Numerical Model for Optical Characteristics of the Human Skin Surface

Kae NAKAMURA†, Tatsuya OGAWA‡, Sadaki TAKATA§ and Jun YAMADA†

Abstract

A numerical model was developed to clarify the optical characteristics of the human skin surface, i.e., the reflection and transmission characteristics. First, the bidirectional reflectance of the skin surface was measured to understand the optical characteristics, and a numerical model was developed to predict the bidirectional reflectance. Then, we developed a numerical model that simulates light behavior on the skin surface at the interface between air and the skin. We proposed two different numerical models based on geometric optics and verified their accuracy by comparing the model results with measurements. The tested models are Model A, which considers only the groove structure on the skin surface, and Model B, which considers the finer structures. By comparing the bidirectional reflectance from the measurement and the numerical analysis, it was found that Model A could not be used for predicting the bidirectional reflectance of the experimental results. However, Model B, which considers the finer structure of the surface as well as the groove structure, enabled us to predict profiles of the bidirectional reflectance, even though it showed slight discrepancies with the measurement results.

Key Words: Human skin surface, Cosmetic particles, Geometric optics, Reflection characteristics, Bidirectional reflectance, Made-up skin, Micro-facet, Monte Carlo method

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
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<th>Unit</th>
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<tr>
<td>q</td>
<td>flux</td>
<td>[W/m²]</td>
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<tr>
<td>I</td>
<td>intensity</td>
<td>[W/m²·sr]</td>
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<tr>
<td>θ</td>
<td>polar angle</td>
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<tr>
<td>φ</td>
<td>azimuthal angle</td>
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<tr>
<td>ρ²</td>
<td>bidirectional reflectance</td>
<td>[-]</td>
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<tr>
<td>Δ</td>
<td>small</td>
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<td>Ω</td>
<td>solid angle</td>
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<td>M</td>
<td>number</td>
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<tr>
<td>x, y</td>
<td>position</td>
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<tr>
<td>z_f</td>
<td>focal distance</td>
<td>[mm]</td>
</tr>
<tr>
<td>A</td>
<td>area</td>
<td>[mm²]</td>
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<tr>
<td>p, f</td>
<td>probability density function</td>
<td>[-]</td>
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<tr>
<td>D, N</td>
<td>unit directional vector</td>
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subscripts

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<tr>
<td>in</td>
<td>incident</td>
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<tr>
<td>r</td>
<td>reflected</td>
</tr>
<tr>
<td>d</td>
<td>perfectly diffused</td>
</tr>
<tr>
<td>e</td>
<td>surface element</td>
</tr>
<tr>
<td>tot</td>
<td>total number</td>
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<tr>
<td>0</td>
<td>projected onto the direction normal</td>
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1. Introduction

Because cosmetic foundation plays an important role in making skin beautiful, cosmetic manufacturers are frequently developing and marketing new products. Foundations consist of particles with diameters ranging from 10 nm to 100 nm that are suspended in glycerol water or alcohol solutions. To further improve the quality of foundations, not only the materials used in the foundations but also the shapes of the particles have been considered. For example, the particles have a specific purpose, such as shading spots, reducing color irregularity, and achieving a glossy feel or appearance.

However, the effects of these particles on the appearance of the skin have not been fully evaluated. Even though particles may exhibit good results in the sensory evaluation, the relationship between the sensory effects and their physical factors such as the optical properties of the particles may not be clear; in other words, the physical factors responsible for the good sensory evaluation cannot be identified. Therefore, trial and error has been required whenever new particles are developed. Thus, it is necessary to clarify the relationship between the particle features such as the material and shape and the skin appearance.

Nishimura et al. [1] reported on the development of makeup foundation that makes the skin look “mizumizushii,” which is a Japanese word describing beautiful skin. They evaluated the cheeks of 100 women and investigated the relationship between the visual evaluation score of “mizumizushii-looking skin” and the

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light reflectance. Then, new makeup foundation that reproduces the light reflectance profile of mizumizushii-looking skin was developed.

On the other hand, Nishikata et al. [2] developed new particles to make the skin look more natural, not artificial. They defined the ratio of the skin’s spectral reflectance measured at an acute incident and reflection angles to the spectral reflectance measured at an obtuse incident and reflection angles (RAO value) related to the spectral reflectance on human skin. Then, they proposed a new particle with an RAO value close to that of beautiful bare skin assessed by visual evaluation.

In both of these studies, the particles developed for application on the skin are verified through visual evaluation. However, the relationship describing how the particle affects the skin appearance and results in a favorable score is not clear.

In order to contribute to the development of the cosmetic particles, the scattering characteristics of cosmetic particles used for makeup must be associated with the appearance of made-up skin. However, the appearance depends not only on the optical characteristics of the skin and particles but also on other factors such as lighting and personal sensibility. Therefore, we have not studied the appearance but the reflection characteristics of made-up skin in our research project, as shown in Fig. 1.

The project consists of the development of three elemental numerical models that simulate (a) light reflection and transmission on the skin surface, (b) light propagation within the skin and (c) light scattering by cosmetics particles or cosmetic particle layers. We consider not only scattering by cosmetic particles but also reflection by the skin. With regard to reflection by the skin, because skin is semitransparent in the visible wavelength range, light scattering within the skin should be considered as well as the surface reflection of skin. Finally, these three numerical models are integrated to develop a model that enables us to clarify the relationship between the reflection characteristics of made-up skin and the scattering characteristics of cosmetic particles.

A numerical model for analyzing the reflection characteristics of made-up skin has been developed. In the report by Okamoto et al. [3], made-up skin was modeled as a three-layered light scattering and absorbing material on which spherical particles are placed. The light scattering on the particles was determined by Mie theory, and the light behavior within the numerical model of made-up skin was analyzed based on geometric optics. The relationship between the diameter of the particles and the spectral reflectance from the model of made-up skin was evaluated to determine the effect of particles on the appearance of made-up skin. However, there was no discussion about the surface structures on the skin in this report, even though it significantly affected the appearance of the skin.

Therefore, in this study, we focus on the elemental numerical model (a) in Fig.1. In order to clarify the optical characteristics of the skin surface, i.e., the reflection and transmission characteristics, first, the bidirectional reflectance of the skin surface was measured to understand the optical characteristics, and a numerical model was then developed that enabled us to

![Fig. 1 The concept of our research project including this study.](image-url)
predict the bidirectional reflectance.

2. Scattering Characteristics of the Skin Surface

Figure 2 shows the skin surface structures obtained using a digital microscope in the area of about 0.9 × 1.2 mm². We observe comparatively larger grooves that form a triangular network (sulcus cutis) as well as fine structures on the hill-shaped area (crista cutis) surrounded by the sulcus cutis. In this study, the larger grooved structure is called the “skin texture,” and the fine structures are referred to as the “microstructure.”

To understand the behavior of the light on the skin surface, we adopted the bidirectional reflectance $\rho^\circ$, which is a fundamental optical characteristic defined as

$$\rho^\circ(\theta_\text{in}, \phi_\text{r}) = \frac{\pi I(\phi_\text{r})}{q_\text{in}(\theta_\text{in})},$$

where $q_\text{in}$ is the radiative flux of the incident light and $I$ is the light intensity reflected by a surface [4]. The angles $\theta_\text{in}$ and $\phi_\text{r}$ are the polar angles of incident light and reflected light, respectively, and $\phi$ is the azimuthal angle measured from the direction of incidence.

When human skin is irradiated by incident light, reflected light arises from both surface reflections on the skin and internal scattering inside the skin. To isolate and evaluate the effects of reflection at the skin surface, an experimental model was constructed to measure the reflected light from the skin without considering the effects of internal scattering. This model is a surface structure on an optical prism, as shown Fig. 3. With this structure, we can evaluate the scattering characteristics of the skin surface because light does not scatter inside the prism.

The prism is made of BK7 because it has a refractive index close to that of human skin, which is around 1.5, depending on the water content. The surface structure of the skin was fabricated on the prism surface with an ultraviolet (UV)-light-curable resin AT3925M (NTT Advanced Technology, Co., LTD.). This resin is transparent in the visible wavelength range, and its refractive index can be controlled by changing a cross-linking agent. The refractive index of the resin is matched to that of the prism so that reflection and refraction do not occur at the interface between the resin and the prism, where there is no air gap.

On the other hand, the light transmitted through the prism surface with the skin structure reaches the back sides of the prism. Reflection and refraction occurs on the surface of the back sides. This reflection affects the measurement of reflection from the front surface of the prism with the skin structure. To reduce the reflected light from the back sides of the prism, we painted the back sides black (Water paint EXE, matte black, Nipponpaint Co., Ltd.).

Silflo (Flexico Developments, Ltd.), a slurry silicon rubber that cures when mixed with a curing agent, was used to make a female die of the skin structure. Silflo was applied together with the curing agent on a skin surface and cured on the surface. With cured Silflo as the female die, we molded the skin structure on the prism surface and cured on the surface. The fabricated skin structure had an area of about 4 cm² and a thickness of less than 1 mm.

The bidirectional reflectance was measured for this experimental model. Fig. 4 and Fig. 5 show the system used for measuring reflected light on the prism with the skin texture and the exterior view of the measurement equipment, respectively [5]. A He–Ne laser (632.8 nm) was used as the light source because the numerical results could easily be compared with the experimental results obtained by a monochromatic measurement.

A paraboloidal mirror and a charge-coupled device (CCD) camera were used to measure the directional intensity profile of the light reflected from the sample. The paraboloidal mirror has an internal diameter of 154 mm, external diameter of 165.5 mm, height of 55 mm, and focal distance of 27 mm. The mirror has a hole with a diameter of 12 mm to guide the incident beam of light to a measured sample. The mirror is positioned so that its symmetry axis is vertical and it faces upward.

As shown in Fig. 4-a, the surface of the sample is placed so that its normal is oriented horizontally and coincides with the focal point of the paraboloidal mirror. The incident light is irradiated in a horizontal direction. The incidence angle $\theta_\text{in}$ between the normal of the sample and the incident light can be varied by rotating the sample around the symmetry axis of the mirror. The reflected light from the sample is again reflected vertically upward by the paraboloidal mirror, reaching the screen above the mirror. The screen is made from polyacetal resin (POM). The light reaching the screen is transmitted, and part of the light is captured by a CCD camera. We could obtain the light reflected by the sample.
over all directions as an image.

When the directional intensity profile of the light reflected from the sample is written as \( I(\theta_r, \phi_r) \) and the radiative flux reaching a small area on the sample surface is written as \( q(x_0, y_0) \), as shown Fig. 4-b, the relationship between these parameters can be given as

\[
q(x_0, y_0) = I(\theta_r, \phi_r) \Delta \Omega_r, \tag{2}
\]

where \( \Delta \Omega_r \) is the solid angle of the small area around the focal point of the paraboloidal mirror from the position \((x_0, y_0)\) on the back of the screen. The output data of the CCD camera used in this measurement (BS-40L, Bitran Co.) was converted to the detected radiative intensity by prior calibration. The position \( x_0 \) and \( y_0 \) can be given by \( \theta_m, \theta \) and \( \phi \) by geometric investigation:

\[
\begin{align*}
x_0 &= 2z_f \left( -\sin \theta \sin \theta_m + 1 \right) \\
y_0 &= \frac{\sin \theta \cos \phi \cos \theta_m - \cos \theta \sin \theta_m}{\sin \theta \cos \phi \cos \theta_m + \cos \theta \cos \phi \sin \theta_m}
\end{align*}
\tag{3}
\]

where \( z_f \) is the focal distance. In addition to \( I(\theta_r, \phi_r) \), the incident flux \( q_{in}(\theta_m) \) is required for deriving the bidirectional reflectance. In this study, we measured the reflected radiative intensity \( I_d \) from the perfectly diffuse reflector instead of directly measuring \( q_{in}(\theta_m) \). Because the intensity reflected on the diffuse reflector \( I_d \) is constant in any direction, the following relationship between \( q_{in}(\theta_m) \) and \( I_d \) is satisfied:

\[
q_{in}(\theta_m) = \pi I_d \quad (I_d = \text{constant}) \tag{4}
\]

The reflector was constructed by spraying barium sulfate paste (6080, Labsphere, Inc., hemispherical reflectance is 95–98%) on a planar mirror (TFA-30C05, Sigmakoki Co., Ltd.). Note that \( I_d \) can be measured in the same way as \( I(\theta_r, \phi_r) \). Therefore, the bidirectional reflectance can be derived by the ratio of the output value from the sample to that from the reflector for pixels at the same position on each CCD image.

Figure 6 shows the profiles of the bidirectional reflectance measured with this apparatus. The measurements were performed on a prism with the abovementioned skin structure. The incident angles of the light were -45° and -30°. In this experiment, we prepared two prisms with the skin structure on the surface. The skin structure was obtained from the inner arm of a 27-year-old woman, and the measurements were
performed at three different locations, which were located about 2 mm apart from each other, on each prism. The range of the data and the values of the average results are shown in Fig. 6.

When measurements were performed several times at the same location, we found good reproducibility. On the other hand, the directional profiles measured at different locations differed, presumably because the irradiated area, which ranged within a radius of 1 mm or less centered on the focal point of the paraboloidal mirror, was too small to smooth out the effects of local surface structures. Although the results contain scatter, the directional profiles were similar.

No peak was observed around $\theta_r$ of 45° or 30°, which is the specular direction corresponding to the incident direction. This means that the skin surface diffusely reflected the incident light. To understand the origin of the bidirectional reflectance, we developed two models and compared the numerical results with the measured results.

3. Numerical Models for Skin Structure

We measured the geometric configuration of the skin surface structure using a confocal laser-scanning microscope (CLSM, Olympus OLS4000) to develop the numerical models. A typical image obtained by the CLSM is shown in Fig. 7. The image area is about 2.5 × 2.5 mm$^2$. The level of brightness in Fig. 7 reflects the depth of the structure; thus, brighter areas represent deeper grooves.

The skin texture (grooves) has a triangular network, as shown in Fig. 7, and the microstructure can be observed over the skin surface. The CLSM image contains not only photo-like image data but also digital data of the geometric configuration. Based the geometric configuration of skin surface, we developed two numerical models for examination.

Figure 8 shows Model A in which only the skin texture is considered; the microstructure is not considered. The depth of the grooves and the size of the triangular network were determined from the CLSM images. We assumed that scattering at the surface was induced by the reflection at the interface between air and skin, which have different refractive indexes (1.0 and about 1.5, respectively). The reflection was assumed to follow geometric optics governed by Fresnel’s relations.

Model B (i.e., the microstructure model) considers the microstructure. In this Model, we examined two cases, as shown in Fig. 9. In one case, the skin surface has only the microstructure (excluding the skin texture) (Fig. 9-a.), and, in the other case, the skin surface has the skin texture as well as the microstructure (Fig. 9-b.). As in Model A, we assumed that scattering at the surface of the microstructure was induced by reflection and refraction at the interface. However, the microstructure on the skin surface (including the skin texture or not) was treated...
statistically instead of being given a specific configuration.

When an ideally fine beam of light hits the surface of the skin and meets a small facet of the surface microstructure, the light is reflected by, or transmitted through, the facet. In this model, the scattering at the microstructure was induced by reflection and refraction by the difference of refractive indices between air and the skin. If we assume that reflection, transmission, or both reflection and transmission obey geometric optics, only the direction of the small surface facet is required for determining the reflected or transmitted direction.

Generally, because the skin surface is widely irradiated, the incident radiation hits many small surface microstructure facets oriented along various directions. Therefore, if we know the directions of the small surface facets, we can evaluate the scattering of radiation. We propose a method to statistically determine the directions of small surface microstructure facets. That is, we determine the probabilities for the direction of the small surface facets irradiated by incident light. To do so, we used the geometric configuration of the microstructure measured by the CLSM, which stores digital data on the height of the surface structure along with the image.

Predicting the reflection characteristics of a non-smooth surface by modeling the surface as an aggregation of micro-facets has been previously proposed[6,7]. In these studies, it was assumed that a micro-facet reflected incident light not only specularly but also diffusely. The probability density function was assumed to be the Gaussian distribution. Therefore, the ratio of diffuse reflection and/or the parameters of the Gaussian distribution must be determined so that the predicted result coincided with the measured result. In contrast, our numerical model requires only the geometric configuration stored in CLSM image to predict the reflection characteristics of surface. The details of our numerical model are presented below.

When a numerical image of a surface facet is obtained from three neighboring data points, as shown in Fig. 9, the direction of the surface facet given by the polar angle \( \theta_e \) and azimuthal angle \( \phi_e \) can be determined by an elementary geometric procedure because the coordinates of the three corners of the triangular surface facet are known. We measured the directions of all surface facets and derived the probability density function \( p(\theta_e, \phi_e) \). When \( \Delta M(\theta_e, \phi_e) \) is the number of surface facets that face a small solid angle \( \Delta \Omega_e \) around \( \theta_e \) and \( \phi_e \), and the total number of surface facets is \( M_{tot} \), the probability density function \( p(\theta_e, \phi_e) \) can be determined as

\[
p(\theta_e, \phi_e) = \lim_{\Delta \Omega_e \to 0} \frac{\Delta M(\theta_e, \phi_e)}{M_{tot} \Delta \Omega_e}.
\]  

(5)

Figure 10 shows the probability density functions for the facet direction \( p(\theta_e, \phi_e) \). The functions shown in Figs. 10-a and 10-b were derived from CLSM images with different surface area sizes. The functions are shown for three different locations on the prism. The functions in Fig. 10-a were derived based on the data from a wide area of \( 0.65 \times 0.65 \) mm\(^2\) in which some grooves exist, and the functions in Fig. 10-b were derived based on the data from a small area of \( 0.13 \times 0.13 \) mm\(^2\) without grooves. The spatial resolution for the geometric configuration of surface including grooves is 0.625 \( \mu \)m in the \( x \)- and \( y \)-directions and 0.2 \( \mu \)m in the \( z \)-direction. The spatial resolution for the geometric configuration without grooves is 0.125 \( \mu \)m in the \( x \)- and \( y \)-directions and 0.06 \( \mu \)m in the \( z \)-direction. The geometric configuration in Fig. 10-a could not be measured with a higher spatial resolution because the grooves were too deep.

The probability density functions based on images of both the wider area (Fig. 10-a) and the narrower (Fig.10-b) area show similar graphical forms regardless of the location. Given that the viewing area measured with the higher spatial resolution (Fig. 10-b) is narrow, it only includes the microstructure inside a triangular network and seldom includes uneven structures such as grooves. In contrast, the viewing area measured with the lower spatial resolution (Fig. 10-a) is wide and includes some grooves; therefore, the influence of an uneven structure on the probability density function is almost averaged out.
The calculated probability density functions are almost identical; thus, the directions of the surface facets are considered to be azimuthally symmetric. The probability density function shown in Fig. 10 shows the direction of a micro-facet that is impinged by incident light normal to the global skin surface. The probability density function was derived based on the slope data of micro-facets having the same projected area viewed from a direction normal to the global skin surface (Fig. 11). When the incident angle of light varies, the direction of a micro-facet impinged by incident light cannot be given by the function in Fig. 10 because the projected area of the micro-facet viewed from the incident direction varies. Considering the projected area, the probability density function for the incident light with the incident angle of \( \theta_m \) can be given by

\[
f(\theta, \phi, \theta_m) = \int_{\Omega} \frac{p(\theta, \phi, \theta_m) A(\theta, \phi, \theta_m)}{\int_{\Omega} p(\theta, \phi) A(\theta, \phi, \theta_m) d\Omega} \, d\Omega, \quad (6)
\]

where \( A(\theta, \phi, \theta_m) \), which is the projected area of a surface facet oriented in the direction of \( \theta \) and \( \phi \) onto the incident direction \( \theta_m \), can be written as

\[
A(\theta, \phi, \theta_m) = A_0 \cdot |\mathbf{D}_m \cdot \mathbf{N}_s| \cos \theta, \quad (7)
\]

where \( A_0 \) is the surface facet area projected onto the direction normal to the skin surface (the direction of the z-axis), which is \( 1/2 \times 0.625 \times 0.625 \mu\text{m}^2 \) or \( 1/2 \times 0.125 \times 0.125 \mu\text{m}^2 \). Here, \( \mathbf{D}_m \) and \( \mathbf{N}_s \) are the unit directional vectors of the incident light and surface facet, respectively.

The probability density functions for \( \theta_m = 0^\circ \) and \(-45^\circ\) are shown in Fig. 12. We found that the function is symmetric to the normal incidence of light (\( \theta_m = 0^\circ \)) because the surface facets are randomly oriented in the azimuthal direction and are azimuthally symmetric. We also found that the function is zero for \( 45^\circ < \theta_m \) when \( \theta_m = -45^\circ \) because the incident light does not hit surface facets oriented at polar angles larger than \( 45^\circ \).

### 4. Results and Discussion

Using the Monte Carlo method [8], we numerically evaluated the bidirectional reflectance of human skin. The number of photon bundles used in each calculation was more than 25 million, and the standard deviations of the predicted results were less than 0.001. The results are shown in Fig. 13. These calculations were performed under the conditions that the incident light was parallel and uniform and had an incident angle of \( 30^\circ \) or \( 45^\circ \), so that the results could be compared with the experimental results. The azimuthal angle of the reflected direction \( \phi \) is \( 0^\circ \), which is on the incident plane shown in Fig. 13.

In this comparison, the measurement locations may not coincide with the locations where the images used to estimate the probability density functions were obtained. However, the estimated bidirectional reflectance did not significantly depend on location because the probability density functions used for the calculation were location-independent, as discussed earlier. Therefore, the comparison shown in Fig. 13 is meaningful even if the measurement location and calculation location are different.

For Model A, the profile of the reflected light depends on the incident axis of the light and the orientation of the skin texture. Although the skin texture on actual skin is randomly oriented, the texture in the model is not randomly oriented. Therefore, we calculated the profiles of reflected light from varying orientations of the skin texture over all azimuthal directions and averaged the calculated profiles. The resultant profile is shown in Fig. 13 by the light green line.

Figure 13 reveals that the numerical results obtained using Model A do not agree with the experimental results. Only strong specular reflection occurred in Model A. Thus, a numerical model with simple structures does not accurately predict the results in the measurement, such as a smooth curve.

For Model B, we calculated the bidirectional reflectances based on two different probability density functions that were derived using the probability density functions \( p(\theta, \phi) \) shown in Fig. 10-a and Fig. 10-b. The red line shows the bidirectional reflectance of the surface containing only the microstructure, and the blue line
shows the bidirectional reflectance of the surface including the grooved structure as well as the microstructure. The numerical results for Model B have profiles similar to those of the experimental results. These comparatively smooth profiles can be attributed to the microstructure on the skin surface, and the difference between the magnitudes of the bidirectional reflection in Model B is due to the skin texture, i.e., grooved structure. Because the light incident into the grooves is hardly reflected because of multi-reflection, the bidirectional reflectance of the surface with the skin texture is lower than that without skin texture.

From the comparison between the measurement results and the numerical results for Model B, the numerical results (red line) based on \( p(\theta, \phi) \) without the grooved structure (Fig. 10-b) overestimated the measurement results. On the other hand, the numerical results (blue line) based on \( p(\theta, \phi) \) with the grooved structure (Fig. 10-a) slightly underestimated the measured results. Although there is small discrepancy, these results (blue line) have a similar profile to the measured results. One reason for this small discrepancy could be the diffraction effects that were not considered in this study. Another reason could be a stray light occurring in the measurement, although we carefully suppressed it. Considering that the diffraction slightly increases reflection over all directions in the numerical results and that the stray light decreases reflection in the measurement results, the numerical and measurement results with the grooved structure could be closer to each other.

Figure 14 shows the comparison between the numerical results and the measured results in other azimuthal directions, namely \( \phi = 30^\circ \) and \( 60^\circ \). Similar to the comparison shown in Fig. 13, the numerical results (blue line) based on \( p(\theta, \phi) \) with the grooved structure slightly underestimate the results, but they are good agreement in their profiles. If this small discrepancy can be acceptable, the present numerical model is useful for simulating the reflection characteristics on the skin surface.

In the present study, we show only the results of the bidirectional reflectance of skin surface that can be compared with the measurement results. If the light bundles transmitted through the skin surface are counted in the Monte Carlo simulation, the transmission characteristics, such as the bidirectional transmission, can be simulated.

5. Conclusions

The goal of our research project shown in Fig. 1 is the development of an integrated numerical model that clarifies the relation between the reflection characteristics of made-up skin and the scattering characteristics of cosmetic particles. In this study, as a part of this project, we developed a numerical model that simulates light behavior on the skin surface at the interface between the air and the skin.

We proposed two different numerical models based on geometric optics and verified their accuracy by comparing the model results with measurements. The tested models are Model A, which considers only the grooved structure on the skin surface (i.e., the “skin texture”), and Model B, which considers the finer structure (i.e., the “microstructure”).

Bidirectional reflectance was adopted as an index to evaluate the numerical models. From the comparison between the measurement results and the numerical results, Model A could not be used for predicting the bidirectional reflectance of the experimental results. On the other hand, Model B, which considered the geometric configuration of surface including the grooved structure, enabled us to predict profiles of the bidirectional reflectance even though it slightly underestimated the measurement results. Thus, Model B is a strong candidate model for simulating light behavior on the skin surface.

Because the present model can be coupled with the numerical model for light propagation in skin [9], the reflection characteristics of human skin can be easily predicted. If a numerical model for light scattering by cosmetics particles or cosmetic particle layers is completed and integrated with the other models, we may further clarify the relationship between the reflection
characteristics of made-up skin and the scattering characteristics of cosmetic particles.

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References


Fig.14 Comparison between numerical and experimental results at $\phi_r = 30^\circ$ and $60^\circ$