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Studies of light scattering from ethnic hair fibers

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Synopsis

One of the most desirable hair attributes to consumers, irrespective of ethnic background, is hair shine. The light reflected from a fiber has two components, specular and diffuse. The specular fraction of reflected light from the front surface of the fiber is generally recognized as a contributor to high luster. The distinction between specular and diffuse reflection is, however, not always clearly defined. In this study an attempt has been made to differentiate between specular and diffuse reflectance by analyzing mathematically goniophotometric curves of light reflected from unaltered single hair fibers from European, African, and Asian ethnic groups. The effect of macroscopic characteristics of the hair fibers, such as fiber diameter, cross-sectional shape, and curvature on luster is demonstrated. Results indicate that broadening of the specular peak reduces luster values, and is related to these characteristics. Thus, specular peak broadening is one of the important features to take into account when evaluating luster. Therefore, a new method for luster evaluation from goniophotometric curves is proposed. Additionally, we present the general model for light scattering, showing how scattering by surface roughness of different origin and magnitudes, and the scattering and absorption processes by the hair's interior, affect the position of the specular reflectance peak and its broadening.

INTRODUCTION

During the last decade the cosmetic industry has increasingly formulated personal care products to meet the needs and expectations of ethnic consumers. For example, consumers of African origin generally prefer straight hairstyles. As a result, they depend heavily on heat and chemical treatments to relax their hair, which result in significant damage to the hair. Therefore, multifunctional products are required to condition, balance moisture, repair damage, and add shine to the hair. Hair care products aimed at Asian and European consumers are required to endow different attributes, where additives to add shine to hair are also of primary importance. Obviously, shine is one of the most desirable hair attributes to consumers, irrespective of ethnic background.

Generally, at TRI light scattering curves from goniophotometric measurements on single hair fibers are used to evaluate hair shine. In addition to quantitative information about hair shine, this method is also capable of providing information about the changes in hair shine due to product deposits and surface damage by various cosmetic treatments and combing (1–5). Apart from other factors, the appearance of hair and its shape is influenced by its ethnic origin. The differences in morphology and composition of some ethnic hair are reported in the literature (6–8). However, to date there has been no major effort made in the direction of understanding how differences arising from ethnic background affect the luster of hair fibers. In this study unaltered hair from European, African, and Asian ethnic groups is investigated by means of goniophotometry.

EXPERIMENTAL

Samples (15-cm-long) of unaltered blond Piedmont hair, light brown European hair, dark brown European hair (purchased from DeoMeo Brothers), black Indian hair, black Japanese hair, and black African-American hair (obtained from a private source) were used. Additionally, we used black Chinese hair from a 35-year-old female with no known history of chemical treatments.

A modified Brice-Phoenix goniophotometer (GP) was used to record the scattered light intensity as a function of the angle. Two light sources were used in this study: a He-Ne laser of 632-nm wavelength and a quartz tungsten halogen lamp emitting white light. Sections of hair at approximately the same distance from the fiber root were used in the measurements. Single hair fibers were mounted horizontally in the sample holder and held in place by clips. Most of the fibers studied here were naturally straight, except for the African-American hair, which was straightened carefully without extending the fiber. The measurements were performed in the root-to-tip direction of the hair fibers at an angle of incidence of 45°. For each hair type, measurements were made on 25 randomly chosen fibers. The reflected light was detected by the photomultiplier as a function of angle. Using peak-fit software, the GP curve was deconvoluted into specular and diffuse components, assuming a Gaussian distribution for the specular peak (see Figure 1). The luster was calculated by

$$L = \frac{S}{(S + D)} \tag{1}$$

where S is defined as the specular peak area obtained from the scattering curve and $(S + D)$ is the total area under the curve. The goniophotometric measurements were also used to determine the scale angle. The scale angle, α, was calculated from the GP curves of the fiber in the root-to-tip and tip-to-root position, using the following expression:

$$\alpha = \frac{\theta_{TR} - \theta_{RT}}{4} \tag{2}$$

where θ_{TR} and θ_{RT} stand for the angle of specular peak for tip-to-root and root-to-tip positions, respectively (9).

Fiber cross-sectional areas and the minor and major axis were measured by a laser scan micrometer (LSM-3100), from which ellipticity indices, i.e., the ratios of fiber major axes over fiber minor axes, were calculated.

RESULTS AND DISCUSSION

EFFECT OF ETHNIC ORIGIN OF HAIR ON FIBER STRUCTURE

Human hair is a complex tissue almost entirely consisting of proteins. By means of

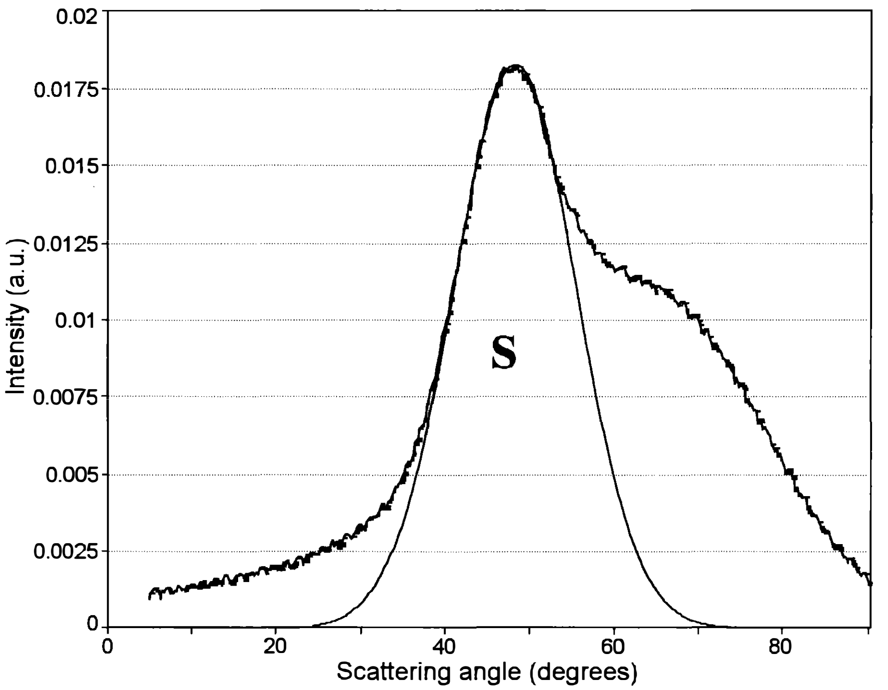

Figure 1. A typical goniophotometric curve and its deconvolution into specular and diffuse components.

electrophoresis, the chemical composition of the hair proteins has not been found to depend on racial origin (7). Yet, a significant variation is found in the morphology of the hair of different ethnic groups. Generally, the hair fiber can be qualitatively divided into distinct regions such as the outermost cuticle layers, inner cortical cells bonded together with the cell membrane complex, and the porous medulla. However, depending on the ethnic origin, the relative dimensions of these layers could differ significantly.

The outermost cuticle, consisting of flat overlapping scales is influenced by the surrounding environment and surface modifying treatments that cause the thinning and fusion of the surface cuticle cell (10). These changes have a significant effect on the optical properties of hair. The cuticle of European and Asian hair consists generally of six to eight layers, whereas the cuticle of African-American hair has a variable thickness with six to eight layers at the ends of the minor axis of the fiber and only one to two layers at the ends of the major axis (11). In this region the structure is weakened and vulnerable during grooming procedures. The structure of the medulla can appear as a continuous or a discontinuous channel, with significant differences in the packing of the medullary cells. It is important to note that in some cases the medulla is completely absent. Often, the absence of the medulla occurs for fine hair with a small diameter, whereas for medium- and large-diameter hair the medulla is generally present (the diameter of hair fibers varies from 40 to 100 μm). Thus, as the diameter of the hair can be related to its ethnic background, as shown below, the amount of medullation can change as well. The medulla is known to have a large effect on optical properties and hair shine (12).

The geometric configuration of hair fibers is known to depend on the relative amount of para- and orthocortical cells and their distribution in the fiber cross section. Observations by Swift suggest the relationship between the curliness of different ethnic hair and their bilateral structure (8). For example, straight Asian hair has only paracortex and slightly curly European hair has a thin one-cell-layer orthocortex at the periphery of the cortex, whereas the most curly African hair has approximately equal amounts of the two cell types.

ELLIPTICITY AND CROSS-SECTIONAL AREAS FOR ETHNIC HAIR

In Table I the data from measurements are presented. The results are organized into three groups as follows: First, hair of European origin with different pigmentation levels (denoted as the European group below); second, hair of Asian origin (denoted as the Asian group below); and finally, the African-American hair, forming the third separate group due to its unique configuration with twists and kinks along the fiber axis. For a given number of fibers from the tresses used in this study, the cross-sectional area was found to be smallest for the fine light-brown European hair, followed by Piedmont hair and Chinese hair. The dark brown European hair had the largest cross-sectional area of the three differently colored hair samples of European origin. Indian and African-American hair had similarly large cross-sectional areas, whereas the largest cross-sectional area was measured for Japanese hair. Measurement reveals that Chinese hair fibers were the most regular, with almost circular cross sections given by an ellipticity index of 1.16. In the Asian hair group, Indian hair had the most asymmetrical shapes, with an ellipticity index of 1.44. Hair of European origin was found to be oval in cross section. Within this ethnic group the ellipticity index increased in the order Piedmont hair (1.36), light brown European hair (1.46), and finally dark brown European hair (1.52). African-American hair fiber had twisted ribbon shapes, which in cross section appeared as flattened or curved ovals. The average ellipticity index for the African hair was found to be 1.6.

The variations in the ellipticity indices found in our study are in good agreement with the general trend reported in the literature (13,14). The hair of Asian background is generally reported to be the closest to having a circular cross section, with an ellipticity index around 1.25, oval European hair having a ratio of 1.35, and African-American hair, with the greatest deviation from circularity, having an average ellipticity index of 1.75. We note that the average ellipticity index of 1.6 obtained in our study for African hair is at the low end of the wide range of ellipticity indices (1.6–1.9) reported in the literature.

From Table I we observe several trends. Within the European hair group, with increasing hair pigmentation levels, luster increases and the width of the specular peak at half height ($W_{1/2}$) decreases. There is also a systematic increase in the ellipticity index and a decrease in $W_{1/2}$ from measurements performed with both laser and white light illumination. Luster increases with the ellipticity index. In the two remaining ethnic groups the hair fibers are all black in color, and thus we assume that the effect of pigmentation level can be neglected in our discussion. Comparable high luster values were obtained for African and Indian hair, followed by Japanese and Chinese hair. As in the case of European hair, luster was found to increase with the ellipticity index. Within the Asian group, under white light illumination, the mean $W_{1/2}$ followed the same trend observed for European hair, i.e., $W_{1/2}$ increasing with the decreasing ellipticity index.

Table I
Experimentally Determined Hair Fiber Characteristics by Ethnic Origin

Hair origin	Cross-sectional area (mm^2) × 10^{-3}	Ellipticity index	Luster (%) (He-Ne laser illumination)	$W_{1/2}$ (degrees)	Scale angle	Luster (%) (white light illumination)	$W_{1/2}$ (degrees)
Piedmont	4.53	1.36	17.35 ± 1.37	5.79 ± 0.3	2.8 ± 0.2	48.2 ± 2.3	20.0 ± 1.5
Light brown European	3.75	1.46	21.53 ± 2.3	4.79 ± 0.4	2.9 ± 0.3	55.3 ± 1	17.6 ± 1.1
Dark brown European	5.08	1.52	27.91 ± 1.47	4.38 ± 0.2	3.0 ± 0.2	63 ± 3.1	15.5 ± 0.8
Indian	5.65	1.44	35.6 ± 3.8	3.67 ± 0.4	3.7 ± 0.3	65 ± 2.26	12.8 ± 0.6
Japanese	6.64	1.33	34.25 ± 4.6	5.04 ± 0.4	3.6 ± 0.3	59.5 ± 3.34	14.8 ± 0.9
Chinese	4.88	1.16	24.05 ± 2.2	4.29 ± 0.3	3.6 ± 0.4	62.4 ± 1.9	15.6 ± 1.9
African-American	5.27	1.6	35.95 ± 4.3	4.83 ± 0.4	2.3 ± 0.4	64.5 ± 2.8	14.1 ± 1.1

With the laser illumination the Indian hair had indeed the smallest $W_{1/2}$, whereas for Japanese and Chinese hair the $W_{1/2}$ values were higher.

It seems that specular peak broadening is one of the important characteristics to take into account when evaluating the luster of hair. On the basis of our observations described above, we suggest that specular peak broadening could be related to changes in the following hair characteristics:

1. Color (or transparency) of the hair fiber
2. Fiber diameter and ellipticity (if the illuminating light beam is larger compared to fiber)
3. Fiber curvature (presence of twists and kinks)
4. Surface roughness, either microscopic or macroscopic (scale angle)

The effect of these characteristics on luster and peak broadening are discussed in more detail in the following paragraphs.

EFFECT OF SURFACE ROUGHNESS ON LUSTER

As mentioned earlier, luster is greatly affected by the surface condition of the hair fiber. The modification in GP curve shape and angular position can arise, depending on the origin of roughness and its magnitude. A general model for light scattering can be successfully used to explain the changes in the GP curve caused by surface roughness. Figure 2 schematically shows the light scattering from surface roughness of different magnitudes. In the uppermost graph, A, specular reflection from the smooth surface occurs at the angle of incidence. Hair fiber can reflect light in a specular manner, almost like a mirror, when a shine spray or oil layer covers the scale structure completely, forming a smooth surface.

The surface with microscopic roughness results in an isotropic surface scattering in addition to specular reflection. In the case of the hair fiber, this situation is caused by

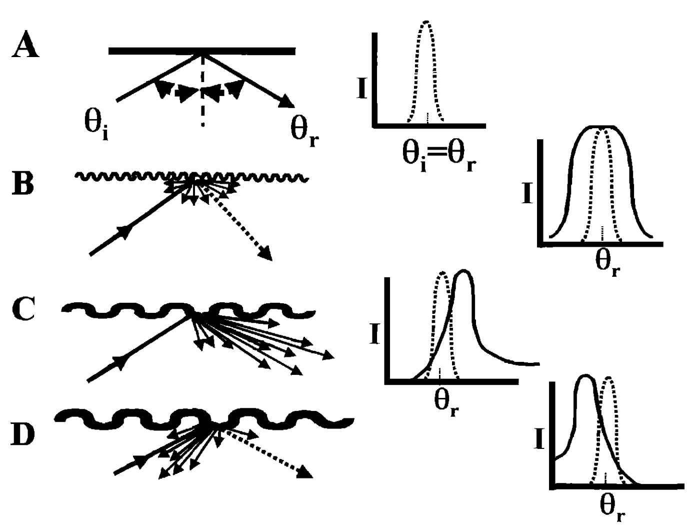

Figure 2. Schematic representation of light scattering model for surfaces with different roughness magnitudes and its effect on goniophotometric intensity scan.

very small particles deposited on the hair surface and by roughness on the scale faces. Isotropic scattering from the surface contributes to the peak broadening observed in the GP curve as shown in Figure 2B. On the other hand, macroscopic roughness as shown in Figure 2C leads to a light scattering profile dominating in the forward direction. In this case, change in direction of the reflection maximum is caused by the macroscopic roughness (scale structure) and results in a peak shift towards higher angles compared to the angle of incidence in the GP curve. This effect is of a general nature and is indeed observed experimentally. Theoretically, a further increase in the magnitude of surface roughness can lead to backward light scattering, which would result in an angular peak position shift toward angles lower than the angle of incidence (Figure 2D). In order to introduce such changes in the GP curve, large particle deposits or extreme scale lifting is necessary, which is generally not observed in the case of ordinary hair. However, tip-to-root (T-R) measurements will lead to a shift of the GP peak to angles lower than the angle of incidence because of back scattering from the scale edges.

Our experimental data allowed us to evaluate the effect of macroscopic surface roughness in the form of scale angles on GP characteristics. The average scale angle values calculated from the goniophotometric intensity scans from root-to-tip and tip-to-root positions are shown in Table I and can be summarized as follows: The lowest scale angle of 2.3° was found for African-American hair, whereas the highest scale angles (around 3.7°) were found for Chinese, Indian, and Japanese hair. The medium scale angle (around 2.9°) was found for European hair independent of pigmentation level (blond, light brown, and dark brown). Examination of the data on luster and $W_{1/2}$ in Table I shows that there is no relationship between these parameters and the scale angle within the range of scale angles studied here. Although the foregoing discussion indicates that microscopic roughness leads to peak broadening, its quantitative contribution to this could not be evaluated at this time but will be attempted in a separate study.

EFFECT OF COLOR ON LUSTER

Hair fiber derives its natural color from polymeric melanin pigment existing as discreet round-to-oval granules (length 0.4–1 μm, breadth 0.1–0.5 μm) in the hair cortex (15). The natural pigment shows semiconductor-like optical properties and absorbs/scatters light from UV to the IR region and has great influence on hair shine. Luster for European hair under monochromatic laser and white light illumination was found to increase with pigmentation in the following order: Piedmont < light brown European < dark brown European hair (see data in Table I). This is in agreement with other studies where the gradual increase in luster is found to be dependent on pigmentation either by melanin or dyes (16,17). We note that the dependence in absolute value of luster on the illuminating light source is caused by differences in light beam characteristics and other instrumental settings, and will not be discussed within this study.

The effect of color on luster can, for instance, be explained by the general light scattering model described in the previous section. In addition to rays being reflected and scattered at the surface, the light is also partially refracted into the fiber. Retracted light may emerge after several internal reflections. The light so emerging and the light directly reflected from the outer surface both contribute to the total scattering by the fiber. Scattering of light from the interior of the fiber can occur because of the medulla, melanin granules or voids, inclusions, and other optical imperfections. Basically, the three modes of light scattering described above can occur inside the hair fiber, depending on the size of the absorbing and scattering entities. For small particles the scattering occurs in all directions, whereas for sizes greater than the wavelength of light, the intensity of the light scattered in the forward direction increases and the scattering profile becomes unsymmetrical, with the intensity maximum generally shifting to angles higher than the angle of incidence. Evidently, the angular distribution of the scattered light depends greatly on the internal structure of the fiber and its absorptive and scattering behavior. If the fiber interior is dominantly absorptive, then there is less scattering and therefore lower diffuse reflectance. Thus, the light scattering by the internal structure contributes to both peak broadening and the diffuse reflectance observed as a second peak in the GP curve. The GP intensity scans shown in Figure 3A–C indicate indeed that the change in luster arises from the decrease in diffuse reflectance due to the efficient light absorption by melanin granules. We note that pigment granules are reported to be larger and more numerous in African-American hair than in European hair (18). These differences are probably less meaningful than the effect of final color on fiber absorptive properties.

In Figure 4 we show a picture taken of the tresses of Piedmont hair, dark brown European hair, and a carbon fiber tape under illumination with white light. The picture demonstrates how absorptivity changes the diffuse reflectance and perceived luster. The surface of the carbon fiber tape is an example of a smooth high specular reflection surface with a high absorbing interior, leading to a bright narrow luster band compared to hair tresses.

EFFECT OF ELLIPTICITY ON LUSTER

In order to eliminate the color effect and demonstrate that the ellipticity index has an effect on luster, we compared the results of the hair fibers in ethnic groups with black color. The typical GP curves for hair fibers of Asian and African-American origins are shown in Figure 5A–D. As mentioned earlier, luster was found to increase, with the ellipticity index similar to that of European hair. The fact that the ellipticity of the fiber is indeed affecting peak broadening, and thus also the luster, is demonstrated by the following experiment. We took nylon fiber with a near ideal surface (no roughness) and with no color. We determined the nylon fiber diameter to be 80 μm and the ellipticity index to be 1, i.e., cylindrical fiber. The goniophotometric intensity scan was recorded with the nylon fiber. Thereafter, the ellipticity index of the same fiber was increased in two steps, to 1.35 and 7, by applying mechanical pressure on the fiber. The results in Figure 6 show the decrease in $W_{1/2}$ with the increased ellipticity index. Simplified schematics in Figure 7 show how the change in ellipticity affects light reflection characteristics. In the case of cylindrical nylon fiber, parallel light rays are reflected and refracted at the surface. The light path length from the near side to the far side of the fiber determines the light scattering volume and also the angular spacing between the specularly reflected light from the front surface and the emerging light from the fiber interior. The result is that the emerging light will be at angles slightly different from the main specular peak, leading to peak broadening. In the case of flattened nylon fiber, the decrease in the minor axis results in a shorter light path length and thus in a smaller scattering volume. Therefore, the angular region of reflected light is close to the specular direction, leading to a narrow peak. Also, a larger major axis creates a larger surface area

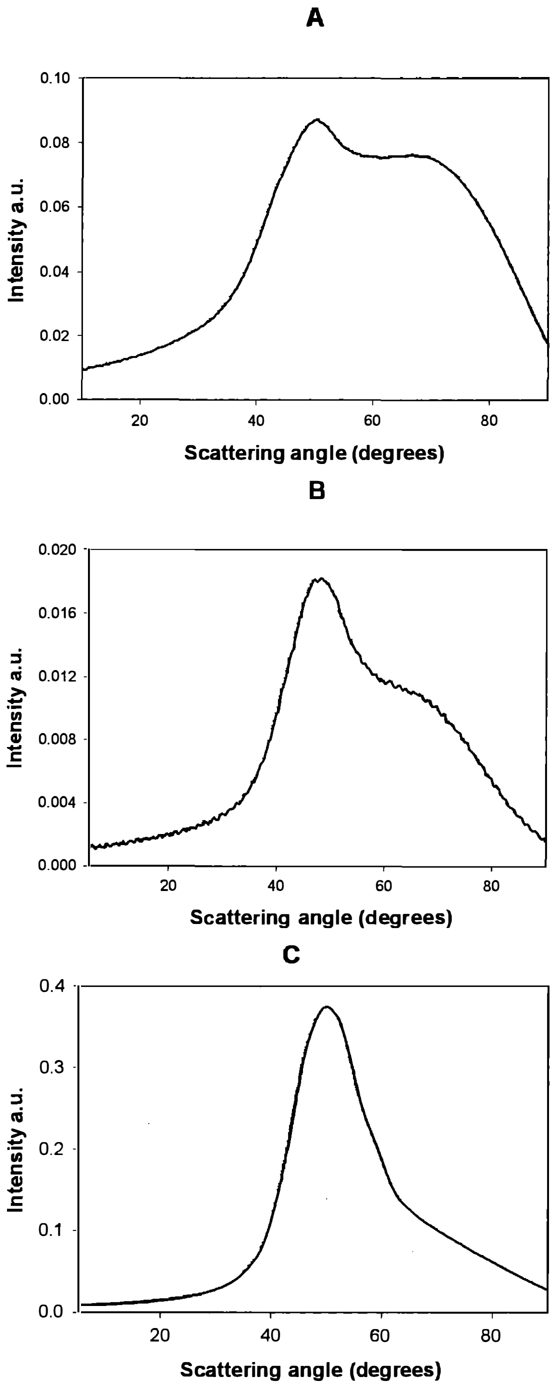

Figure 3. GP intensity scans under white light illumination for (A) blond Piedmont hair, (B) light brown European hair, and (C) dark brown European hair.

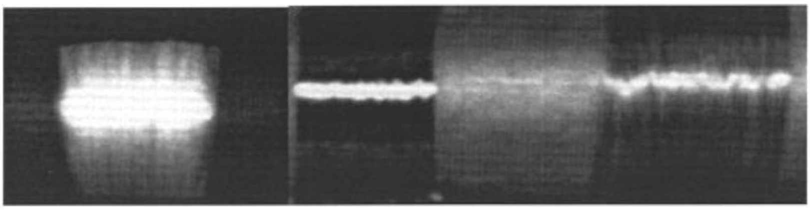

Figure 4. Picture illustrating the effect of color on luster. From the left: blond Piedmont hair tress, black carbon fiber tape, and tress of dark brown European hair.

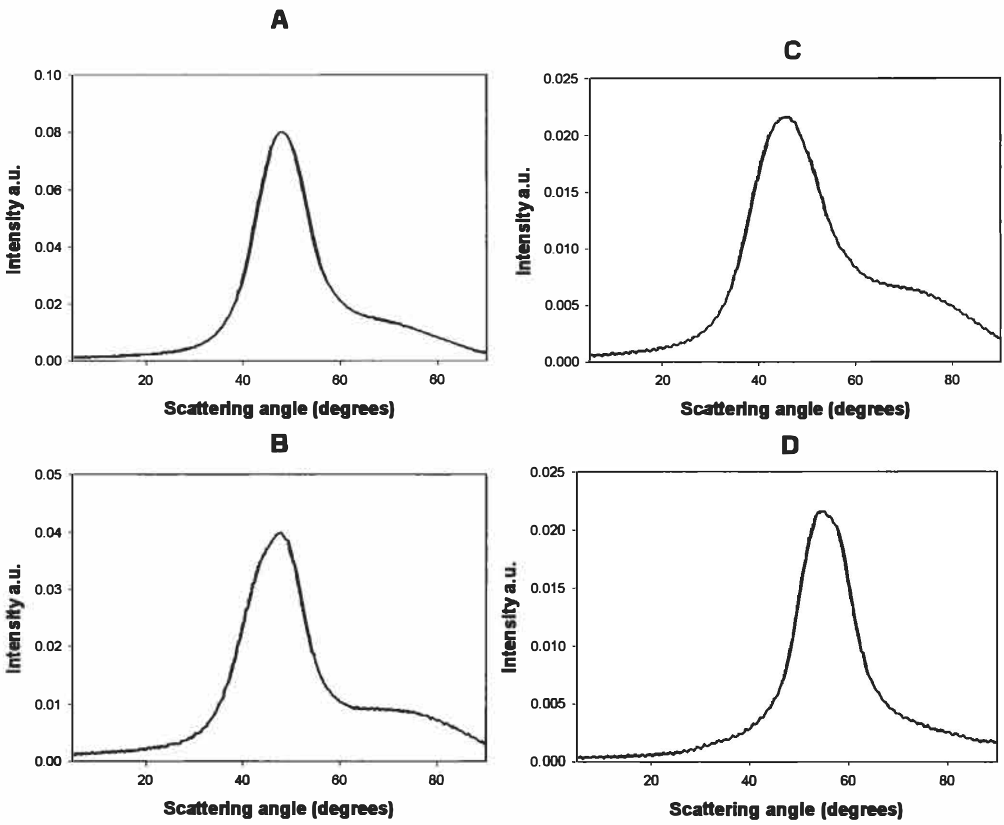

Figure 5. GP curves under white light illumination for (A) Indian, (B) Japanese, (C) Chinese, and (D) African-American hair.

available for specular reflection, observed by higher specular reflection intensities. Thus, with other parameters held constant, the increase in the fiber major axis facing the light source increases the luster as a result of decreased contribution from diffuse scattering. In the case of a hair fiber with a scale structure, the effect of the increased fiber major axis is more complicated, affecting both the $W_{1/2}$ and the nature of the diffuse peak associated with the light emerging from the far side of the fiber.

EFFECT OF CURL ON LUSTER

Permanent waves and hair relaxers function primarily by changing fiber curvature to

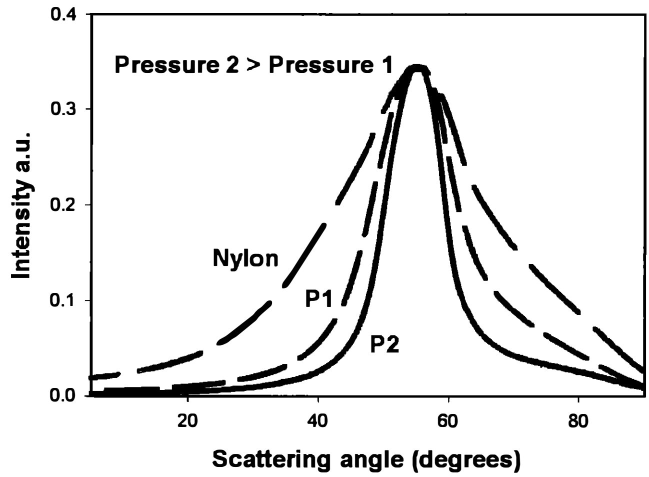

Figure 6. Nylon fiber ellipticity effect on GP intensity scan under white light illumination. Intensities are normalized.

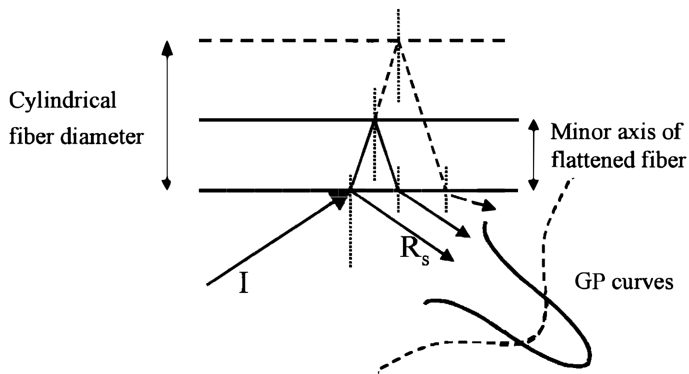

Figure 7. The effect of ellipticity on GP intensity scan. Simplified model for light reflection from cylindrical nylon fiber (dotted lines) and flattened nylon fiber (solid lines).

either a curlier or a straighter form. When the curvature is large, it dominates many physical fiber properties like fiber friction, flyaway hair, luster, combing ease, manageability, and hair body (19,20). Generally, the low luster of curly hair is related to poor fiber alignment. The ethnic hair of African origin used in this study has a natural distinctive and unique configuration, with twists along the fiber leading to a curly structure. As mentioned in the Experimental section, the African-American hair fibers were pulled straight in order to record the GP spectra. Therefore, twists and kinks are more important than a curly structure with large coils. In order to demonstrate the effect of the fiber twist on luster, the goniophotometric intensity curves were recorded first for the nylon fiber with a high ellipticity index and then for the same fiber twisted repeatedly over its longitudinal axis. The result is presented in Figure 8. The following features are observed: shift of the position of the specular peak towards the higher angles, increased $W_{1/2}$, and increased diffuse reflectance. The reason is that upon illumination of the surface of a twisted fiber, there are number of planes of incidence, i.e., the light reflection occurs at various angles of incidence. Thus, along the fiber, luster is reduced

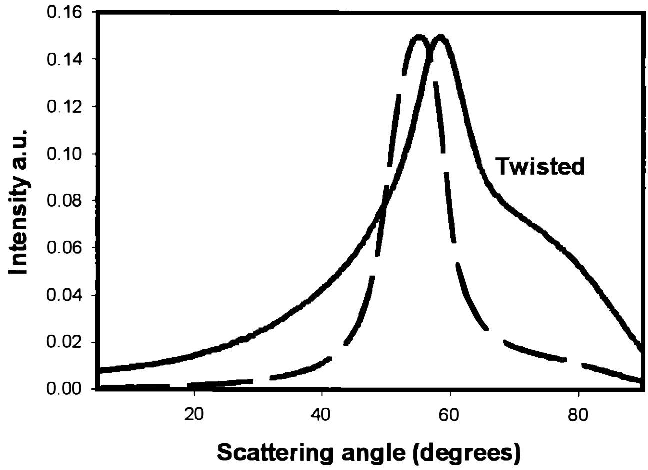

Figure 8. GP intensity scan from nylon fiber with increased ellipticity index and when twisted over its longitudinal axis.

at the locations where the fiber twists. From the GP curves the specular peak for African-American hair compared to other hair appeared shifted indeed to higher angles (as shown in Figure 5).

LUSTER CALCULATIONS REVISED

Although luster used to be calculated at TRI using equation 1, the realization that broadening of the specular peak is detrimental to luster necessitates its revision. Based on the work of Reich and Robbins (1), we have incorporated the width of the specular peak at half height into the luster equation, as shown in equation 3:

$$L = \frac{S}{(S + D) \cdot W_{1/2}} \tag{3}$$

Since luster obtained from equation 3 is not dimensionless, we have further refined it by incorporating peak width at half height of a standard specular reflector. This gives equation 4:

$$L = \frac{S}{(S + D)} \cdot \frac{W_{1/2}^{\text{standard}}}{W_{1/2}^{\text{sample}}}. \tag{4}$$

Here the first term of the equation takes into account the contributions from the specular and diffuse reflectance, whereas the second term represents the peak broadening. The second term represents a normalization factor, obtained by dividing the peak width at half height of a standard specular reflector into the width at half height of the specular peak obtained from the fiber of interest. As a standard we used the black mirror provided by Hunter Lab as a black reflection standard. The GP curve of a black mirror under He-Ne laser illumination is given in Figure 9. It has no diffuse reflectance and, therefore, has a luster of 1, or 100%. The reflection profile of a single carbon fiber from the tape shown in Figure 4 is similar to that of Figure 9.

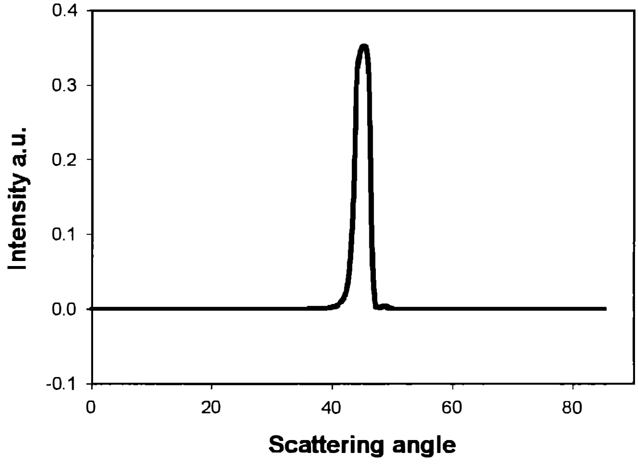

Figure 9. Goniophotometric intensity scan under He-Ne laser illumination for a standard black mirror from Hunter Lab.

Table II
Luster Calculated by Equations 1 and 4

Hair origin	Luster (%) by equation 1 (He-Ne laser illumination)	Luster (%) by equation 4 (He-Ne laser illumination)
Piedmont	17.35	8.4
Light brown European	21.53	12.6
Dark brown European	27.91	17.8
Indian	35.6	27.2
Japanese	34.25	19.1
Chinese	24.05	15.7
African-American	35.95	20.8

The luster values calculated from equations 1 and 4 are given in Table II. The absolute luster values calculated by equation 4 progressively decrease because of the nature of this equation. However, we note that there are comparable changes in the luster values calculated using equations 1 and 4 for European hair with various pigmentation levels. This indicates that in the case of European hair the peak broadening is dominantly caused by a gradual decrease in pigmentation, leading to increased scattering by the hair's interior. However, for hair of Asian origin the use of the latter equation differentiates similar luster values (e.g., Indian and Japanese hair) obtained by using equation 1. Hence, equation 4 is more discriminating. For hair with Asian origin the pigmentation is similar, and therefore the peak broadening should be explained by differences in the hair's internal structure, e.g., the presence or absence of the medulla. Japanese hair is known to have a high medullation, leading to increased internal light scattering.

SUMMARY

In this study the optical properties of hair from various ethnic backgrounds are studied

using a goniophotometer. The effect of fiber characteristics, such as fiber diameter, ellipticity, and curvature, on luster is demonstrated. The general model for light scattering is used for showing how scattering by microscopic and macroscopic surface roughness, as well as scattering and absorption processes by the hair's interior, affect the position of the specular reflectance peak and its broadening. Absorption characteristics of the fibers are found to play a major role on the luster of hair. Results indicate that the specular peak broadening is one of the important features to take into account when evaluating luster. Therefore, a new equation for luster calculation from GP curves has been proposed. It takes into account the broadening of the specular reflection peak that reduces luster values. Furthermore, by using normalized $W_{1/2}$ values in the equation, a dimensionless luster value is obtained. Luster defined by equation 4 can be adopted as a standard for hair.

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