, which as indicated in the figures can be assigned to specular reflections from both convex and concave portions of the hair bundle. Based on these plots, several luster parameters may be calculated, which include integrated specular intensity (S), integrated diffuse intensity (D), and Stamm's luster (L_{Stamm}) (Table V). A line drawn at the base of each peak indicates the integration limits, with the integrated diffuse reflection corresponding to the area between the line and the distance axis, while the integrated specular reflection corresponds to an area under the scattering curve. This is analogous to the method we employed previously to calculate the luster of a non-curly hair tress (1). Stamm's luster parameter was calculated using the formula $L_{Stamm} = S/(S - D)$. The results indicate that luster parameters are slightly higher for convex reflections than for concave reflections. Further, we find that very curly hair appears to be more lustrous than curly hair or frizzy hair. This may be attributed to the well-defined nature of the curls in the very curly hair and their high curvature as compared to the relatively low curvature of curly hair. On the other hand, integrated specular intensities were higher for convex reflections in curly hair.

We also employed image threshold analysis in order to isolate the specular reflection centers on a black background for frizzy, very curly, and curly hair. Figures 14A–14C contain the images of isolated specular reflection centers for frizzy, very curly, and curly hair, respectively, and Table VI collects the results of calculations.

The data include the total number of pixels and the breakdown for black and white pixels for the three types of hair under investigation. Frizzy hair has the largest number of total pixels since it occupies the greatest area for a given image size, followed by very curly and curly hair. Similarly, the image of frizzy hair contains the largest amount of black pixels, followed by successively lower quantities in the very curly and curly hair samples. On the other hand, curly hair contains the highest percentage of white pixels, with decreasing amounts found in very curly and frizzy hair. Both absolute and relative contents of white pixels (or specular reflections) may also contribute to the overall perception of luster, since it was shown in the previous paragraph that a reduction of luster is associated with a decrease in the number of reflections centers.

Figure 14. Image threshold of the images shown in Figure 13: (A) frizzy hair, (B) very curly hair, and (C) curly hair. (See overleaf for parts B and C.)

CONCLUSIONS

The conventional way of measuring luster involves the use of hair tresses or single fibers and their careful orientation in goniophotometric instrumentation by the use of special mounting frames. The geometry imparted to hair and the uniform illumination of the hair sample produces specular and diffuse reflections, which can be characterized by light-scattering curves obtained as a plot of light intensity as a function of angle (or distance) along the fiber length.

In this paper we have explored alternative ways of measuring luster:

1. We have carried out microscopic analysis of light reflected from hair, achieved by means of high-resolution digital photography. This study has revealed a dot-like structure of reflected light from individual fibers. The contrast between the dots (specular reflection) and the darker regions (diffuse reflection) of the entire reflection band was characterized quantitatively by plots of luminance as a function of distance across the specular reflection band (perpendicular to the fibers). These data were further converted into two-dimensional distributions of luminosity, histograms for the frequency of appearance for peak maxima and minima in luminosity distribution plots, and histograms of absolute maxima and minima of luminosity along the length of the fibers. The difference between the peak maxima and peak minima curves provided us with an indication of the microcontrast related to the dot-like appearance of the specular reflection band. This parameter, similarly to Stamm and Robbins' defined luster indices, was found to increase with increasing pigmentation of hair.

Figure 14. Continued.

Table VI
Quantification of Reflection Sites on Frizzy, Very Curly, and Curly Hair by Using Image Threshold Technique

	Total pixels	Black pixels	White pixels	% Black	% White
Frizzy	1,804,101	1,783,515	20,586	98.86	1.14
Very curly	921,160	905,242	15,918	98.27	1.73
Curly	636,629	622,296	14,333	97.75	2.25

2. Image analysis was employed to analyze random reflection patterns in untreated and modified African hair. In images of hair, all of the specular reflection sites have been isolated on a black background using an image threshold technique. This permitted us to count the total number of the brightest reflections, the number of which decreased significantly after treatment of hair with sebum.
3. Image analysis also allowed us to characterize quantitatively the luster of tresses with hair types characterized as frizzy, curly, and very curly. Curly and very curly hair was studied by measuring light-scattering profiles, which allowed for the calculation of specular/diffuse light intensities and luster parameters. All three types of hair were also studied using an image threshold technique, which permitted ranking them according to the absolute and relative content of specular reflections.

In our subsequent work we would like to explore the effect of styling, conditioning, and special treatments on the luster of hair, utilizing mannequin or human model heads. We believe that digital photography and image analysis coupled with data analysis, similar to that presented in this paper, could lead to a quantitative luster evaluation in natural hair assemblies.

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