Journal of Biomedical Optics

BiomedicalOptics.SPIEDigitalLibrary.org

Review of human hair optical properties in possible relation to melanoma development

Xiyong Huang
Michael D. Protheroe
Ahmed M. Al-Jumaily
Sharad P. Paul
Andrew N. Chalmers

SPIE.

Xiyong Huang, Michael D. Protheroe, Ahmed M. Al-Jumaily, Sharad P. Paul, Andrew N. Chalmers, "Review of human hair optical properties in possible relation to melanoma development," *J. Biomed. Opt.* **23**(5), 050901 (2018), doi: 10.1117/1.JBO.23.5.050901.

Journal of Biomedical Optics 23(5), 050901 (May 2018)

REVIEW

Review of human hair optical properties in possible relation to melanoma development

Xiyong Huang,[a,*] Michael D. Protheroe,[a] Ahmed M. Al-Jumaily,[a] Sharad P. Paul,[b] and Andrew N. Chalmers[a]
[a]Auckland University of Technology, Institute of Biomedical Technologies, Auckland, New Zealand
[b]Auckland University, Faculty of Surgery, Auckland, New Zealand

Abstract. Immigration and epidemiological studies provide evidence indicating the correlation of high ultraviolet exposure during childhood and increased risks of melanoma in later life. While the explanation of this phenomenon has not been found in the skin, a class of hair has been hypothesized to be involved in this process by transmitting sufficient ultraviolet rays along the hair shaft to possibly cause damage to the stem cells in the hair follicle, ultimately resulting in melanoma in later life. First, the anatomy of hair and its possible contribution to melanoma development, and the tissue optical properties are briefly introduced to provide the necessary background. This paper emphasizes on the review of the experimental studies of the optical properties of human hair, which include the sample preparation, measurement techniques, results, and statistical analysis. The Monte Carlo photon simulation of human hair is next outlined. Finally, current knowledge of the optical studies of hair is discussed in the light of their possible contribution to melanoma development; the necessary future work needed to support this hypothesis is suggested.
[DOI: 10.1117/1.JBO.23.5.050901]

Keywords: hair optical properties; tissue optics; melanoma; cancer stem cells; sunlight; sunscreen.

Paper 180087VRR received Feb. 8, 2018; accepted for publication Apr. 24, 2018; published online May 11, 2018.

1 Introduction

Immigration and epidemiological studies provide convincing evidence showing that children are more vulnerable to sun exposure; sunburn or excessive sun exposure during childhood would lead to increased risk of melanoma in later life.[1–6] While the difference of skin in childhood and adulthood has not provided explanations for this phenomenon,[7] recently the childhood hair (vellus hair) has been hypothesized to allow efficient transmission of ultraviolet (UV) energy along the shaft to possibly cause damage to the stem cells in the hair follicle, ultimately resulting in melanomas in later life.[8,9] As early as about three decades ago, it was observed that lightly pigmented human hairs act as natural optical fibers which may transmit light along their shafts to the follicular epithelium and dermis.[10] Human hair shafts were shown to transmit UV light down to the bulb region a decade later.[11] Whether the UV transmission in the hair shafts can affect the hair follicles and skin strongly depends on their optical properties, especially in the UV region. The goals of this review paper are (1) to review the studies of the optical properties of human hair in the literature and discuss whether current knowledge is able to support the hypothesis; (2) to provide detailed experimental measurement methods and analysis to guide researchers in future investigations.

This article first introduces the anatomy of human hair to provide necessary background for understanding its possible connection to melanoma development (Sec. 2). This is followed by a brief introduction to the optical properties and the experimental measurement techniques used in biological tissues (Sec. 3). Sections 2 and 3 offer biological and optical knowledge for the following sections. Section 4 is the focus of this paper. It delivers a review of the optical studies of human hair up to date, which include the details of sample preparation, experimental methods, results, and statistical analysis. When the UV optical properties of hair are known, examining the radiant energy in the stem cells region from sun exposure is critical to support the hypothesis. Therefore, Sec. 5 reviews the Monte Carlo (MC) method of photon simulation used in human hair studies and outlines the application of the research. Finally, current knowledge of the optical properties of human hair in the literature are discussed, together with their possible contribution to melanoma development; the necessary future work needed to support the hypothesis is suggested.

2 Hair Anatomy and Its Connection to Melanoma Development

This section explains the anatomy of human hair, to provide an understanding of the possible involvement of hair in melanoma development and provide biological background for the optical studies to be presented and discussed in Secs. 4–6.

2.1 *Hair Anatomy*

The hair shaft is mainly composed of keratin (a protein). It is generated by the living portion of hair called the hair follicle, a complex miniorgan of the skin.[12] Figure 1 shows a schematic diagram of a hair follicle. The cuticle is the outermost layer of the hair shaft. It is translucent so allows light to penetrate into the inner cortex layer. The cortex is the bulk of the hair shaft, which contains longitudinally oriented cells.[13] The medulla is a vertical column of horizontal cells that are filled with large air

*Address all correspondence to: Xiyong Huang, E-mail: xiyong.huang@aut.ac.nz

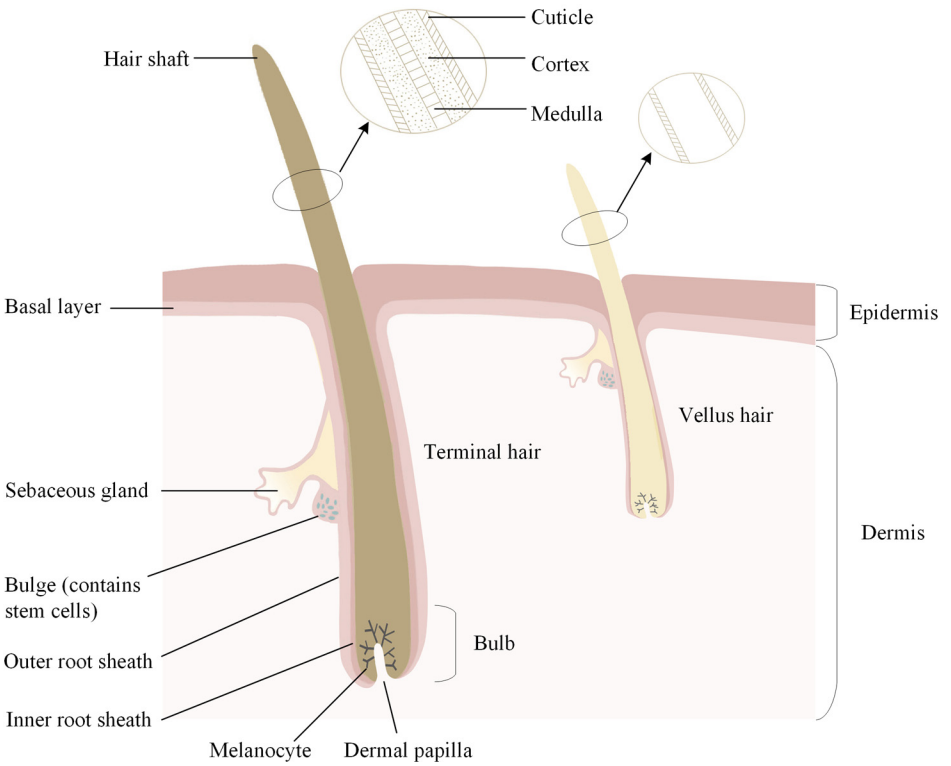

Fig. 1 Schematic diagram of skin layers containing terminal and vellus hair follicle.

spaces, at the center of the cortex.[13] There are two types of melanin found in the cortex of hair: eumelanin and pheomelanin. It is known that light-colored hair (e.g., red and blond) has predominantly pheomelanin whereas eumelanin is responsible for dark-colored hair (e.g., black and brown).[14] Melanin can also be absent in gray hair. Melanin is responsible for the majority of light absorption, especially at shorter wavelengths (e.g., the UV region).[15]

Vellus and terminal hairs have distinct morphologies. Vellus hair is short (less than 2 mm from the skin surface), fine ($\leq$30 μm in diameter), and unpigmented or little pigmented.[16,17] As people experience puberty, some vellus hairs will develop into terminal hairs due to hormonal changes.[16] Therefore, prepubertal children have a much higher proportion of vellus hair as compared to adults. In contrast to vellus hair, terminal hair is coarse and pigmented, with length and diameter longer than 2 mm and thicker than 60 μm.[16,17] Unlike vellus hair consisting of only the cuticle and cortex, terminal hair also contains the medulla, which has high light scattering characteristics.[18] Overall, the anatomy of hair suggests that UV radiation might penetrate in vellus hair more easily than terminal hair. Furthermore, the bulge in the outer root sheath of the hair follicle that houses the stem cells is located $\sim$1200 μm from the exposed skin surface in the terminal hair, which is more than three times deeper than the location of the bulge in the vellus hair, about 360 μm,[19] implying that the stem cells in the vellus hair follicles are less protected from sun exposure than terminal hair follicles.

2.2 *Human Hair and Melanoma*

No significant difference was found in the UV sensitivity of children and adult's skins, from the aspects of UV-induced skin reactions and anatomic structures.[20,21] However, a positive correlation has been found between the incidence of melanoma and the number of vellus hair follicles.[8] As melanomas derive from melanocytes and the stem cells residing in the bulge region of hair follicles have the ability to differentiate into melanocytes,[22,23] vellus hairs have been hypothesized to transmit UV energy more efficiently than terminal hairs and to damage the stem cells in the hair follicles (due to their unique morphologies). The cumulatively damaged stem cells are proposed to have the potential to become melanocytes and melanomas in later life. This hypothesis is further supported by Fang et al. who found that melanomas contain a stem cell population.[24]

As the first step to proving the hypothesis, the optical properties of human hair (vellus and terminal hair) need to be well understood. More specifically, the overall optical properties of vellus hair are thought to be responsible for deeper penetration depth of UV radiation than in terminal hair.

3 Introduction to the Optical Properties of Tissue

Section 3 briefly introduces the properties used to describe the optical characteristics of biological tissues and the different measurement techniques, which build the fundamental knowledge of biomedical optics for understanding the following sections.

Absorption and scattering are the two phenomena that occur when light interacts with tissues. The optical properties are used to describe the light propagation in tissues, which are commonly expressed in terms of the scattering coefficient μ_s, absorption coefficient μ_a, scattering phase function p, and refractive index n.[25] Absorption and scattering coefficients are commonly measured in inverse millimeters and the reciprocal of them are the average distance that photons will travel before being absorbed or scattered in tissues.[26] The scattering phase function is used to describe the angular distribution of photons after

a single scattering. When multiple scattering occurs in thick tissues, the scattering profile is conveniently described by a dimensionless parameter, anisotropy factor g (mean cosine of the scattering angle), which characterizes the tissue scattering pattern by its asymmetry.[25,27] The reduced scattering coefficient μ_s', combines the scattering coefficient and the anisotropy factor as $\mu_s' = \mu_s(1-g)$. The sum of the absorption and scattering coefficients is called the attenuation coefficient μ_t, which determines how far light can propagate in tissues before being scattered or absorbed. The refractive index describes how light refracts/bends when it encounters an interface between differing media.

Optical properties of biological tissues can be calculated by converting measurements of observable quantities into standard parameters.[27] Measurement techniques are classified into two categories (direct and indirect methods). Direct methods use basic principles of light to calculate the optical properties of optically thin tissue sections (single scattering) from measured quantities, which do not involve the use of a model of light transport in tissue. For instance, the attenuation coefficient of a sample can be calculated from the collimated transmittance measurement using Beer's law.[28] By contrast, indirect methods involve measuring quantities such as diffuse reflection and transmission, from which the optical properties of optically thick tissue sections (multiple scattering) can be determined by solving an "inverse problem" based on a model of light transport in tissue.[27,29–31] Using the inverse MC method to estimate the optical properties of tissues by fitting the simulated results to the experimentally measured quantities is often used as an indirect technique.[32–34]

4 Experimental Measurement of Optical Properties of Hair

Human hair is delicate and its average diameter is smaller than that of some common optical fibers. Therefore, holding the hair sample in place for precise optical measurement is challenging. The optical properties of human hair have been investigated by a number of groups. Among them, some works were mainly devoted to the optical properties of hair surface,[18,35–39] whereas others contributed to the knowledge of light propagation through hair.[40–45] This section explains in detail the experimental investigations of light propagation properties of hair.

4.1 *Sample Preparation*

To ensure the hair samples are not attached to contaminants (e.g., dirt and oil), which could influence the measured results, samples are cleaned with ethanol or shampoo before the measurement.[40,41] For microspectrophotometry of hair, the samples are placed between a microscope slide and a cover slip[43,44] or mounted on a triholed metal slide.[40] Some sample holders can also be used to mount the hair and adjust its position and orientation.[41,45] The refractive index of human hair is about 1.54, which is higher than that of air.[46] So some researchers used the refractive index-matching liquid to minimize the light loss from the surface scattering in measurement,[43–45] whereas others included the mismatch of refractive index on the measurement results.[40–42] When UV light is involved in the measurement, a quartz microscope slide needs to be used instead of a glass one as glass absorbs UV and could mask the spectral result. It is noted that the refractive index-matching liquid (mounting media) should not degrade the hair sample nor absorb UV.[40]

The optical properties in the transversal (cross sectional) direction of hair were studied by most of the groups because of the relatively simple sample preparation procedures.[40–45] In contrast, the properties in the longitudinal direction of hair were rarely examined due to the difficulties of achieving a flat cross section of hair and positioning it accurately for illumination. However, one group achieved this by mounting the properly cleaved hair to a thin metal wire, wrapped with double-sided tape.[41] Although there are several techniques for preparing the hair samples with neat cross sections through several steps, involving the use of mounting media (e.g., paraffin and resin) and microtome sectioning, they are technically more difficult and time consuming to implement.[47–52] In one case, it was found that hairs with different colors sectioned from a microtome were too short to give discrimination in the spectrophotometry readings.[44] Also, when paraffin is used as a mounting medium since the keratin of hair is harder than paraffin, the hair could split, break, or move within the block.[48]

4.2 *Measurement Techniques*

The optical properties of biological tissues are commonly measured using an integrating sphere.[31,53] However, human hair has never been studied using this method due to the difficulty of accurately focusing light onto hair inside an integrating sphere. Nevertheless, the optical characteristics of some relatively larger mammals' hair have been investigated using these techniques.[54,55] Instead, human hair was primarily studied using a common confocal setup.[18,35–45]

A confocal setup of collimated transmittance measurement, as shown in Fig. 2, was constructed by Kharin et al. [45] to examine the attenuation coefficient of human scalp hair. Five laser sources with different wavelengths ranging from 409 to 1064 nm were used to examine the wavelength dependence of the optical properties of different hairs. In addition, for the first time in the literature, a multiorder wave plate was used in this study to rotate the light polarization for studying the sensitivity of the optical properties on polarization of light.

Constructing a confocal setup for optical measurements of such a small object could be costly and time consuming, if starting from scratch. Alternatively, given the advantages of accurately focusing light onto hair using an optical microscope, a video camera and a light source that are attached to an optical microscope has been commonly used in the past to study the optical properties of human hair.[40,42–44] The Craic microspectrophotometer and Jasco spectrophotometer are two modern instruments in the market that can be used to study the optical properties of microscale materials.[56,57] They are powerful but expensive devices that combine the techniques of microscopy and spectrophotometry, providing measurement of the UV–visible–NIR range of transmission, absorbance, and reflectance

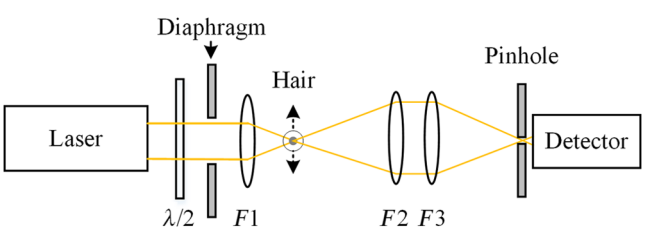

Fig. 2 Schematic diagram of the confocal setup used for the measurement of collimated transmittance through a hair: $\lambda/2$, a multiorder half-lambda waveplate; $F1$, a 20×0.4 NA microscope objective; $F2$, a 40-mm-focal-distance lens; $F3$, a 100-mm-focal-distance lens. Reproduced figure with permission.[45]

for sampling areas as small as 10 μm × 10 μm.[57] In the microspectrophotometry studies of hair, the incident light was focused down to a size smaller than the diameter of human hair to obtain the absorbance or transmission spectra of hair samples.[40,43,44] A dark scan and a reference scan were required during measurement to obtain accurate spectra graphs. At a given wavelength, transmittance, T, for example, is calculated using Eq. (1), where I_D is the dark reading measured by a detector when the light source is turned off while I_R is the reference reading when the hair sample is absent in the light path; I_{hair} is the reading when the hair sample is in place. To reduce the uncertainties of the result on each hair, I_{hair} was determined by averaging multiple measurements along the length of the hair shaft[40,43,45]

$$T = \frac{I_{\text{hair}} - I_D}{I_R - I_D}. \tag{1}$$

From the transmittance measurement, the attenuation coefficients of hairs were estimated using Beer's law, as shown in Eq. (2), where L is the thickness of the material.[43,45] The diameters of the hair samples have been measured conveniently using a video camera that is fitted to the microscope[42,43,45]

$$\mu_T = -\frac{-\ln T}{L}. \tag{2}$$

However, by assuming the measured transmitted light is collimated, the attenuation coefficients were underestimated. Another limitation of only conducting the transmittance measurement is the difficulty of distinguishing the absorption and scattering coefficients from the attenuation coefficient on its own. Rather than calculating the attenuation coefficient from Beer's law, Bashkatov et al.[42] took a similar approach using a digital video microscopic system. The images of hairs in the reflectance and transmittance modes of a microscope were acquired and analyzed. From the color images of hair shafts, their absorption and reduced scattering coefficients were estimated using the inverse MC method. Readings from white and black papers were used as a reference and a background signal in the reflectance measurement, while the readings from a transparent glass were used as a reference in the transmittance measurement.

The refractive index of scalp hair was determined by increasing the refractive index of the hairs' mounting media in small intervals until they matched, in which case the hair became invisible under a transmittance microscope.[46,58] Wang et al.[41] used the optical low-coherence reflectometry (OLCR) technique to investigate the refractive index of human scalp hair at a wavelength of 850 nm. Different single hair shafts were scanned both longitudinally and transversely. The refractive index of hair was calculated as a ratio of the scan length of the reference mirror in the OLCR result and the physical length of the hair shaft. Although the attenuation coefficients were not reported in this study, they were estimated by Kharin et al.[45] using Beer's law based on the magnitude of the interference signals in OCLR graph.

4.3 *Hair Optical Characteristics*

Wells observed that gray hair acts as a natural optical fiber, transmitting light along the hair shaft.[10] The transmittance microscope image of hair in his work illustrated that the cortex of the hair behaved like the core of an optical fiber, allowing the passage of light. In contrast to the cortex, the air-filled medulla at the center of the shaft appeared dark, implying no light transmitted through this region. Wells also pointed out that the color of hair is the most important factor affecting the light transmission along the shaft: darkly pigmented brown hair transmitted little or no light. Although no corresponding optical properties of hair were reported, these findings were confirmed by other later studies that presented numerical values.[41–43,45] These studies show that highly pigmented brown and black hairs have, as expected, the highest absorption and attenuation coefficients, whereas little- or unpigmented blond and gray hairs have the least (and insignificant) values. Among these studies, Kharin et al.[45] demonstrated that the attenuation coefficient of the medulla was dramatically higher than that of the cortex, especially in blond and gray hairs. This explains why the cortex of the gray hair appeared extremely bright while the medulla appeared completely dark in Wells' study. In contrast with other measurement and analysis methods, Bashkatov et al.[42] discriminated between the absorption and reduced scattering coefficients.[42] However, lightly pigmented blond and gray hairs showed significantly higher reduced scattering coefficient, which is inconsistent with Wang's results.[41] This great inconsistency of results may be due to the fact that hair samples with and without medulla were studied by the two research groups, respectively. Apart from the dependence of the optical properties of hair on its color and the presence of a medulla, the attenuation, absorption, and reduced scattering coefficients all increase with a decrease in the wavelength.[42,45] In addition, the difference between the optical properties in highly and lightly pigmented hair increases with a decrease in wavelength.[42,45] These relations can be seen from Kharin et al.'s results in Fig. 3.[45] This observed result is primarily due to the fact that the absorption and scattering coefficients of melanin become progressively more significant as the wavelength decreases.[59,60] Therefore, it is inferred that the difference between the optical properties (absorption and scattering coefficients) of highly and unpigmented hairs (e.g., terminal and vellus hairs) will peak in the UV wavelength region. This means that UV rays are expected to penetrate deeper in vellus hair than terminal hair.

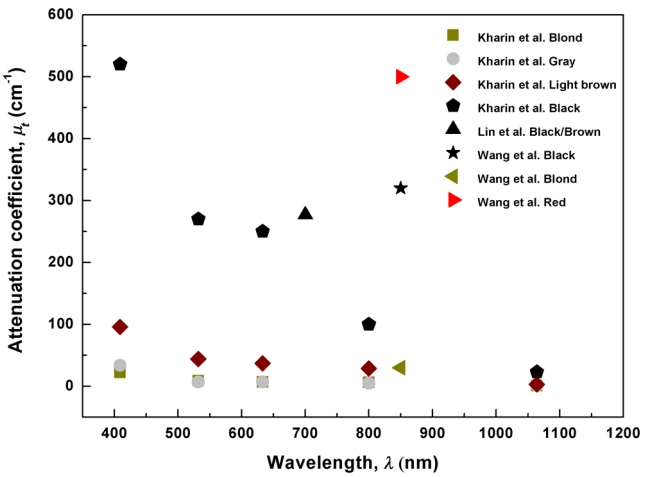

Fig. 3 Attenuation coefficient of human hair with different colors. Data are obtained from Kharin et al.,[45] Lin et al.,[43] and Wang et al.[41] The properties of the black and blond hair samples are measured in the longitudinal direction while the rest of the data are all measured in the transverse direction.

Table 1 Summary of the experimental factors in the studies of the attenuation coefficient of human hair.[41,43,45] The details of the hair samples used by Wang et al. are not reported.

	Hair sample	Experimental method	Direction of measurement	Refractive index-matching
Kharin et al.[45]	Nonmedullated scalp hair	Collimated transmittance measurement	Transverse	Yes
Lin et al.[43]	Medullated body hair	Microspectrophotometry	Transverse	Yes
Wang et al.[41]	—	OLCR	Transverse and longitudinal	No

The attenuation coefficient is the most commonly reported property of human hair in the literature because it can be estimated conveniently by applying Beer's law. Figure 3 illustrates a summary of the attenuation coefficient of different colored hairs at different wavelengths, obtained from three research groups.[41,43,45] Table 1 summarizes the varied experimental factors (different hair samples, experimental methods, directions of measurement, and refractive index-matching conditions) in these studies, which may result in the difference seen in their results. The attenuation coefficient of black hair at the wavelength of 700 nm determined by Lin et al.[43] is inconsistent with the wavelength-dependency of the black hair observed in Kharin et al.'s work.[45] This inconsistency is probably attributed to the presence of medulla since the high scattering effect of medulla can contribute to overall attenuation coefficient of hair. In addition, different morphologies of scalp and body hair samples may result in different optical properties. In contrast, the attenuation coefficient of black hair reported by Wang et al.[41] again differs to the other two studies. One fact is that Wang et al.[41] performed the measurement in air, in which the surface scattering effect is taken into the total attenuation coefficient. Furthermore, the black and blond hairs were measured in the longitudinal direction by Wang et al.,[41] whereas the rest were measured in the transverse direction. The attenuation coefficient of red hair measured in the transverse direction is surprisingly much higher than that of black hair at the same wavelength, both determined by Wang et al.[41] It is too early to draw a solid conclusion that the optical properties are different in the transverse and longitudinal directions since other variables such as measurement techniques and hair samples may all affect the published results.

The lowest attenuation coefficient is expected to be observed in the cortex of the blond hair, because it mainly contains pheomelanin. The attenuation coefficient of the cortex of hair in Kharin et al.'s study shows an exponential relation with the wavelength. Based on the current knowledge, the cortex of the blond scalp hair is considered to be mostly close to that of vellus hair. Therefore, we extrapolate the attenuation coefficient of the cortex of blond hair at a wavelength of 350 nm to be 26 cm^{-1}. By assuming the absorption to be dominant to the scattering in the cortex of blond hair, we estimated its penetration depth (at 350 nm wavelength) to be 376 μm, using Beer's law, which is about six times deeper than that of fair Caucasian skin,[61] implying that UV may penetrate much deeper in vellus hair than skin. The contribution of vellus hair in the UV energy delivery is to be verified by determining the UV optical properties of vellus hair.

As presented by Barrett et al.,[40] the absorbance spectra (200 to 700 nm) of scalp hairs with different colors peaked in a wavelength range of 300 to 400 nm. However, no numerical values of the optical properties of hairs were reported and the absorbance spectra graphs have no scale for comparison. In another spectrophotometry study of red and brown hairs, the absorbance spectra (400 to 800 nm) of hairs from red-haired people differed noticeably to those from brown-haired people, but both peaked at a wavelength of about 440 nm.[44] In contrast, the absorbance spectra of melanin isolated from red and black hairs continuously decreased in the wavelength range of 270 to 700 nm; while a more marked decrease was observed in red hair.[62] Greenwell et al.[46] found that regardless of age, gender, and race, the refractive index of the cuticles of hairs varied slightly from 1.543 to 1.554. As noted in this study, females and children have similar values of the refractive index, which tend to be higher than that of males. In contrast, Wang et al.[41] showed that the refractive indices of the hair cortical regions were in a range of 1.56 to 1.59.

Studies in the literature so far have mainly looked at the influence of color on the optical properties of scalp hair in the visible and infrared range of wavelength. In addition, the hair examined was primarily adult terminal hair, and very little investigation was done on children's hair and none on vellus hair. All in all, current knowledge of the optical properties of hair cannot provide enough evidence to support our hypothesis.

4.4 *Statistical Analysis*

The anatomy of human hair varies with color, age, gender, race, and body site. Achieving statistically significant optical properties requires a substantial amount of work. Statistically significant results of the refractive index of human scalp hairs (2529 hairs from 97 individuals) were obtained by Grenwell et al., taking into consideration different races, sexes, and ages.[44] The dispersion of the result was about 1%. Similarly, a large number of samples (1080 hairs from 54 brown-haired individuals, 420 hairs from 21 red-haired individuals) were used in Nicholls' study to determine their absorbance spectra. Wang et al. also investigated the refractive index of the cortical region (cortex and medulla) in the longitudinal direction of scalp hairs.[41] However, the identities of the hairs and the number of samples were not reported. Kharin et al. used five hair samples from single individuals with different hair color (black, light brown, gray, and blond).[45] In this study, the age and gender of the individuals were not specified. Over 30 hair samples each from 10 individuals were used in Bashkatov et al.'s study.[42] The age, gender, and hair color were specified in the paper. Barrett et al. also used five natural scalp hair samples each from seven groups of color (each group consisting of 1 to 5 individuals) to study the variation in their absorbance spectra due to the different levels of brown and blond colors.[40] However, no other information about the characteristics of the hair samples was given. In Lin et al.'s study, about five body hair samples each from about 45 individuals were used to determine the attenuation coefficient of human body hair.[43] This study calculated the mean attenuation coefficient of the hairs with different colors (auburn,

Table 2 Summary of the optical properties of black hair in the transverse direction and their standard derivation.[42,43,45]

	Wavelength (nm)	Optical properties (cm^{-1})	Standard derivation (±)
Bashkatov et al.[42]	600	28.5[a]	6.3
		37.5[b]	18.8
Kharin et al.[45]	633	250[c]	20
Lin et al.[43]	700	277[d]	111

[a]Absorption coefficient of scalp hair.
[b]Reduced scattering coefficient of scalp hair.
[c]Attenuation coefficient of the cortex of scalp hair.
[d]Attenuation coefficient of body hair.

brown, and black), from different gender, body sites (back, forearm, thigh, lower leg, shoulder, etc.), and ages (21 to 61). However, due to the randomness of the samples measured and multiple colors of hair samples involved, the statistical dispersion is more significant than scalp hair, as it can be seen from Table 2. Table 2 presents a summary of the optical properties of black hair and their standard deviation, for wavelengths from 600 to 700 nm.

In the literature, the influences of gender, age, race and, more importantly, hair type on the optical properties of hair have not been investigated deeply. Since there are vellus and terminal hairs existing at different sections of human bodies and their morphologies vary greatly, if human body hairs are to be examined, the color, type, and site of hair are the main categories to be considered in any future statistical analysis.

5 Light Transport in Hair

The stem cells are located ~360 and 1200 μm from the exposed skin surface in vellus and terminal hair follicles, respectively. Examination of the significance of the radiant energy density in these locations due to sun exposure may provide more information and evidence to support the hypothesis. The MC method for modeling photon propagation in biological tissues has been considered as the gold standard method.[63–66] As a statistical approach to light transport in tissues is based on the fact that photons exhibit a "random walk" as they propagate in a medium which involves scattering and absorption. Energy transfer and radiant energy in the hair follicle and skin due to light exposure has been simulated using the MC method for the application of epilation (hair removal).[67–70] Figure 4 shows a diagram of the principle of using the MC simulation to determine the energy exposure deposited in the hair follicle from a Ruby laser beam.[67]

Broadband light sources that deliver polychromatic light with various intensities at different wavelengths have also been commonly used for epilation. The principle of this method is to select the appropriate wavelength, pulse duration, and fluence (radiant exposure) from a broadband light source to damage the stem cells of hair follicles (for permanent hair removal) with the least interference to the surrounding tissues (selective photothermolysis). However, since the MC method requires the input of the optical properties of the tissues (epidermis, dermis, and hair), which are strongly wavelength-dependent, thus cannot be averaged over the range of the light source spectrum. For this reason, implementing the MC photon simulation to tissues subjected to light with varied wavelengths is challenging.[68,69]

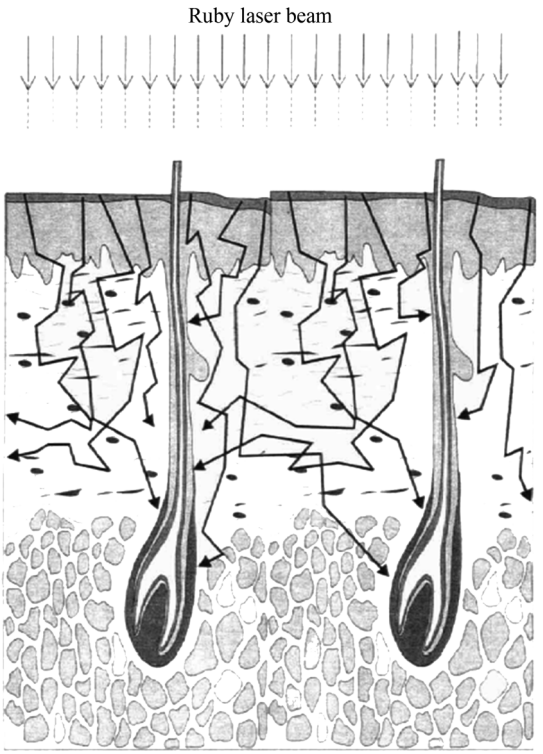

Fig. 4 Diagram of the principle of the Monte Carlo photon simulation in the skin and hair follicle. Reproduced figure with permission.[67]

To overcome this challenge, Ash et al.[69] ran the MC photon simulation simultaneously for each wavelength comprising the spectrum of the broadband light source. In contrast, Sun et al.[68] applied a spectrum-intensity-weighted method to estimate the effective absorption and scattering coefficients of the tissues. Table 3 summarizes the optical properties of hair reported in their publications. However, the optical properties of the hair, epidermis, and dermis in their numerical model were only estimations. The absorption and scattering coefficients of hair were estimated by assuming the melanin and water contents to be 0.3 and 0.25, respectively.[68] The temperature of the hair follicle in the simulation was validated by measuring the temperature values in a two-layered, agar gel skin phantom using a thermocouple.[68] The agar gel skin model, having the same optical properties as skin was made by dissolving the granulated agar, dyes, and milk into boiling distilled water. The refractive-index-mismatch of hair and skin was taken into consideration in Ash et al.'s simulation.[69,70] Theoretically, the MC photon simulation in hair requires the knowledge of its absorption coefficient, scattering coefficient, refractive index, and anisotropy factor. However, it is difficult to experimentally determine all the properties, due to the small size of hair. In addition, the inhomogeneous structures of hair make realistic photon simulation more challenging. Therefore, the refractive index and anisotropy factor of hair are usually assumed and the hair is often simply modeled as a cylinder in the MC simulation.[67–70]

Hair, like skin, can also be damaged by the UV rays. For example, prolonged sun exposure can cause hair to develop split ends, brittleness, dryness, and color fading through photoaging and photodegradation processes.[71–73] The influence of sun exposure on the appearance of scalp hair has drawn more attention recently. Several sunscreens that can be used for hair (both body and scalp hair) are available in the market.[73–77] Unlike

Table 3 Summary of the optical properties of hair used in MC simulation.[68–70] The absorption and scattering coefficients of hair are not reported in Ash et al.'s publication.

	Absorption coefficient (cm^{-1})	Scattering coefficient (cm^{-1})	Refractive index	Anisotropy factor
Sun et al.[68]	36.61	13.45	1.37	0.79
Ash et al.[69,70]	—	—	1.7	0.789

skin, the human hair shaft is nonliving and carcinogenesis within the hair is not possible. If human hair is damaged by sun exposure, it will be replaced by new grown hair in the next hair cycle. Therefore, lack of UV protection for hair does not seem life-threatening. However, if hair shafts act like UV-transmitting media and have the potential to cause damage to the hair follicle and skin, resulting in skin cancers, developing sunscreens that provide effective photoprotection for the skin and the hair becomes essential; and the effectiveness of current sunscreens on hair becomes worth investigating.

6 Concluding Remarks

The optical properties of human hair have most commonly been studied using the optical spectral measurements based on an optical microscope. Those studies have shown that the optical properties of human hair depend strongly on the type and concentration of melanin contained in the hair shafts, the site of the hair, the presence of the medulla, and the wavelength being measured. It is well accepted that eumelanin-dominated dark hair has higher absorption and scattering coefficients than pheomelanin-dominated light hair. The optical properties (absorption coefficient, reduced scattering coefficient, and attenuation coefficient) of hair increase with a decrease in wavelength, meaning fewer photons at shorter wavelengths are transmitted through hair. This phenomenon is much more pronounced for dark hair. Therefore, based on the unique morphologies of vellus hair (absent of medulla and little or no melanin present), it is extrapolated that UV radiation would penetrate deeper in lightly or nonpigmented vellus hair than highly pigmented terminal hair. However, the studies in the literature have focused only on examining the optical properties of human scalp hair (terminal hair) in the visible and infrared range of wavelength; so, current knowledge of the optical properties of hair cannot provide enough evidence to support our hypothesis. Therefore, the UV optical properties of vellus hair need to be explored; whether vellus hair transmits more UV light than terminal hair is yet to be answered.

As the structures of the cortex and medulla are anisotropic, the optical properties of hair in the transverse and longitudinal directions could be significantly different. If they are different, whether light can propagate along the hair shaft depends predominantly on the optical properties in the longitudinal direction. The properties in the longitudinal direction of hair shafts need to be investigated further, which will require proper hair sample preparation, precise instrumentation, and statistical analysis of the results. In addition, the cortex of hair has been found to have a much lower attenuation coefficient than the medulla, which is a strongly scattering structure in the center of the hair shaft, implying that the light is primarily propagated in the cortex. It is possible that UV penetrates through the cuticle of vellus hair from all directions and travels in the cortex of the hair shafts deeper into the follicle region. Some of the transmitted light is then scattered to the stem cells, possibly causing damage to these cells. The cumulatively damaged stem cells have the potential to become melanocytes and melanomas in later life. If this hypothesis is proved to be true, it may reveal why children are more vulnerable to sun exposure, and the consequent increased melanoma incidence seen in adults who have experienced excessive sun exposure or sunburn in their childhood. It will also explain the positive correlation between melanoma incidence and the number of vellus hair follicles.

Children younger than 10 have a noticeable proportion of "vellus-like" scalp hair and their terminal hairs on the scalp are generally finer than those of adults.[78,79] Therefore, children's scalp hair could be studied more conveniently by researchers than fine and short bodily vellus hair. The wide variations of the optical properties of hair indicate that statistically significant measurements of hair properties need to be achieved for reliable comparisons.

As human skin is exposed to the sunlight, the energy may not only penetrate through the skin but also hair. Examining and comparing the radiant energy in the bulge regions of hair follicles using the MC photon simulation could provide evidence to support the hypothesis. It will also allow us to visualize the contribution of hair in the energy transfer process. The outcome of this research may contribute to the prevention of melanoma.

Disclosures

No conflict of interest to disclose.

Acknowledgments

The authors acknowledge the doctoral scholarship provided by Auckland University of Technology for this research.

References

1. C. D. Holman and B. K. Armstrong, "Cutaneous malignant melanoma and indicators of total accumulated exposure to the sun: an analysis separating histogenetic types," *J. Natl. Cancer Inst.* **73**(1), 75–82 (1984).
2. P. Autier et al., "Melanoma risk and residence in sunny areas. EORTC Melanoma Co-operative Group. European Organization for Research and Treatment of Cancer," *Br. J. Cancer* **76**(11), 1521–1524 (1997).
3. T. M. Mack and B. Floderus, "Malignant melanoma risk by nativity, place of residence at diagnosis, and age at migration," *Cancer Causes Control* **2**(6), 401–411 (1991).
4. K. Cooke and J. Fraser, "Migration and death from malignant melanoma," *Int. J. Cancer* **36**(2), 175–178 (1985).
5. D. R. English and B. K. Armstrong, "Identifying people at high risk of cutaneous malignant melanoma: results from a case-control study in Western Australia," *Br. Med. J. (Clin. Res. Ed.)* **296**(6632), 1285 (1988).
6. S. A. Oliveria et al., "Sun exposure and risk of melanoma," *Arch. Dis. Childhood* **91**(2), 131–138 (2006).
7. S. J. Balk, "Ultraviolet radiation: a hazard to children and adolescents," *Pediatrics* **127**(3), e791–e817 (2011).
8. A. M. G. Garcia, C. E. McLaren, and F. L. Meyskens, "Melanoma: is hair the root of the problem?" *Pigm. Cell Melanoma Res.* **24**(1), 110–118 (2011).
9. X. Huang et al., "The significance of hair thermal diffusivity on melanoma incidence," in *ASME 2017 Int. Mechanical Engineering Congress and Exposition*, p. V003T004A060 (2017).
10. J. Wells, "Hair light guide," *Nature* **338**(6210), 23–23 (1989).
11. B. Iyengar, "The hair follicle: a specialised UV receptor in the human skin?" *Biol. Signals Recept.* **7**(3), 188–194 (1998).

12. M. R. Schneider, R. Schmidt-Ullrich, and R. Paus, "The hair follicle as a dynamic miniorgan," *Curr. Biol.* **19**(3), R132–R142 (2009).
13. L. Langbein et al., "The keratins of the human beard hair medulla: the riddle in the middle," *J. Invest. Dermatol.* **130**(1), 55–73 (2010).
14. S. Ito and K. Fujita, "Microanalysis of eumelanin and pheomelanin in hair and melanomas by chemical degradation and liquid chromatography," *Anal. Biochem.* **144**(2), 527–536 (1985).
15. R. R. Anderson and J. A. Parrish, "The optics of human skin," *J. Invest. Dermatol.* **77**(1), 13–19 (1981).
16. V. A. Randall, "Androgens and hair growth," *Dermatol. Ther.* **21**(5), 314–328 (2008).
17. U. Blume-Peytavi, D. A. Whiting, and R. M. Trüeb, *Hair Growth and Disorders*, Springer Science & Business Media, Berlin (2008).
18. S. Nagase et al., "Influence of internal structures of hair fiber on hair appearance. I. Light scattering from the porous structure of the medulla of human hair," *J. Cosmet. Sci.* **53**(2), 89–100 (2002).
19. A. Vogt et al., "Morphometry of human terminal and vellus hair follicles," *Exp. Dermatol.* **16**(11), 946–950 (2007).
20. N. H. Cox, B. L. Diffey, and P. M. Farr, "The relationship between chronological age and the erythemal response to ultraviolet B radiation," *Br. J. Dermatol.* **126**(4), 315–319 (1992).
21. B. Volkmer and R. Greinert, "UV and children's skin," *Prog. Biophys. Mol. Biol.* **107**(3), 386–388 (2011).
22. H. Yu et al., "Isolation of a novel population of multipotent adult stem cells from human hair follicles," *Am. J. Pathol.* **168**(6), 1879–1888 (2006).
23. H. Yu et al., "Stem cells with neural crest characteristics derived from the Bulge region of cultured human hair follicles," *J. Invest. Dermatol.* **130**(5), 1227–1236 (2010).
24. D. Fang et al., "A tumorigenic subpopulation with stem cell properties in melanomas," *Cancer Res.* **65**(20), 9328–9337 (2005).
25. S. L. Jacques, "Optical properties of biological tissues: a review," *Phys. Med. Biol.* **58**(11), R37 (2013).
26. S. A. Prahl, "Light transport in tissue," PhD Thesis, University of Texas, Austin (1998).
27. W.-F. Cheong, S. A. Prahl, and A. J. Welch, "A review of the optical properties of biological tissues," *IEEE J. Quantum Electron.* **26**(12), 2166–2185 (1990).
28. O. Hamdy et al., "A method for medical diagnosis based on optical fluence rate distribution at tissue surface," *Materials* **10**(9), 1104 (2017).
29. B. Wilson, M. Patterson, and S. Flock, "Indirect versus direct techniques for the measurement of the optical properties of tissues," *Photochem. Photobiol.* **46**(5), 601–608 (1987).
30. A. J. Welch and M. J. Van Gemert, *Optical-Thermal Response of Laser-Irradiated Tissue*, Springer, New York (2011).
31. A. N. Bashkatov, E. A. Genina, and V. V. Tuchin, "Optical properties of skin, subcutaneous, and muscle tissues: a review," *J. Innovative Opt. Health Sci.* **4**(01), 9–38 (2011).
32. M. Friebel et al., "Determination of optical properties of human blood in the spectral range 250 to 1100 nm using Monte Carlo simulations with hematocrit-dependent effective scattering phase functions," *J. Biomed. Opt.* **11**(3), 034021 (2006).
33. V. Peters et al., "Optical properties of normal and diseased human breast tissues in the visible and near infrared," *Phys. Med. Biol.* **35**(9), 1317–1334 (1990).
34. E. Salomatina et al., "Optical properties of normal and cancerous human skin in the visible and near-infrared spectral range," *J. Biomed. Opt.* **11**(6), 064026 (2006).
35. H. K. Bustard and R. W. Smith, "Studies of factors affecting light scattering by individual human hair fibres," *Int. J. Cosmet. Sci.* **12**(3), 121–133 (1990).
36. A. Guiolet, J. Garson, and J. Levecque, "Study of the optical properties of human hair," *Int. J. Cosmet. Sci.* **9**(3), 111–124 (1987).
37. H. K. Bustard and R. W. Smith, "Investigation into the scattering of light by human hair," *Appl. Opt.* **30**(24), 3485–3491 (1991).
38. R. F. Stamm, M. L. Garcia, and J. J. Fuchs, "The optical properties of human hair I. Fundamental considerations and goniophotometer curves," *J. Soc. Cosmet. Chem.* **28**(9), 571 (1977).
39. R. F. Stamm, M. L. Garcia, and J. J. Fuchs, "The optical properties of human hair II. The luster of hair fibers," *J. Soc. Cosmet. Chem.* **28**(9), 601 (1977).
40. J. A. Barrett, J. A. Siegel, and J. V. Goodpaster, "Forensic discrimination of dyed hair color: I. UV-visible microspectrophotometry," *J. Forensic Sci.* **55**(2), 323–333 (2010).
41. X. Wang et al., "Characterization of human scalp hairs by optical low-coherence reflectometry," *Opt. Lett.* **20**(6), 524–526 (1995).
42. A. N. Bashkatov et al., "Optical properties of hair shafts estimated using the digital video microscopic system and inverse Monte Carlo method," in *Int. Symp. on Biomedical Optics*, pp. 1–9 (2002).
43. T.-Y. Lin et al., "Reduction of regrowing hair shaft size and pigmentation after ruby and diode laser treatment," *Arch. Dermatol. Res.* **292**(2), 60–67 (2000).
44. E. Nicholls, "Microspectrophotometry in the study of red hair," *Ann. Hum. Genet.* **32**(1), 15–26 (1968).
45. A. Kharin et al., "Optical properties of the medulla and the cortex of human scalp hair," *J. Biomed. Opt.* **14**(2), 024035 (2009).
46. M. Greenwell, A. Willner, and P. L. Kirk, "Human hair studies. III. Refractive index of crown hair," *J. Crim. Law Criminol.* **31**(6), 746–752 (1941).
47. A. Douglas, "A new method of cross-sectioning hair of larger mammals," *S. Afr. J. Wildl. Res.-24-Month Delayed Open Access* **19**(2), 73–76 (1989).
48. M. C. Pepper and S. D. Lantis, "A new technique for cross sectioning free hairs," *J. Invest. Dermatol.* **68**(2), 111–112 (1977).
49. W. B. Shelley and S. Öhman, "Technique for cross sectioning hair specimens," *J. Invest. Dermatol.* **52**(6), 533–536 (1969).
50. M. Kneberg, "Improved technique for hair examination," *Am. J. Phys. Anthropol.* **20**(1), 51–67 (1935).
51. M. Steggerda, "Cross sections of human hair from four racial groups," *J. Hered.* **31**(11), 474–476 (1940).
52. F. Formanek et al., "Investigation of dyed human hair fibres using apertureless near-field scanning optical microscopy," *J. Microsc.* **224**(2), 197–202 (2006).
53. T. Lister, P. A. Wright, and P. H. Chappell, "Optical properties of human skin," *J. Biomed. Opt.* **17**(9), 090901 (2012).
54. D. W. Koon, "Is polar bear hair fiber optic?" *Appl. Opt.* **37**(15), 3198–3200 (1998).
55. H. Tributsch et al., "Light collection and solar sensing through the polar bear pelt," *Solar Energy Mater.* **21**(2–3), 219–236 (1990).
56. G. Kalyuzhny et al., "UV/Vis spectroscopy of metalloporphyrin and metallophthalocyanine monolayers self-assembled on ultrathin gold films," *J. Phys. Chem. B* **104**(34), 8238–8244 (2000).
57. S. Walkbridge-Jones, "Microspectrophotometry for textile fiber color measurement," in *Identification of Textile Fibers*, M. M. Houck, Ed., pp. 165–180, CRC Press, Boca Raton, Florida (2009).
58. E. M. Chamot and C. W. Mason, *Handbook of Chemical Microscopy*, John Wiley and Sons, New York (1938).
59. H. Van de Hulst, *Light Scattering by Small Particles*, p. 127, Dover, New York (1981).
60. M. Wolbarsht, A. Walsh, and G. George, "Melanin, a unique biological absorber," *Appl. Opt.* **20**(13), 2184–2186 (1981).
61. R. Anderson and J. Parrish, "Optical properties of human skin," in *The Science of Photomedicine*, pp. 147–194, Springer, New York (1982).
62. I. A. Menon et al., "A comparative study of the physical and chemical properties of melanins isolated from human black and red hair," *J. Invest. Dermatol.* **80**(3), 202–206 (1983).
63. L. Wang, S. L. Jacques, and L. Zheng, "MCML: Monte Carlo modeling of light transport in multi-layered tissues," *Comput. Meth. Programs Biomed.* **47**(2), 131–146 (1995).
64. L. Wang, S. L. Jacques, and L. Zheng, "CONV: convolution for responses to a finite diameter photon beam incident on multi-layered tissues," *Comput. Meth. Programs Biomed.* **54**(3), 141–150 (1997).
65. G. W. Lucassen et al., "Light distributions in a port wine stain model containing multiple cylindrical and curved blood vessels," *Lasers Surg. Med.* **18**(4), 345–357 (1996).
66. C. Zhu and Q. Liu, "Review of Monte Carlo modeling of light transport in tissues," *J. Biomed. Opt.* **18**(5), 050902 (2013).
67. G. Lask et al., "Laser-assisted hair removal by selective photothermolysis preliminary results," *Dermatol. Surg.* **23**(9), 737–739 (1997).
68. F. Sun et al., "Thermal modeling and experimental validation of human hair and skin heated by broadband light," *Lasers Surg. Med.* **41**(2), 161–169 (2009).

69. C. Ash et al., "Mathematical modeling of the optimum pulse structure for safe and effective photo epilation using broadband pulsed light," *J. Appl. Clin. Med. Phys.* **13**(5), 290–299 (2012).
70. C. Ash et al., "Effect of wavelength and beam width on penetration in light-tissue interaction using computational methods," *Lasers Med. Sci.* **32**(8), 1909–1918 (2017).
71. Z. D. Draelos, "Sunscreens and hair photoprotection," *Dermatol. Clin.* **24**(1), 81–84 (2006).
72. C. R. Robbins and C. R. Robbins, *Chemical and Physical Behavior of Human Hair*, Springer, New York (2002).
73. J. SaNogueira and T. Russo, "Sunscreen for the scalp hair and hair," Google Patents, U.S. Patent No. 6190645B1 (2001).
74. J. P. Ciaudelli and E. Brand, "Sunscreen composition for hair protection," Google Patents, U.S. Patent No. 4567038A (1986).
75. C. D. Vaughan, "Ultraviolet resistant sunscreen compositions," Google Patents, U.S. Patent No. 5208011A (1993).
76. M. E. Nambudiry and V. N. Collur, "Sunscreen compositions comprising pongomol," Google Patents, U.S. Patent No. 5152983A (1992).
77. J. F. Grollier et al., "Cosmetic composition containing aloesin as an agent for protection against sunlight and its use for skin and hair protection," Google Patents, U.S. Patent No. 4656029A (1987).
78. R. Sinclair et al., "Morphological approach to hair disorders," *J. Invest. Dermatol. Symp. Proc.* **8**, 56–64 (2003).
79. E. M. Wynkoop, "A study of the age correlations of the cuticular scales, medullas, and shaft diameters of human head hair," *Am. J. Phys. Anthropol.* **13**(2), 177–188 (1929).

Xiyong Huang is currently a PhD candidate at Auckland University of Technology's Institute of Biomedical Technologies. His research involves characterizing the optical properties of human tissues (especially in the ultraviolet range of wavelength), investigation of melanomagenesis from the stem cells of human hair follicles, and the Monte Carlo simulation of light transport in biological tissue.

Michael D. Protheroe is a programme leader and senior lecturer in the Mechanical Engineering Department at Auckland University of technology. His teaching and research interests include thermodynamics, heat transfer, and control engineering.

Ahmed M. Al-Jumaily is currently a professor of biomechanical engineering at Auckland University of Technology's Institute of Biomedical Technologies, New Zealand. He is a member of 11 international professional societies. He is the editor-in-chief of the ASME *Journal of Engineering and Science in Medical Diagnostics and Therapy* and of the ASME monograph series *Biomedical and Nanomedical Technologies*. He has published more than 300 papers in the international journals and conference proceedings in the area of biomedical applications.

Sharad P. Paul is a director of a Skin Surgery Clinic, adjunct professor at Auckland University of Technology, and a senior lecturer (skin cancer and surgery) at the Universities of Queensland and Auckland, respectively. His research interests are in cutaneous surgery, cutaneous oncology, and the biomechanics of skin. He has received numerous awards, notably the Ko Awatea International Excellence Award for Leading (Health) Improvement on a Global Scale in 2015.

Andrew N. Chalmers is currently an honorary research fellow at the Institute of Biomedical Technologies of the Auckland University of Technology, New Zealand. He previously taught at Manukau Institute of Technology in Auckland, and the University of Natal in Durban, South Africa. His PhD was awarded by the latter University in 1989. He has a strong interest in optical engineering, particularly in the visual and biological effects of light and radiation.