Optical properties of the medulla and the cortex of human scalp hair

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Abstract. An increasing number of applications, including non- or minimally invasive diagnostics and treatment as well as various cosmetic procedures, has resulted in a need to determine the optical properties of hair and its structures. We report on the measurement of the total attenuation coefficient of the cortex and the medulla of blond, gray, and Asian black human scalp hair at a 633-nm wavelength. Our results show that for blond and gray hair the total attenuation coefficient of the medulla is more than 200 times higher compared to that of the cortex. This difference is only 1.5 times for Asian black hair. Furthermore, we present the total attenuation coefficient of the cortex of blond, gray, light brown, and Asian black hair measured at wavelengths of 409, 532, 633, 800, and 1064 nm. The total attenuation coefficient consistently decreases with an increase in wavelength, as well as with a decrease in hair pigmentation. Additionally, we demonstrate the dependence of the total attenuation coefficient of the cortex and the medulla of Asian black hair on the polarization of incident light. A similar dependence is observed for the cortex of blond and gray hair but not for the medulla of these hair types. [DOI: 10.1117/1.3116712]

Keywords: hair optical properties; hair total attenuation coefficient; medulla optical properties; cortex optical properties; collimated transmittance measurement.

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1 Introduction

During the past three decades, there has been strongly increasing interest in applying optical techniques in the analysis of skin and skin structures.[1] Many applications for non- and minimally invasive diagnostics and treatment, cosmetic procedures for skin care, and skin rendering in computer graphics[2] are based on the interaction of light with skin. The skin is a complex organ containing sweat glands, hairs, pigmented lesions, and other structures. As a result, it does not have uniform optical properties, as is often assumed, e.g., when modeling light propagation and interaction with the skin.

A human terminal hair, due to its relatively large size, is the most prominent structure present in the skin. It originates in the hair follicle within the subcutaneous layer, protrudes through the dermis and epidermis, and emerges from the skin surface. Having[3] a diameter of approximately 100 μm, a human hair is comparable to the size of the optical fiber often used in devices to deliver light to the skin and/or to collect it. Furthermore, in some applications, such as noninvasive blood analysis,[4–7] the size of a hair is comparable to that of the tissue volume from which the signal is collected. It was even observed by Wells[8] earlier that some hairs can act as an optical fiber transmitting light along the hair shaft, though no corresponding numerical values were reported. Therefore, the presence of hairs both at the surface of the skin and inside it should not be neglected during such measurements.

The strong interest in the determining optical properties of hair, from both the perspective of cosmetic applications and of accurate modeling and rendering of the skin in computer graphics, is reflected in the increasing number of scientific publications devoted to light interaction with hair.[9–12] However, these works were mainly devoted to the hair surface optical properties. Therefore, the obtained data cannot be used to fully describe light transport through hair located in the skin or hair submerged in an index-matching fluid. This is because in these cases the hair surface contribution to the light transport is eliminated.

However, quantitative information about the scattering coefficient μ_s and the absorption coefficient μ_a of hair is scarce. Furthermore, the available data are contradictory, for example, the reported values of the scattering coefficient of hair having different pigmentation varies by over one order of magnitude.[13,14]

The current data on the absorption and the scattering coefficient of hair is based on the results reported by Bashkatov et al.,[13] Wang et al.,[14] and Lin et al.[15]

Bashkatov et al.[13] reported on the absorption and the reduced scattering coefficients of human scalp hairs with different pigmentation for 600-, 540-, and 460-nm wavelength

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Table 1 Summary of the optical properties of hair reported in literature.[13–15]

Wavelength	Hair Color	μ_a (mm^{-1})	μ_s' (mm^{-1})	μ_t (mm^{-1})
	black	2.85	3.75	—
	brown	1.45	4.06	—
600 nm (Ref. 13)	light brown	0.22	9.46	—
	blond	0.050	16.11	—
	gray	0.060	18.90	—
700 nm (Ref. 15)	brown/black	—	—	27–30
850 nm (Ref. 14)	black	—	—	32[b]
	blond	—	—	3[b]
	red	—	—	50[a]

[a]Calculated based on the cross-sectional OCT scan of the hair.
[b]Calculated based on the longitudinal OCT scan of the hair.

obtained by measuring the transmittance and the reflectance through the hair using a microscope and applying an inverse Monte Carlo method.

Wang et al.[14] performed a cross-sectional and a longitudinal scan of red, blond, and black human scalp hairs using optical coherence tomography (OCT) at a 850-nm wavelength. Though the numerical values of the total attenuation coefficient μ_t of the hairs were not presented in this publication, the reported magnitude of the OCT signal allows for its estimation by using

$$I = I_0 \exp(-\mu_t l) \tag{1}$$

where I_0 and I are the magnitudes of the OCT signal at the first and the last interfaces between the hair and the medium, respectively; $\mu_t = \mu_a + \mu_s$ is the total attenuation coefficient of the hair; and l is the hair thickness in a double pass.

Lin et al.[15] estimated the total attenuation coefficient of brown/black human hairs. This was achieved by focusing light from an incandescent source into a hair and measuring the transmittance at 700 nm wavelength. The measurements were performed using index-matching oil ($n=1.515$), thereby minimizing the effects of light interaction with the hair surface. The total attenuation coefficient was estimated using Beer's law.

A summary of the optical properties of hair, as reported in literature, is presented in Table 1. Of the data reported by Bashkatov et al.[13] only the data set at the 600-nm wavelength is included in this table because this is the closest wavelength to those reported by Lin et al.[15] and Wang et al.[14] This establishes a degree of consistency in the tabulated data. A striking observation is the approximately five times higher reduced scattering coefficient of lightly pigmented hair with respect to that of black hair.[13] Note that neither Bashkatov et al.[13] nor Wang et al.[14] used index-matching liquid, i.e., all the measurements were performed in air. However, there is a large difference between the refractive index of a hair and the surrounding air [$n=1.548$ (Ref. 9) and $n=1.0$, respectively]. Therefore one cannot exclude the influence of the refractive index mismatch on the reported results. It appears at this moment that the data on the optical properties of hair available in literature are not consistent and strongly depend on the applied measurement method. Note here that a hair itself is a heterogeneous structure. It consists of a thin outermost layer, the cuticle, a porous central part, the medulla, and the cortex. It is known from literature that the medulla, when present, induces light scattering.[16] However, in the experiments reported so far no distinction was made between the optical properties of the different hair structures, such as the cortex and the medulla.

In this paper, we report for the first time on the measurement of the total attenuation coefficient of the cortex and the medulla of blond, gray, and Asian black human scalp hair, of Indian origin, measured at a 633-nm wavelength. Furthermore, we present the total attenuation coefficient of the cortex of blond, gray, light brown, and Asian black human scalp hair at five different wavelengths, namely, 409, 532, 633, 800, and 1064 nm, which are frequently used in biomedical and cosmetic research. Additionally, we show the dependence of the total attenuation coefficient of the cortex and the medulla of Asian hair and the cortex of blond and gray hair on the polarization of the incident light.

2 Methods and Instrumentation

2.1 *Cross-Polarized Confocal Microscope*

To qualitatively demonstrate the significant difference in the scattering properties of the cortex and the medulla, we used a cross-polarized confocal scanning laser microscope (CP-CLSM, Type VivaScope 1000, Lucid Inc., Rochester, New York) in reflection mode to obtain confocal images of human hair using different immersion media. A 30×0.90 numerical aperture (NA) water immersion microscope objective corrected for cover a glass was used (Lomo, Vermont Optechs, Charlotte, Vermont) to focus the light emitted by a 830-nm laser diode. The maximum field of view using this objective was 480×260 μm.

2.2 *Selected Method*

To measure the optical properties, such as the absorption coefficient μ_a, the scattering coefficient μ_s, and the anisotropy of scattering g, a number of standard techniques are commonly used.[17,18] These measurements, however, are suitable only for relatively large samples, in the order of tens of millimeters. The small size of the cortex and the medulla, which is typically equal to one third of the total hair diameter, makes conventional methods for measuring optical properties inappropriate.

To measure the optical properties of the cortex and the medulla we implemented the conventional principle of collimated transmittance measurements[18,19] in a confocal setup, which enables the measurements of the optical properties of small samples with a high lateral resolution. This is described in detail in the following.

2.3 *Experimental Setup*

Figure 1 presents a schematic diagram of a confocal setup used to measure the collimated transmittance through a hair. The setup was constructed to enable coupling of one of the

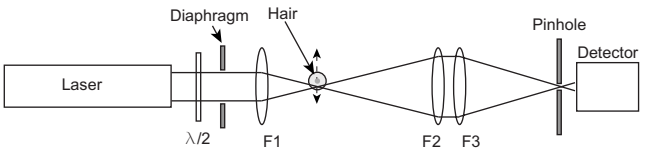

Fig. 1 Schematic diagram of the confocal setup used for the measurement of collimated transmittance through a hair: λ/2, a multiorder half-lambda waveplate; F1, a 20×0.4 NA microscope objective; F2, a 40-mm-focal-distance lens; F3, a 100-mm-focal-distance lens.

five laser sources at a time. They included a 409-nm diode laser (Nichia Corporation), a 532-nm laser (Solid state laser, Melles Griot), a 633-nm HeNe laser (JDS Uniphase Corporation), a 800-nm laser (Tiger, Diode-pumped Solid State Laser, Time-Bandwidth Products, Inc.), and a 1064-nm laser (LCS-DTL-332, Laser Export Co. Ltd). A multiorder half-lambda waveplate for 632.8 nm (Newport Corporation) was used to rotate the light polarization, when necessary.

The laser light was focused in a cuvette (OG, 10-mm pathlength, Hellma GmbH & Co.) using a 20×, 0.4 NA microscope objective (Leica Microsystems). A diaphragm placed directly in front of the microscope objective was used to adjust the size of the beam and thereby vary the effective NA of the objective. The light was collected and then focused onto a pinhole (Linos Photonics Inc.) using 40- and 100-mm-focal-length lenses (Linos Photonics Inc.), respectively. The power transmitted through the pinhole was recorded using a power meter (Nova II, Ophir Optronics Ltd.).

For accurate measurements of collimated transmittance (1) a sample must be optically thin, i.e., the sample thickness should be comparable with a mean free path of a photon in a medium, $l=1/\mu_t$; (2) its geometrical thickness must be equal to or smaller than the depth of focus (DOF); and (3) the measuring volume must be controlled. Based on the data presented earlier (see Table 1) we considered a hair to be optically thin. The DOF was adjusted for each of the five selected wavelengths by varying the size of the beam filling the entrance pupil of the objective, thereby varying its numerical aperture. The measuring volume was controlled by varying the pinhole diameter.

The diameter of the focal spot d was calculated as

$$d=\frac{1.22\lambda}{\mathrm{NA}}, \tag{2}$$

where λ is the wavelength of light, and NA is the numerical aperture of the objective. The depth of focus was calculated as

$$\mathrm{DOF}=\frac{2\lambda}{4\mathrm{NA}^2}. \tag{3}$$

The elongation of the DOF due to focusing through a high refractive index medium[20–22] was estimated as[23]

$$\mathrm{DOF}=\frac{2\lambda}{4n\{1-[1-(\mathrm{NA}/n)^2]^{1/2}\}}, \tag{4}$$

where n is the refractive index of the immersion fluid.

During the experiments with five different wavelengths ranging from 409 to 1064 nm the depth of focus was kept constant at 100 μm, which was slightly larger than the diameter of the hairs used in our experiments, that being equal to 70 μm. As stated earlier, the constant DOF at the selected wavelengths was achieved by varying the diameter of the diaphragm in front of the microscope objective from 1.6 to 2.6 mm, and thus, varying the diameter of the beam waist in the focal plane from 6.2 to 10 μm, respectively. The corresponding diameter of the beam waist at the position of the pinhole was ranged from 22 to 36 μm. To reject out-of-focus light, the pinholes with a diameter equal to 30 and 50 μm were used for 409 nm and for the rest of the wavelengths, respectively. The corresponding axial resolution was determined by back-projecting the pinhole on the focal plane of the objective using the total magnification of the system, equal to 2.5×.

In summary, for all the selected wavelengths, the lateral resolution of the setup was sufficient to discriminate between the cortex and the medulla, the DOF was large enough compared to the hair size, and the axial resolution was sufficient to reject out-of-focus light.

All the experiments on measuring the total attenuation coefficient were performed using human scalp hairs. An individual hair was mounted in a holder that allowed for 3-D position control. During each measurement, a hair was placed in a cuvette filled with ethyl cinnamate and positioned within the focal plane of the microscope objective. The intensity of light transmitted through the hair was measured after the pinhole. In addition, after each measurement on the hair, the intensity of the light transmitted through the cuvette filled with ethyl cinnamate was detected after the pinhole. The collimated transmittance through the hair was calculated by dividing the corresponding transmittance values. Low absorption of ethyl cinnamate at the five selected wavelengths was confirmed by measuring the transmittance through a 10-mm cuvette. For all the selected wavelengths the transmittance was higher than 80%.

2.4 *Experimental Procedure*

2.4.1 *Cross-polarized confocal microscope*

In the experiment using a CP-CLSM, a human scalp hair was mounted in the center of a 600-μm-thick cuvette. The cuvette was filled either with demineralized water ($n=1.33$) or with ethyl cinnamate ($n=1.548$) to provide different refractive index matching. CP-CLSM images were obtained by focusing the laser beam into the hair.

2.4.2 *Total attenuation coefficient of the cortex and the medulla*

Two human scalp hairs (DeMeo Brothers, Inc.) of four different colors, namely, blond, gray, light brown, and Asian black were studied. Gray and Asian black hairs were of Indian origin. Gray hairs were originally black and were discolored due to ageing.

Five hair pairs of each color (each pair containing medullated and nonmedullated hair) were randomly taken from a lock of hair originating from a single individual. For each hair, the collimated transmittance was measured at a number

(at least 5) of randomly chosen positions along the hair shaft. These data were used to find the average value and the standard deviation thereof.

To make a distinction between the total attenuation coefficient of the cortex and the medulla and to obtain information on the scattering coefficient of blond and gray hair we used several assumptions and approximations. These are described in the following.

The collimated transmittance through a nonmedullated hair was measured using the confocal setup. The transmittance values together with the hair thickness were used to determine the corresponding total attenuation coefficient of the hair cortex μ_{tC} as

$$I = I_0 \exp(-\mu_{tC} l_C), \tag{5}$$

where I is the collimated transmittance; I_0 is the initial light intensity; and μ_{tC} and l_C are the total attenuation coefficient of the cortex and its thicknesses, respectively.

This was followed by measuring the collimated transmittance through a medullated hair. The thickness of a hair and that of the medulla was measured as described in the following. In this case, the light attenuation was

$$I = I_0 \exp(-\mu_{tH} l_H) = I_0 \exp[-(\mu_{tC} l_C + \mu_{tM} l_M)], \tag{6}$$

where μ_{tH} and l_H are the total attenuation coefficient of the hair and its thickness, respectively; and μ_{tM} and l_M are the total attenuation coefficient of the medulla and its thickness, respectively. Knowing the total attenuation coefficient of the hair cortex μ_{tC} and the total attenuation coefficient of the hair μ_{tH}, the total attenuation coefficient of the medulla μ_{tM} was determined using Eq. (6).

The total thickness of each hair and that of the medulla was estimated by making an image of a hair using a transmittance microscope (DMLM Leica Microsystems) equipped with a digital camera (Q imaging) and a standard graticule. (5-μm resolution, Leica Microsystems). To establish the dependence of the total attenuation coefficient of the hair cortex and the medulla on the polarization of incident light at 632.8 nm, a half-lambda waveplate for the corresponding wavelength was placed in the illumination path.

2.4.3 *Scattering coefficient of the cortex and the medulla of blond and gray hair*

The total attenuation coefficient μ_t is a sum of the absorption and the scattering coefficients μ_a and μ_s, respectively. The measurement of the total attenuation coefficient on its own does not enable one to discriminate between these two parameters.

However, it is known that blond and gray hair contain only a minute amount of melanin. Furthermore, the absorption coefficient of keratin, the major protein composing the cortex, is[24] also very low in the wavelength above 400 nm. As a result, the total attenuation coefficient is dominated by the scattering coefficient. Therefore, in the case of blond and gray hair, the value of the total attenuation coefficient gives a relevant indication of the scattering coefficient.

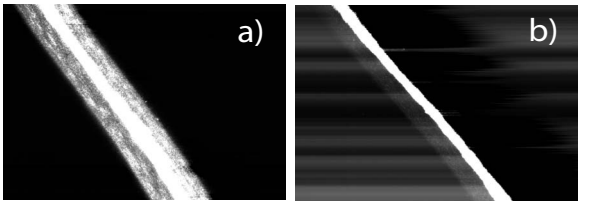

Fig. 2 Human medullated blond scalp hair as observed using a cross-polarized confocal laser microscope (a) in water and (b) in ethyl cinnamate. Note the absence of a signal originating from the hair cortex when a hair was imaged in ethyl cinnamate.

Note that in the case of black hair, the total attenuation coefficient in the visible and near-infrared (NIR) spectral range will be dominated by the absorption coefficient of melanin.

3 Results and Discussion

3.1 *Qualitative Assessment of the Scattering Induced by the Cortex and the Medulla*

The confocal images of a nonmedullated blond hair obtained with CP-CLSM are shown in Fig. 2. When a hair was imaged in water, the signal originated due to both light reflection at the interfaces and scattering at the internal structures. In this case, the signal from both the cortex and the medulla was detected [see Fig. 2(a)]. However, when a hair was imaged in ethyl cinnamate, the effects of light reflection at the interfaces were minimized. In this case, only the signal originating from the medulla was detected [see Fig. 2(b)]. Therefore, the results of this experiment suggest a relatively low scattering coefficient of the cortex and a very high scattering coefficient of the medulla.

These qualitative results clearly demonstrate a significant difference between the scattering induced by the cortex and by the medulla, thereby illustrating the importance of determining separate values for the optical properties of these structures.

The results of the quantitative assessment of the total attenuation coefficient of the cortex and the medulla are described next.

3.2 *Quantitative Assessment of the Scattering Induced by the Cortex and the Medulla*

The results of the measurements of the total attenuation coefficient of the medulla and the cortex of blond, gray, and Asian black human scalp hair are presented in Table 2. The data were obtained at a selected wavelength of 633 nm.

As we can see from Table 2, the observed total attenuation coefficient induced by the medulla of lightly pigmented hair is very high, being equal to 190 mm^{-1} for blond and 160 mm^{-1} for gray, respectively.

As was mentioned earlier, the measured values of μ_t for blond and gray hair in the spectral region above 400 nm provide a relevant estimate of the scattering coefficient. Therefore, it can be concluded that the medulla of blond and gray hair has a very large scattering coefficient. In contrast, the

Table 2 The total attenuation coefficient of the cortex and the medulla for blond, gray, and Asian black human scalp hair at a 633-nm wavelength (the data are given in inverse millimeters).

	Cortex			Medulla			Hair		
Polarization State	∥[a]	⊥[b]	Mean[c]	∥[a]	⊥[b]	Mean[c]	∥[a]	⊥[b]	Mean[c]
Blond	0.7±0.3	0.4±0.3	0.6±0.3	190±5	190±5	190±5	52±5	52±5	52±5
Gray	1.4±0.4	1.2±0.4	1.3±0.4	160±6	160±6	160±6	61±6	61±6	61±6
Black	37±3	31±3	34±3	53±5	47±5	50±5	42±4	36±4	39±4

[a]Electrical vector of the illuminating beam is parallel to the long hair axis
[b]Electrical vector of the illuminating beam is perpendicular to the long hair axis
[c]Average value of [a,b].

cortex of blond and gray hair is extremely weakly scattering, where the attenuation coefficient is below 0.7 mm^{-1} (see Table 2).

In contrast to lightly pigmented hair, the attenuation coefficient of the medulla of Asian black hair (though it comprises both absorption and scattering effects) is rather low, in the order of 50 mm^{-1} (see Table 2). It is most likely that in this case of Asian black hairs we deal with a lock of hairs, which tend to have to have not very prominent and hence, weakly-scattering medulla.[25]

To establish a trend in the wavelength dependence of the total attenuation coefficient of the cortex of hairs with different pigmentation we measured the total attenuation coefficient as a function of wavelength. The results of the measurement of the total attenuation coefficient of the cortex of blond, gray, light brown, and Asian black human scalp hair at the five selected wavelengths are summarized in Table 3. The corresponding data are also shown in Fig. 3.

The total attenuation coefficient for all hair colors demonstrates a clear wavelength dependence; namely, the total attenuation coefficient decreases with an increase in wavelength. Furthermore, it decreases with an increase in hair pigmentation. The total attenuation coefficient is defined as the sum of the absorption and scattering coefficients. Therefore, the observed behavior is in agreement with the generally known wavelength dependence of the absorption coefficient of melanin and that of the scattering coefficient.[26,27] The absorption coefficient of keratin, the major protein from which the hair cortex composed, is very low[24] in the wavelength range above 400 nm, and therefore does not contribute to the measurements.

As we can see from Table 3, the measured total attenuation coefficient of the cortex of Asian black hair in the spectral region from 409 to 1064 nm was found to be 20 to 9 times higher compared to that of weakly pigmented or nonpigmented hair. This is partially due to the high absorption of melanin present in heavily pigmented hairs.

The scattering coefficient of the cortex of blond and gray hair in the whole spectral range from 409 to 1064 nm was negligible, i.e., below 4 mm^{-1}.

Our results on the polarization-sensitive measurements of the attenuation coefficient of hair show approximately 50% difference between the attenuation coefficient of the cortex of blond hair for the polarizations parallel and perpendicular to the long hair axis. The same tendency was observed for the cortex of Asian black hair, where the difference was about 20%. No dependence on light polarization was found for the total attenuation coefficient of the medulla in both blond and gray hair. At the same time, such a dependence was still observed for the medulla of Asian black hair.

Although at this moment it is too early to draw a solid conclusion about the underlying reasons for the polarization dependence of the total attenuation coefficient of the hair cortex, our first suggestion would be to consider polarization-dependent scattering of the hair cortex originating from its birefringence, which in its turn originates from longitudinal alignment of keratin fibers.[28,29] Additionally, one can consider

Table 3 The total attenuation coefficient of the hair cortex for blond, gray, light brown, and Asian black hair[a] (the data are given in inverse millimeters).

	Wavelength (nm)				
Hair Color	409	532	633	800	1064
Blond	2.2±0.2	0.9±0.1	0.7±0.1	0.6±0.1	0.07±0.05
Gray	3.4±0.7	0.7±0.2	0.7±0.2	0.5±0.1	0.10±0.04
Light brown	9.6±0.4	4.4±0.4	3.7±0.6	2.9±0.1	0.3±0.1
Asian black	52±2	27±3	25±2	10±1	2.3±0.2

[a]No polarization control was used during these measurements.

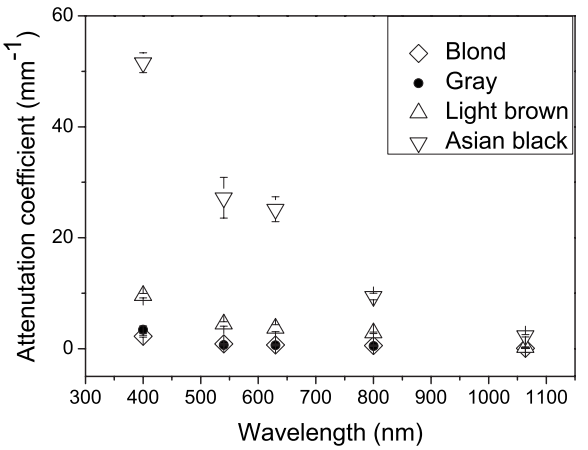

Fig. 3 Total attenuation coefficient of the cortex of blond, gray, light brown, and Asian black human scalp hairs as a function of wavelength.

preferential absorption by melanin granules, as mentioned by Wolbarsht et al.[27] In heavily pigmented hairs, however, the polarization dependence could be masked by scattering by melanin granules. As a result, this effect will be prominent for lightly pigmented hair only.

4 Conclusions

We showed the total attenuation coefficient of the cortex and the medulla of human scalp hair. All results were obtained by implementing the principle of collimated transmittance measurements in a confocal setup, where the effects of the refractive index mismatch were minimized by the use of index-matching fluid. The quantitative results obtained at a 633-nm wavelength show a very large scattering coefficient of the medulla of lightly pigmented hair. However, this is not the case for Asian black hair.

Furthermore, we presented the data on the total attenuation coefficient of the cortex of blond, gray, light brown, and Asian black human scalp hairs in the spectral range from 409 to 1064 nm. The measured total attenuation coefficient of the cortex of blond hair is 20 to 9 times larger than that of black hair in the spectral range between 409 and 1064 nm. The total attenuation coefficient of the cortex of hairs of all colors shows a dependence on the wavelength. This behavior is in agreement with the general dependence of melanin absorption and the scattering coefficient of biological tissue on the wavelength.

The results obtained for Asian black hair are in agreement with the earlier presented data.[13–15] The large differences observed between the total attenuation coefficient of the cortex and the medulla of lightly pigmented hair helps to explain the inconsistency between the data reported by Bashkatov et al.[13] and Wang et al.[14] In particular, the very low total attenuation coefficient of blond hair[14] was most likely obtained for a non-medullated sample, whereas the very high attenuation coefficient of the blond and gray hair[13] was most likely observed on a medullated sample.

The presented experimental results have potential applications in fundamental as well as applied research: in modeling light propagation in skin and hair and in applying optical techniques for analyzing skin and skin structures.

The knowledge of the optical properties of human scalp hair can further be broadened in at least two directions. These include the investigation of the medulla structure and the corresponding medulla optical properties as well as the investigation of the origin of the observed polarization dependence of the total attenuation coefficient.

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