

Analyzing the laser-light reflection from human hair fibers. II. Deriving a measure of hair luster

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Synopsis

Hair shine or luster is perceived as an important, though analytically somewhat elusive, attribute of beauty, primarily associated with clean and healthy hair. Principles for the assessment of hair luster are developed that are consistent with the practical situation. These principles are related to the components of light, specularly and diffusely reflected from single hair fibers, as measured by laser-based, multiangle goniophotometry, presented in Part I. Considering various definitions of gloss, their tradition, practical implementation, and their inherent limitations for testing hair, the gloss index as a physically consistent measure of hair luster is derived from the ratio of the integral intensities of the light components. Changes of the parameter values along hair length, namely their decrease, are analyzed for hairs of different color and ethnic origin. The correlation with shine evaluations of hair tresses by panels, based on literature data, is analyzed and ascertained.

INTRODUCTION

When applying hair cosmetic products the consumer expects perceivable, beneficial effects. Since among our senses vision undoubtedly plays a most important role, claims for increased hair shine (luster, gloss) are frequent for hair cosmetic consumer products, as well as for the raw materials they contain. This is due to the fact that hair shine is perceived as an important, though analytically somewhat elusive, attribute of beauty, primarily associated with clean and healthy hair.

Hair shine is generated when a beam of light strikes the hair surface. Parts of the light are specularly reflected and then perceived at a particular angle and direction, generating surface highlights and brightness contrast, while other parts are scattered and diffusely reflected. A further fraction of light is refracted into the hair, where it is absorbed, scattered, or reflected. All of the effects depend on the geometry of the hair surface, the

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refractive index, the incident angle of the light, the angle of observation, and the external and internal structure of the hair fiber.

Part I (1) described the application of multichannel laser goniophotometry to determine the angular distribution of reflected light from single hairs. Analyzing these distributions for hairs differing in ethnic origin and color gave details on changes of light reflection, including information on the cuticle angle. These were discussed in terms of changes of the hair surface along the hair length.

The principles for the generation of hair shine, as outlined above, are in our view directly related to the practical situation. Figure 1 shows the appearance of an Asian black (Fig. 1A), a medium-brown (Fig. 1B), and a blonde Caucasian (Fig. 1C) clean hair tress spotlighted under a stereomicroscope at a magnification of approx. 20 \times . Such tresses can be taken to represent a freely moving hair style without major fiber interactions. Largely white light reflexes are observed on single hairs that contrast with nonreflecting adjacent areas, which are either dark or light, depending on hair color.

Against the background of the technical terminology (2,3), as discussed in detail below, the phenomena observed in Figure 1 are appropriately termed "hair luster," because they are associated with the contrast gloss (2) of dark areas adjacent to light reflexes. These highlights are due to specularly reflected light from single fibers, where a high number of intensive, white reflexes, dynamically appearing and vanishing with the movement of the hair, give "shine" and enhance the appearance of beauty. The overall level of shine that may be achieved on the basis of a given degree of luster strongly depends on hairstyle (4).

Various approaches have been described to determine hair luster on hair tresses as a measurable quantity, applying goniophotometry (e.g., 5,6). Further approaches have been color measurements (7) and image analysis (e.g., 8). In parallel, the common laboratory practice for screening products is to use expert or consumer panels to subjectively rank hair luster, e.g., by means of a "shine box" (6,9–12). Noteworthy is the approach by Tango and Shimmoto (13) to develop a method and a device for the *in vivo* determination of hair shine that is related to the principles of commercial "gloss meters" (10,14).

More fundamental investigations also applied goniophotometry to single hair fibers and arrays of parallel, single fibers (5,11,13,15–17). Though gross changes in hair appearance through hair care products may well be detected on hair tresses, effects related to the assembly as such complicate if not prevent a detailed interpretation of the results.

In the case of single fibers, this method gives detailed insight into the interaction between light and the fiber surface, and a variety of parameters can be defined in terms of the intensities of specularly and diffusely reflected light. In view of the conclusions drawn from Figure 1, the use of goniophotometry would appear to be an especially promising approach. Problems with this method in the past (5,11), due to inherent large variations between individual hairs, as well as long recording times, have been overcome through multi-angle detection and fast data acquisition for the complete angular intensity distribution of reflected light, as described in Part I (1). On this basis a physically, practically plausible, and mathematically stable parameter to describe hair gloss, luster, and shine is introduced and assessed.

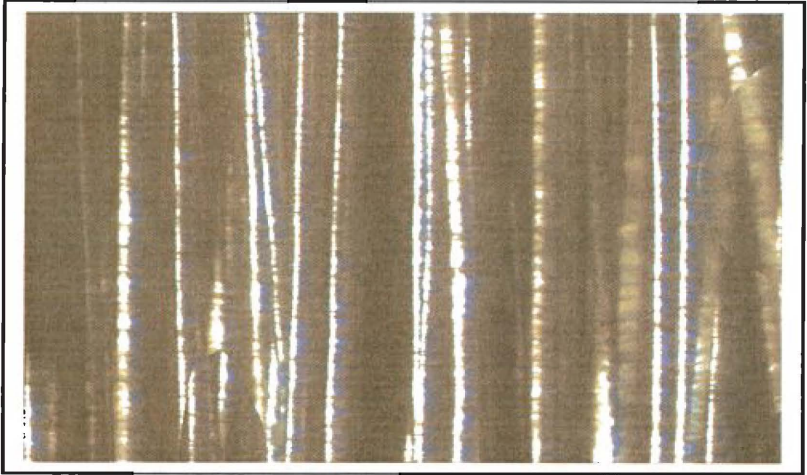
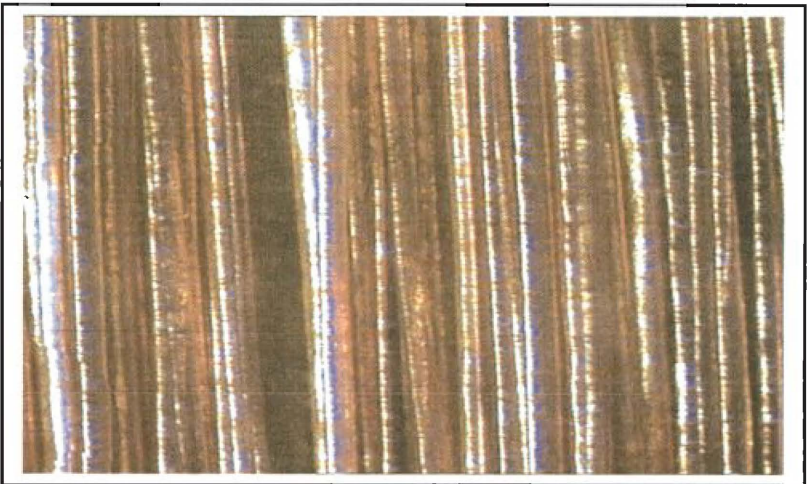
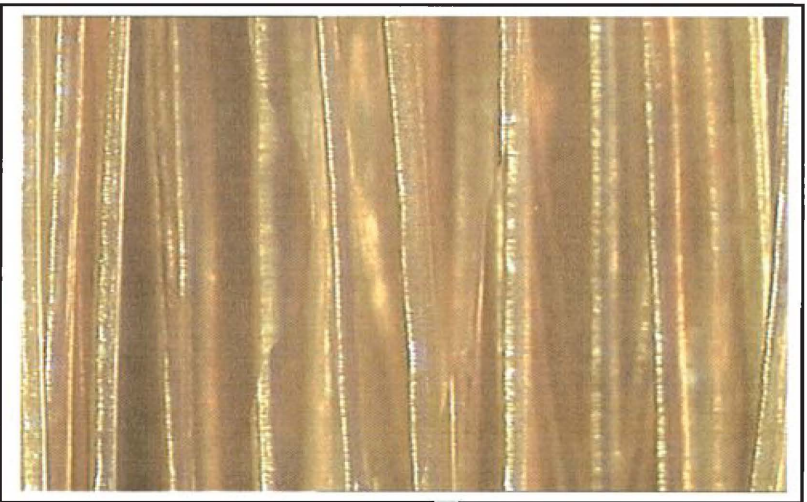
A**B****C**

Figure 1. Spotlighted tresses of black Asian (A) and brown (B) and blonde (C) Caucasian hair, respectively, under a light microscope at an initial 20 \times magnification.

DERIVING A MEASURE FOR HAIR LUSTER

MEASUREMENT AND ANALYSIS OF LIGHT REFLECTANCE FROM HUMAN HAIR

The measurement of light reflectance from single human hairs, as described in detail in Part 1 of this paper (1), is based on the determination of the angle-dependent intensity of the light from a green laser ($\lambda = 532$ nm) scattered from a single fiber. The wave length was chosen such as to be in that range where the daylight sensitivity of the human eye is at its maximum.

The basis for the investigation was three types of hair, namely black Asian and brown and blonde Caucasian hair (see Figure 1). Each sample was taken from the head of a female volunteer and exceeded in all cases 20 cm in length. The hairs were shampooed (LES 15%, pH 5.5), rinsed, dried, and stored under ambient conditions until measurement.

The experimental setup (1) is such that the vertically polarized laser beam (approx. 50 μ W) meets the hair fiber, arranged horizontally under slight tension and in ambient, though stable, room conditions (approx. 22°C, 50% RH), at an incident angle of 40° (beam spot diameter 100 μ m). The detection of the reflected light is conducted within about 100 ms in the horizontal plane containing the fiber and the incident light beam through a range of 6.5° to 173.5° with an Optical Multi-Channel Analyzer.

The solid line in Figure 2 shows the so-called goniophotometric (GP) curve, derived by smoothing the angular light intensity data for the most general case, namely light

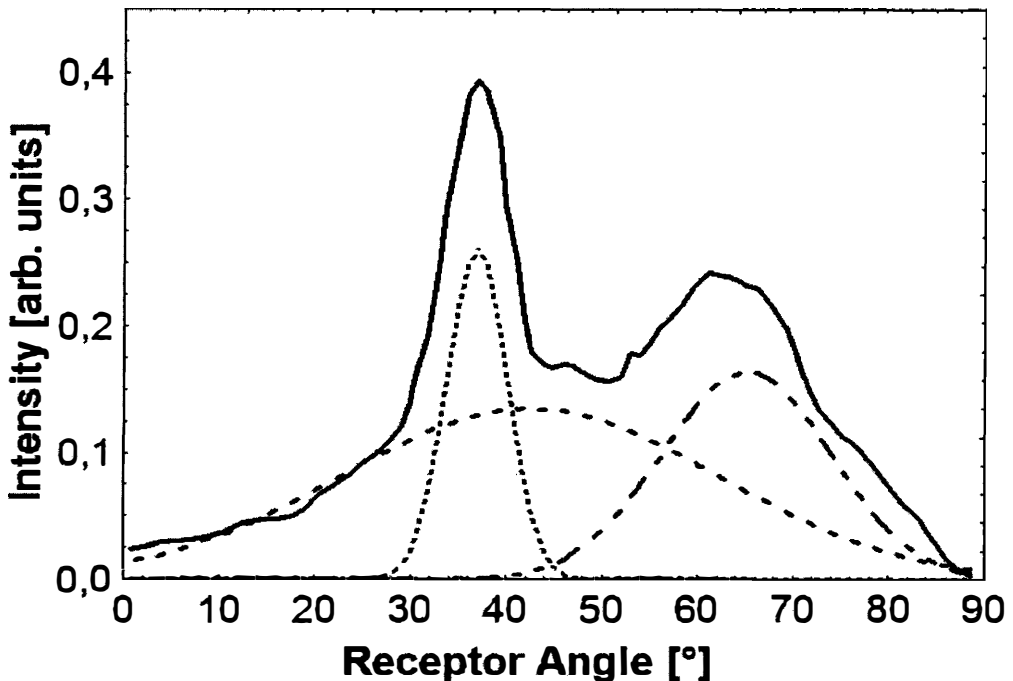


Figure 2. GP curve data (—) for a light blonde hair measured at a position near the tip end. Gaussian distributions for specularly (.....), diffusely (---), and internally (— · —) reflected light, as fitted to the GP curve (see Figure 7 in ref. 1).

blonde, Caucasian hair measured at a position near the tip end. In this context it is important to note that the surface of hair is not smooth but features cuticle cells in a tile-like arrangement, where the cell scale edges point towards the fiber tip. To ensure a consistent bias of light reflection due to the cuticle inclination angle (1), all measurements were carried out with the direction of the incident light toward the tip end of the hair.

In view of the surface and overall morphological structure of human hair, the reflection of light is subject to a special type of geometry that in turn and with the principles of geometrical optics leads one to expect three principal components of light reflection. These are represented by the three Gaussian distributions fitted to the GP curve in Figure 2. Details of the fitting procedure and the parameters derived thereof are given in Part 1 (1).

When the incident beam hits the fiber surface in the root-to-tip (RT) direction at the incident angle ϵ_i (1), a first fraction of the light, S , is specularly reflected at the receptor angle γ_s . For the experimental setup, using the incident angle $\epsilon_i = 40^\circ$ and assuming a tilt angle for the cuticle of 2.5° leads to an expectation value for the receptor angle of the specularly reflected light of $\gamma_s = 35^\circ$. At this position, Figure 2 shows the peak describing the intensity distribution of specularly reflected light with a width at half-height of 9° – 10° .

A second fraction of light, D_s , is diffusely scattered at and near the fiber surface, namely at surface roughnesses (18), at the various interfaces between the cuticle cell layers of human hair (19), at the interface of cuticle and cortex, and at optical imperfections of the cortex, such as voids and inclusions.

Figure 2 shows between 40° and 45° the broad Gaussian distribution for diffuse reflection. It is important to note from Figure 2 that the hair surface cannot be considered as being primarily an ideal, diffuse reflector for which scattering occurs such that the intensity of the diffusely reflected light is uniform. Though on the basis of Reich and Robbins' analysis (11) of GP curves, the existence of a uniform contribution for D_s is assumed, its magnitude is obviously small compared to the non-uniform effect and covered by the broad Gaussian distribution for diffuse reflection.

A further part of the incident beam is refracted into the fiber according to Snell's or Descartes' law. Inside the hair the light is scattered at voids and inclusions, is partly absorbed by hair pigment and color, and is thus wavelength filtered, depending on the color and its intensity. Diffuse reflection takes place at structural inhomogeneities within the cortex. For lightly colored hair, light may be diffusely reflected at or in the medulla (4,20), a more or less continuous and hollow, tube-like structure in the fiber interior.

In very blonde or white hair a significant amount of light may be reflected at the backside of the fiber, that is, from the hair/air surface interface opposite the point of incidence. When this third component of light re-emerges from the fiber, it is experimentally observed, as shown in Figure 2, as a separate peak in the GP curve (5,15,17) at angles around 64° with a width of 25° (1). This type of light is considered as a specific fraction of diffusely reflected light, termed D_i , since it is related to the internal reflection effect.

DEFINING HAIR GLOSS

Surfaces and objects often show gloss, which is attributed to specular reflectance at the respective surface. Due to the diversity of surface structures, different kinds of gloss can be observed. Hunter, as early as 1937 (2), intensively investigated the phenomenon of gloss and arrived at a classification with six different types of gloss that were defined in terms of measurable parameters.

Stamm *et al.* (5) reviewed the semantics of gloss, luster, shine, etc. for human hair. Measuring by goniophotometry light reflected from single hairs or hair strings, Bustard and Smith (15) and Stamm *et al.* (5), respectively, chose one of these classes, namely "contrast gloss," to represent the "luster" of hair. Their approach relates to the work by Nickerson on the gloss of cotton yarn and fabric (3), where she found this type of gloss well applicable to test textile luster in correspondence with the visual assessment.

Hunter (2) defines contrast gloss as "contrast between specularly reflecting areas and other areas." It is measured by comparing the intensity of the light that is specularly reflected with the intensity of that which is diffusely scattered, so that:

$$g_c^H = s/d \quad (1)$$

g_c^H is Hunter contrast gloss. s and d are the intensities of specular and diffuse reflection, respectively, measured at two positions, namely (a) at the expected receptor angle for specularly reflected light and (b) normal to the material surface. Following the notation introduced by Stamm *et al.* (5), lower case letters are employed to designate these so-called spot values. Since Equation 1 goes to infinity as d approaches zero, Nickerson suggested as an alternative:

$$g_c^N = (s - d)/s \quad (2)$$

where g_c^N is the "Nickerson contrast gloss," considered to represent luster. For cotton, Nickerson (3) found a good correlation between contrast gloss values and visual estimates of luster.

Nickerson contrast gloss becomes zero when d equals s , unity when d equals zero, and negative when $d > s$. In view of the complex structures of the GP curves for different types of hair (1), all three cases are likely to occur in practice.

The approach applying spot values is valid, notably for flat surfaces, where the angle of incidence and the receptor angle for specularly reflected light are equal and where the intensity of the scattered light shows no angular dependence. However, both of these conditions are obviously not fulfilled for human hair, implying that spot measurements, as implemented in commercial testing devices (10,13,14) are expected to be at best of very limited use for determining hair gloss. In this view, it is not unexpected, that Stamm *et al.* (5), Bustard and Smith (15), and Guiolet *et al.* (17) found that the gloss parameters defined in equations 1 and 2, based on spot values, have high precision but poor sensitivity.

Various approaches have been devised to determine integral values for specularly and diffusely reflected light (5,11,15), applying the principles inherent to equation 1 and especially equation 2 in order to derive parameters to describe hair luster. The definition of these parameters was either based on theoretical considerations (5,15) or on empirical observations (11). Inherent to the approaches is the principle that diffuse reflection from hair occurs uniformly.

Dismissing this assumption in view of the positions and shapes of the light intensity distributions underlying the GP curves (see Figure 2) and of our interpretation of Figure 1, we propose that the effect of hair luster and of the shine of a given hairstyle is related to the ratio of the total amount of light reflected specularly from single hairs to the overall amount of reflected light:

$$G_L = S/(D + S) \quad (3)$$

with

$$D = D_S + D_i \quad (4)$$

Following the notation of Stamm *et al.* (5), capital letters are employed to mark the integral values of light intensity. G_L , the gloss index, is considered to describe "specular gloss," as a measure of luster, in correspondence to earlier definitions and subjective descriptions as "brilliance of specularly reflected light" (2) and "brilliance of highlights" (3).

S and the components of D are determined from the complete goniophotometric curves for single human hairs through separating and integrating the intensities of the specularly and diffusely reflected light components, respectively, by fitting three Gaussian distributions (see Figure 2). With the exception of light blonde or white hair, D_i can usually be neglected, greatly simplifying the determination of the components of equation 3.

The properties of equation 3 are plausibly connected with practical observations. If there is no specularly reflected light, $S = 0$ and hence $G_L = 0$. In the case of $D = 0$, there is no diffusely reflected light, and perfect luster is achieved with $G_L = 1$. If the situation arises that the integral intensities of specular and diffuse reflections are equal so that $S = D$, equation 3 yields 50% gloss. By darkening or lightening hair, the diffuse component, due to changes in light absorption in the fiber, will decrease or increase, respectively. If the specular component remains unchanged, gloss will increase or decrease, respectively, by the coloring of the hair alone. This corresponds to the practical observation that dark hair always tends to appear more lustrous than blonde hair.

RESULTS AND DISCUSSION

By fitting Gaussian distributions to the GP curves, locations and widths for the three types of reflected light were determined for the different types of hair. The parameter values and their changes along the hair length, including cuticle angle, are presented and discussed in detail in Part I of this paper (1).

By far, most GP curves could well be analyzed by considering just S and D_s , that is, by a two-component approach. Only for light blonde hair did D_i as a further component of diffuse reflection have to be considered. Introducing the areas of the fitted peaks for a given GP curve into equation 3 yields the respective value for the gloss index G_L .

All data were checked for outliers prior to further analysis by assessing them in so-called normal probability plots as implemented in the applied statistics software (21). In this type of plot, cumulative data frequencies follow a straight line when the data are normally distributed. On this basis, three obvious outliers were readily identified ($G_L < 10\%$) in these plots for brown hair and removed prior to further analysis of the data.

The data given in Table I represent the accepted data for the gloss index and are arithmetic means for measurements taken at a given position relative to the root end on a number of hairs (N) of the same type. For a given hair type the data are summarized in group means. Data are further summarized over all hair types in the form of a grand mean.

Effects of measurement position and hair type on the parameters were assessed for significance by analysis of variance (ANOVA) and linear regression (LR). In those cases where ANOVA indicated inhomogeneity, multiple comparison of means analysis was conducted, applying the nonconservative LSD test (21). Statistical significance of effects (ANOVA: inhomogeneity of data; LSD: differences between data groups; LR: slope of the regression line) is characterized throughout by the α -value (22), which is the probability of committing a so-called Type I error, i.e., by finding an effect that in fact does not exist. In cases where $\alpha < 0.05$, effects are significant at the usual 95% level and beyond.

The results for the three hair types are summarized in Figure 3 in the form of a box-and-whisker plot. Analysis of variance shows that, in agreement with the visual impression, the data are inhomogeneous well beyond the 95% level ($\alpha < 0.0001$), where the LSD test identifies the α -levels for the differences, as given on the horizontal whiskers in Figure 3. Here it is shown that the gloss index shows no significant difference between black and brown, but is decreased rather dramatically for the blonde hair. This effect can be largely attributed to the absorption of refracted light for the two dark hair types, which suppresses diffuse light reflection from the hair interior and thus induces a strong and brilliant hair luster.

Table I
Values for the Gloss Index G_L Derived from the GP Curves for Various Hair Types

Hair type	Position (cm)	N	G_L (%)
Black	1	12	64.1
	5	3	53.2
	10	7	59.3
	15	3	59.8
	20	7	57.4
	Group mean \pm q	32	60.2 \pm 3.33
Brown	1	10	66.5
	10	9	54.4
	20	7	55.8
	25	4	55.6
	30	10	57.6
	Group mean \pm q	40	58.6 \pm 3.05
Blonde	1	10	31.8
	5	9	32.2
	10	9	30.7
	15	9	14.9
	20	10	14.7
	Group mean \pm q	47	24.8 \pm 3.84
Grand mean \pm q		119	45.7 \pm 3.66

A number of hairs (N) were measured at various positions relative to the root. Group and grand mean values are given with their 95% confidence range \pm q.

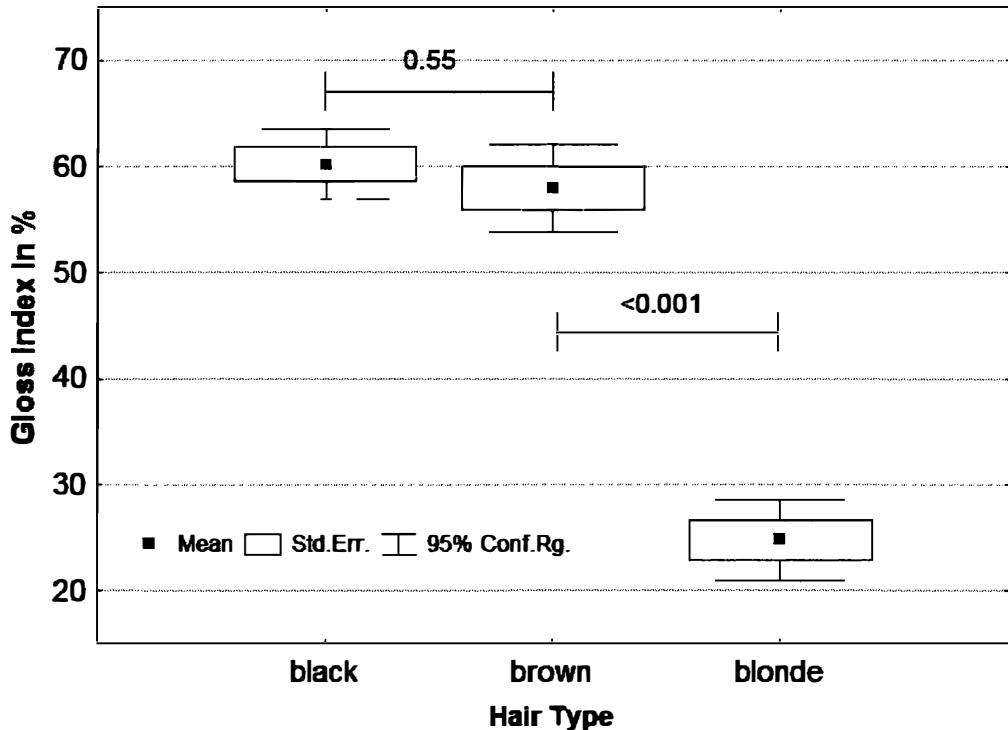


Figure 3. Box-and-whisker plot summarizing gloss index values for the three hair types. Data points, boxes, and whiskers are defined by their arithmetic group mean (Mean), the standard error (Std. Err.), and the limiting value for the 95% confidence range (95% Conf. Rg). The horizontal whiskers signify a specific comparison of means (LSD test), given with the α -value to characterize the significance of the difference.

There are changes in the gloss index along the hair length, as summarized graphically in Figure 4. Each straight line represents a fit to the mean values given. Considerations of statistical significance relate, however, to fits of the single data. For the black hair, the change of gloss along the hair length is a tendency at best, but in fact not significant at the chosen 95% significance level ($\alpha = 0.2$). The level of the grand mean for the gloss index of the black hair is marked in Figure 4. For the brown hair, the decrease of gloss along the hair length is more pronounced and the significance of the slope of the regression line just misses the 95% level ($\alpha = 0.054$). For the blonde hair, gloss starts from an already comparatively low level at the root and then decreases strongly and significantly towards the tip ($\alpha < 0.001$).

The decrease in hair gloss due to a relative increase in the intensity of diffusely reflected light can be attributed to hair color lightening towards the fiber tip combined with the formation of damage-related structures, such as cracks or voids, that scatter light, which have been induced by daily hair grooming practices including heat treatments (20,23), sunlight exposure, etc. Black and brown hair reach values around 65% gloss near the root ends, which may be considered a reasonable estimate for the maximum natural gloss of hair.

For natural black or dark brown hair, diffuse reflection from the fiber interior will be negligible due to the absorption of the refracted light. However, for all hair types, cuticle

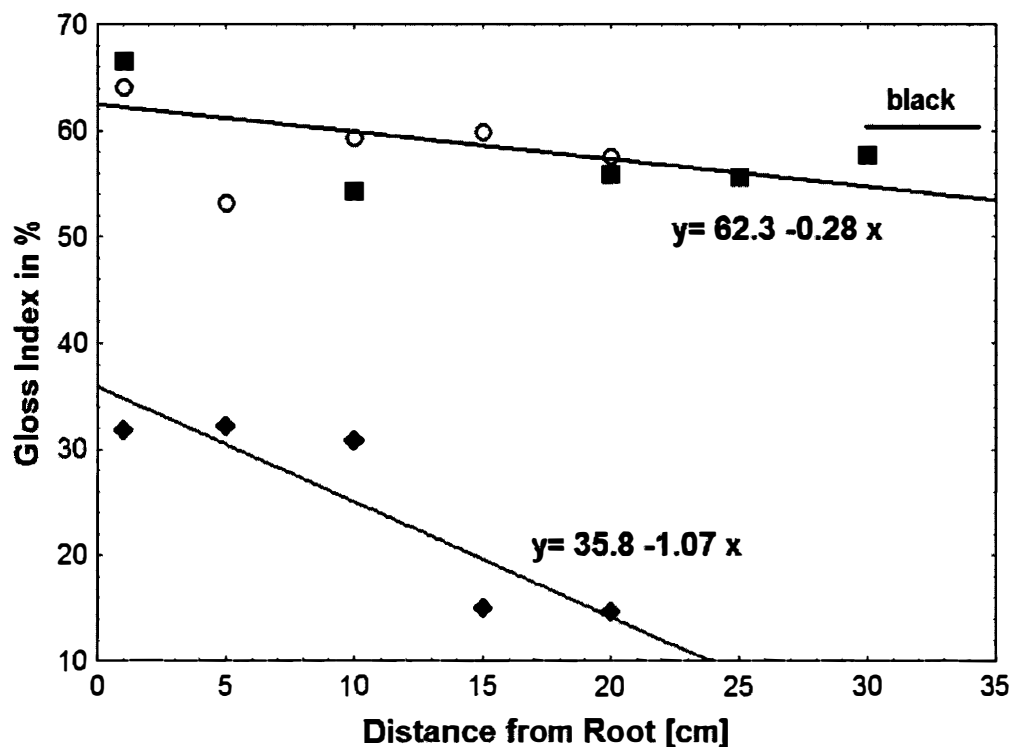


Figure 4. Means for the gloss index G_L at various positions along the hair, given as distance from the hair root for black (○), brown (■), and blonde (◆) hair, respectively. The solid lines are the linear regression lines through the data for brown and blonde hair. Filled symbols are used for those cases where the slope of the regression line has a relevant statistical significance. The equations that are given on the graph specifically relate to the individual results. The horizontal line on the right marks the group mean (60.2%) for black hair (see Table I), where the decrease along the hair length is not significant.

cells will as a rule not contain pigment. Light is hence refracted into the cuticle and passes through a substantial number of cuticle cells with reflection, refraction, and scattering at the cell interfaces until ultimate reflection at the cuticle/cortex interface generates a major component of what is observed as diffusely reflected light.

This effect will further be intensified if, through hair damage, delamination has occurred between cuticle cell layers (19,23) or if, more generally, cracks, voids, or inclusions have been formed. The gloss measurement of hair, which due to its color does not allow light reflection from the fiber interior, thus provides through the diffuse component of reflected light information on the structural status of its cuticle layer. In this context the differences in the change of gloss along the hair length for the black and the brown hair (see Figure 4) are interesting to note.

It is important to note that the approach, described in this paper, for determining the gloss index is equally applicable for African hair, despite its strong ellipticity and curliness. However, this type of hair was not included in the study, since it was considered as being less suitable in the context of determining the effects of hair color and along-hair changes.

In practice, hair shine is a very complex phenomenon (16,24), which involves physical, physiological, and psychophysical considerations. G_L , on the other hand, provides an absolute, numerical scale.

In this view, it has to be noted that consumer perception cannot be expected to follow an equisense scale in which a unit of difference indicates an equal sensory difference in luster (3). In practice, an expert or a consumer will generally rank product performance in a contrast situation (half-head test, before-vs-after, product A vs product B, etc.) relating to relative changes of appearance (4), rather than work on the basis of ordinal sensory units. As was shown in small scale panel tests (18,25), these rank differences appear to be closely related to the laboratory situation of gloss testing of single hair fibers described here.

However, a somewhat more comprehensive argument for the feasibility of the gloss index to model the assessment of hair luster by a consumer panel is derived from the extensive investigations by Reich and Robbins (11). They found a linear relationship between the inverse of the width of the GP curve at half height and the luster ranking by panels.

Applying the data given in Part I (1) for the positions and widths of the Gaussian distributions describing specular and diffuse reflection, theoretical GP curves were calculated on the basis of equation 3, assuming the presence of S and D_s only, for a wide range of G_L values. Finally, the width at half-height w of the theoretical GP curves was

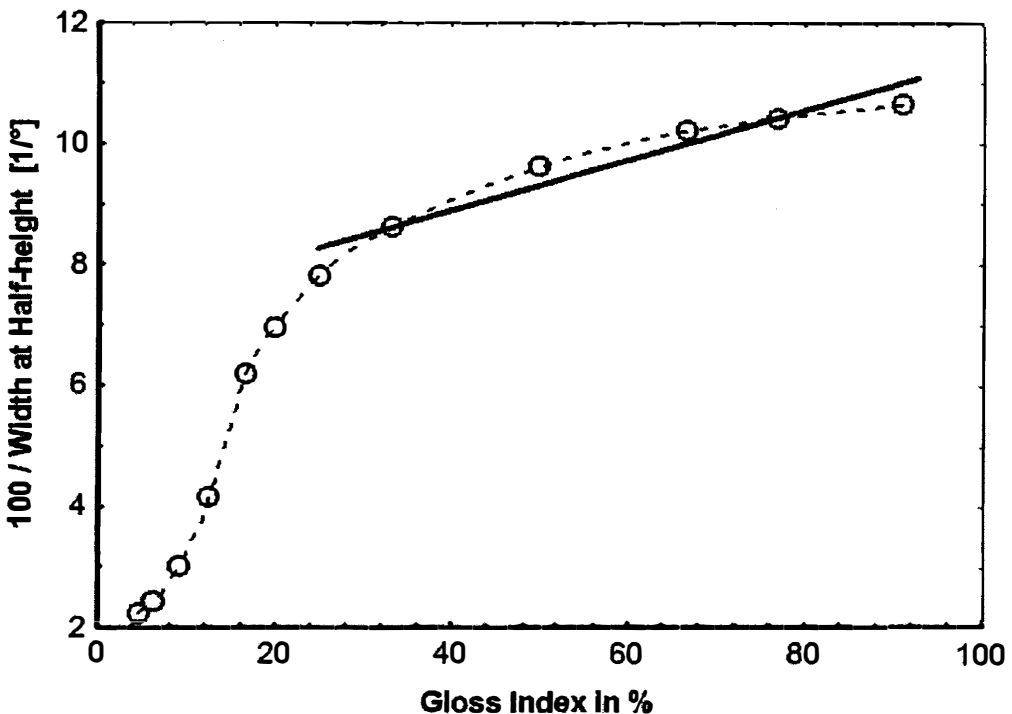


Figure 5. Inverse of the width at half-height for calculated GP curves on the basis of a presumed value for the gloss index. The largely linear relationship for G_L values beyond 25% is indicated by the straight line.

derived. Figure 5 shows the relation between the data derived in this manner for $1/w$ and the presumed gloss index values.

When appreciable hair gloss is generated, i.e., when the peak for specular reflection starts to dominate the GP curves, which occurs around $G_L > 20\text{--}30\%$, a largely linear relationship is observed, as marked in Figure 5, which corresponds to Reich and Robbins' observation (11). In this view, the hypothesis that the gloss index is a valid measure for hair luster that correlates with the consumer's perception of hair shine is further corroborated. Furthermore, more elusive facets related to hair gloss, such as "silky" or "greasy" hair shine, are the objective of current investigations.

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