Development of Measurement Instrument for Optical Properties of Human Skin in Vivo

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In order to measure the optical properties of human skin in vivo, we developed a practical instrument that provides simple, prompt, and accurate measurements. The instrument utilized a reflection spatial profile measurement (RSPM), which estimated the optical properties by measuring radiation reflected from skin under stripe-patterned irradiation. RSPM can measure optical properties over a wide wavelength range, but it carries the risk of aberrations in the optical system that decrease measurement accuracy. Therefore, in this study, Zemax optical design software was used to evaluate the optical performance, and the percentage error caused by the optical performance was clarified by Monte Carlo simulations. Using the results, we developed a high-performance instrument with only $-0.4\%$ error in measurement accuracy. In addition, we demonstrated that the instrument enables us to measure differences in optical properties caused by changing the moisture content of skin.

[Keywords: optical properties, albedo, extinction coefficient, human skin]

1. INTRODUCTION

In advertising for cosmetics, qualitative words are typically used to describe the effects of a product, rather than numerical values. For example, in Japan, the adjectives “bright,” “Toumeikan-no-aru,” and “Mizumizushii” are used to describe the beauty of human skin treated with certain skincare products. “Toumeikan-no-aru” refers to skin that appears translucent and free of dullness, while “Mizumizushii” refers to skin that appears moisturized. However, neither of these words has a specific definition. Consequently, consumers can only select cosmetics products according to qualitative words used in advertising and the image of the brand, without a quantitative understanding of the extent of the specified effects of the product. This is because the cosmetics industry does not have standard indices to evaluate the appearance of skin by physical quantities. Many researchers have investigated the appearance of skin in various fields, such as cosmetics [1], medicine [2], and computer graphics [3]. However, no one has successfully determined an evaluation of skin based on physical quantities [4].

From the perspective of optics, human skin is a scattering and absorbing medium. The radiation propagated in skin is treated by the following radiation transfer equation [5,6].

$$\frac{1}{\beta} \frac{dI(s,\Omega)}{ds} = -I(s,\Omega) + \frac{\omega}{4\pi} \int_{4\pi} p(\Omega' \rightarrow \Omega) I(s,\Omega')d\Omega'. \quad (1)$$

where $I$ is the intensity of the radiation, $\Omega$ is a unit vector representing the propagation direction of the radiation, and $s$ is the coordinate along this direction. The radiation transfer equation includes three optical properties: the extinction coefficient $\beta$, albedo $\omega$, and scattering phase function $p$. In order to evaluate radiation transfer using Eq. (1), it is necessary to know the values of these optical properties.

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The factors that affect the appearance of skin can be split into two categories: those relating to the skin surface and those of internal media. When the incidence of radiation on skin is calculated by Fresnel’s law (the refractive index of skin is 1.5 and the incident angle of radiation is 30°), the reflected energy of the skin's surface is approximately 4% of the incident energy; the remaining 96% is transmitted by the skin and either scattered or absorbed by the subsurface medium. Thus, while the surface structure of skin is important to skin appearance [7,8], understanding the propagation of radiation in the subsurface skin, which holds the majority of the energy, is more important in evaluating appearance. However, few studies have investigated the connection between the radiation propagated in skin and the evaluation of skin appearance. This is because the method for measuring the radiation propagated in skin is very complex, and there is no standard measurement instrument as widely used.

The goal of this study is to develop a standard measurement instrument for the optical properties of human skin, which can then be used to evaluate the appearance of skin. The appearance of human skin differs with not only ethnicity, region, age, and health conditions, but also bathing or sun exposure, all of which can change the optical properties. For evaluating and measuring various types of skin, an instrument that can measure optical properties in situ must be developed and used to accumulate an enormous amount of data. Therefore, it is essential to develop a practical standard measurement instrument that can perform measurements quickly and simply after clarifying the reliability of the measurements. To be a standard instrument, the instrument must investigate clearly the connection between the radiation propagated in skin and the skin appearance and assess the effect of skincare products using not qualitative words, but standard indices.

Thus far, the optical properties of skin have mainly been investigated for medical applications, with significant research reflecting this focus [9-14]. The methods used for measuring optical properties include the integrating sphere technique [10], diffuse optical spectroscopic imaging (DOSI) [11,12], and the reflection spatial profile measurement (RSPM) [14] proposed by the current authors. Integrating sphere techniques are widely used to measure the optical properties of both skin and various scattering and absorbing media. This method measures transmitted radiation and estimates the optical properties based on transmission. However, it requires in vitro skin samples, where the conditions of blood, moisture levels, and other properties differ significantly from those of a living person. Therefore, in recent years, research into in vivo measurements of the optical properties of skin has progressed. These methods include DOSI and RSPM. DOSI combines measurements in the frequency domain using several laser diodes with measurements in the steady state using a white light source. The optical properties are estimated from the measured results. Meanwhile, RSPM can estimate optical properties by only steady-state spatial domain measurements using a white light source. It employs structured light patterns that are projected onto tissue and measures reflection profile from the tissue. From the results in spatial domain, the tissue optical properties are inversely estimated by fitting them to a diffusion model of light transport. This means that RSPM systems can easily estimate optical properties without the need for complex optical systems or measurement methods (details of our method in Section 2). D. J. Cuccia et al researched measurement accuracy of their system by measuring turbid phantoms using the spatial domain method [13]. They concluded that excellent accuracy in optical properties in the phantom validation measurement. However, they also mentioned that there might be estimating errors in the optical properties caused by the optical performance of the measurement instrument. Although, the detail of the way to project structured light patterns and measure the spatial profile, the measurement accuracy of our method also depends on the optical performance. Therefore, in this study, Zemax optical design software (Zemax, LLC) was used to evaluate the optical performance of the measurement instrument, and the estimation error of the instrument utilizing RSPM was clarified by simulations through the Monte Carlo method.

Finally, use of the developed instrument was demonstrated by measuring the change in optical properties with variations in the moisture levels of skin. In this paper, we will discuss usefulness of the developed instrument through the simulations and the demonstration.

2. ESTIMATION OF OPTICAL PROPERTIES BY RSPM

2.1 Principle of the Estimation Method

The method for estimating optical properties utilizing a reflection spatial profile is schematically shown in Fig. 1. In this method, skin is exposed to stripe-patterned radiation, in which one stripe portion of the skin surface is exposed to uniform radiation, and the next portion is not. This irradiation pattern is repeated periodically. If skin were opaque, as with metals, no reflection from the dark region would exist because the skin surface is not exposed to incident radiation. However, skin is semitransparent, and a portion of the incident radiation is scattered into the dark region and exits through it; the radiation transmitted to the skin is scattered and absorbed. This means that reflection
Fig. 1 Reflection by surfaces exposed to stripe-patterned radiation

from the dark region can exist, and the spatial profile of the reflected radiation includes information regarding the optical characteristics of the skin. In this method, the optical properties of the albedo and extinction coefficient are determined by an inverse analysis based on the measurement results for the spatial profile of the radiation reflected by the skin.

2.2 Numerical Model for Inverse Method

The numerical model used for the inverse analysis is based on that previously reported [14]. Skin is assumed an infinitely wide and parallel plane. Because the typical optical thickness of human skin is sufficiently thick, the tissue below the skin has a negligible effect on the reflection characteristics of skin. Therefore, the optical thickness of the skin is set to 20 and the boundary conditions of the bottom surface are set as complete absorption. The upper surface is assumed as smooth and the reflection at the surface is assumed to follow the Fresnel relations. The refractive index of skin is assumed as 1.5.

The calculated intensity profiles of the radiation reflected by skin are shown in Fig. 2. These results are normalized by the intensity of the incident radiation at the irradiated part divided by $\pi$. Here, skin is exposed to striped radiation with a 2-mm pitch, so the irradiated and non-irradiated portions are each 1 mm in width. The angle of irradiation is 30° and the reflected radiation is measured from the direction normal to the surface (0°). As shown in Fig. 2, sinusoidal profiles are observed for the calculated radiation intensities, which reflect the intensity profile of the incoming radiation. The amplitude of the sinusoidal profile depends on both the extinction coefficient and albedo. However, the average intensity depends on only the albedo. This facilitates the determination of optical properties by inverse analysis; the albedo is estimated first, based on the average intensity, and then used to estimate the extinction coefficient.

With the extinction coefficient and albedo estimated, it is possible to estimate the scattering phase function; however, the inverse analysis for estimating all optical properties becomes complicated and the estimation error for each property increases. Thus, the scattering phase function is fixed in this inverse analysis. The phase functions adopted in this analysis are shown in Fig. 3, where the red dots indicate measured data [15] and the lines indicate the adopted phase functions. The two Henyey-Greenstein phase functions shown in Fig. 3 are used to approximate the measured data.
3. OPTICAL DESIGN

3.1 The Impact of Instrument Performance on Estimation of Optical Properties

A schematic of the measurement instrument is shown in Fig. 4. A halogen lamp is used as the radiation source, and a multi-slit mask is set in front of the lamp to produce the striped pattern. The radiation is passed through the multi-slit mask and projected onto the skin surface by an extended projection lens. The radiation intensity profile along the direction perpendicular to the multi-slit mask is captured by a cooled charge-coupled device (CCD) camera. Because this optical system includes a spectroscopic system, the spectral information for the radiation intensity profile is also recorded by the CCD camera. A typical image captured using the CCD camera is shown in Fig. 4. The vertical direction shows the radiation intensity profile, while the horizontal direction represents the spectral dependence of the profile. Therefore, the RSPM can estimate the optical properties by taking a single picture.

When an imaging optical system is constructed, aberrations due to diffraction limits cannot be avoided. If the original image is a point source of energy, it is projected as an expanding energy distribution because of aberrations in the optical system. Although the expansion differs depending on the type of aberration, larger aberrations cause wider energy distributions. For the RSPM, the distribution of the reflected radiation measured from the skin is wider, and changes in the amplitude of this distribution cause estimation errors in the optical properties.

In this section, an example of an optical design for the RSPM, which has better optical performance to avoid estimation error, is shown. The effect on the estimation error caused by the optical performance is then clarified by simulation.

3.2 Optical Design for High-performance Measurement System

In general, the modulation transfer function (MTF) was used to evaluate the performance of the optical system. MTF is the parameter that can best show the performance of an optical system; it expresses a contrast reproduction ratio against the spatial frequency in units of line pairs (lp)/mm (number of input signals for a pair of black and white lines per millimeter) [16,17]. For an optical system with large aberrations, the contrast reproduction ratio and the MTF value are decreased.

The optical system for RSPM is divided into the two parts of an extended projector and a spectroscope. In this section, an example of optical design for the spectroscopic part is discussed in detail.

The radiation reflected from skin in front of the diffraction grating must be parallel. Generally, an off-axis parabolic mirror or a collimator lens can be used to collimate the radiation. Therefore, the optical performance of each component was evaluated by using Zemax optical design software and an optical design with the best MTF for each component is created.

The MTF values for each component at the center (y = 0 mm) and end (y = 8.5 mm) of the projected stripe-patterned irradiated areas on skin are shown in Fig. 5.

The results in Fig. 5 show that the ideal off-axis parabolic mirror has extremely high performance in the center of the projected area; however, it is low-
performance at the end of the projected area. On the other hand, the collimator lens (SIGMAKOKI Co., LTD., DLB-50-200PM) appears to have high performance throughout the area from center to end. To show the reasons for this, the Seidel aberration coefficients categorized for each type of aberration are shown in Fig. 6. At higher values of the aberration coefficients, the MTF values become lower. Spherical and color aberrations do not occur in the off-axis parabolic mirror, but other aberrations occur at high values. This is because the MTF worsens as the aberrations approach the end of the projected area. With the collimator lens, all types of aberration occur, including color aberrations; however, the values are small. This explains the high MTF values of the collimator lens over a wide area. Therefore, the collimator lens was used for the spectroscope in our developed measurement instrument.

The MTF also relies on the specification of the lens. Thus, a collimator lens for which the MTF was maximized was selected. Regarding the extended projection part, a similar analysis was performed for determining the optical design of the instrument. A specification list of the chosen components is shown in Table 1.

### Table 1 Specification list

| Extended projection part |  |
|-------------------------|--|
| Light source            | Type: Halogen lamp (ILX-64620, Osram GmbH) Power: 15 V 150 W Color Temperature: 3270 K |
| Multi-slit mask          | Slit size (H×V): 1 mm × 0.1 mm Number: 9 Pitch: 0.2 mm |
| Extended projection lens | HF16SA-1, FUJINON MTF: 0.75 (Spatial frequency – 83 lp/mm, on axis) Focal length: 16 mm Magnification ratio: 10 |
| Spectroscopic part       |  |
| Aperture                | Size (H × V): 1.0 mm × 40 mm Distance from skin = 25 mm |
| Collimator lens          | DLB-50-200PM, SIGMAKOKI Co., LTD. Type: Achromat lens Focal length: 200 mm |
| Diffraction grating      | Type: Transmission Grating Blaze wavelength: 515 nm Groove density: 300 grooves/mm |
| CCD camera               | Type: Monochrome Pixel number (H × V): 1360 × 1024 Pixel size (H × V): 6.45 mm × 6.45 mm |
| CCD camera lens          | INF50SA-1, FUJINON MTF: 0.70 (Spatial frequency = 83 lp/mm, on axis) Focal length: 50 mm |

### 3.3 Analysis Result for Percentage Error of Developing Instrument

The estimating error caused by aberrations of the developed instrument was clarified by numerically simulating the estimated extinction coefficient for two optical systems. One system was an ideal optical system without aberrations and the other was the present system with aberrations.

When no aberration exists, the projected stripe-patterned irradiation is sharp. The profile of the radiation reflected from the skin is correctly measured and the true value of the extinction coefficient, which assigned to the skin in this simulation, is estimated. However, when aberrations exist, the original stripe-patterned distribution...
of the projected irradiation becomes wave-like. In addition, the profile of the radiation reflected from the skin becomes somewhat decreased relative to the ideal profile without aberration. The deformation of the measured profile of the reflected radiation is dependent on the MTF values of both the extended projection and spectroscopic parts of the system, and the profile deformation induces an estimation error in the extinction coefficient.

To numerically estimate the profile deformation, the line spread function (LSF) [16], which provides a spread distribution of the image of a narrow line source through an optical system, was used. We numerically determined the LSFs of the extended projection and spectroscopic parts by converting the MTFs of the present optical system by inverse one-dimensional Fourier transform. The functions \( L_{ep}(y) \) and \( L_{ss}(y) \) shown in Fig. 7 are the LSFs for the extended projection and spectroscopic parts, respectively. Using the LSFs, we simulate the estimation process of the extinction coefficient when we use the present optical system. The simulation process is shown in Fig. 8.

For the present optical system with aberrations, when the stripe-patterned profile is expressed by the function \( U_{in}(y) \), the profile of the irradiation can be expressed by:

\[
U_{in}^{pre}(y) = \int_{-\infty}^{\infty} U_{in}(y - r)L_{ep}(r)dr.
\]

In the simulation, the irradiation is input according to the function \( U_{in}^{pre}(y) \).

The profile of the radiation reflected by the skin is calculated by the Monte Carlo method based on the model introduced in Section 2. When the profile of the reflected radiation is expressed by function of \( U_{refl}(y) \), the measured profile of the reflected radiation \( U_{refl}^{pre}(y) \) through the present optical system becomes

\[
U_{refl}^{pre}(y) = \int_{-\infty}^{\infty} U_{refl}(y - r)L_{ss}(r)dr.
\]

The extinction coefficient is estimated based on the profile \( U_{refl}^{pre}(y) \) in this simulation.

Figure 9 shows the percentage error \( P_{er} \) (Eq. 4) caused by the aberrations in the developed instrument, as determined by comparing those two simulations:

\[
P_{er} = \frac{\beta_a - \beta_e}{\beta_a} \times 100,
\]

where \( \beta_e \) is the estimated extinction coefficient with aberration and \( \beta_a \) is the true value of the extinction coefficient assigned to the numerical model without aberration. The results demonstrate that our optical system has a maximum \( P_{er} \) of \(-0.4\); it can measure the extinction coefficient with high accuracy.

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Fig. 7 Calculated LSFs of extended projection part \( L_{ep}(y) \) and spectroscopic part \( L_{ss}(y) \) at the center \( (y=0 \text{ mm}) \) and end \( (y=8.5 \text{ mm}) \) of the projected stripe-patterned irradiated area on skin.

Fig. 8 Process of simulation.
4. MEASUREMENT INSTRUMENT

Based on the optical design investigated in Section 3, a measurement instrument was developed with consideration for both portability and operability. Figure 10 shows the measurement instrument. All components are fixed within the instrument, so the structure requires no adjustments at the time of measuring. In addition, the instrument can be disassembled into three parts and stored in a case. After transporting the instrument, it can be assembled and ready for use in approximately 10 min.

5. EXPERIMENTAL RESULTS

To show the benefits of the developed measurement instrument, a demonstration was performed. It is commonly said that skin appearing to be moistened by water, such as that after bathing, looks beautiful. Therefore, the influence of the moisture levels of skin on changes in the optical properties was assessed using the developed instrument.

The results of the measured optical properties for the skin of the inside forearm of a 27-year-old male before and after soaking the arm in water for 30 min are shown in Fig. 11. Capturing an image using CCD camera required 1 s and the inverse analysis using the image required approximately 5 s to estimate spectral optical properties.

The error bars show the standard deviations for measurements at nine different points on the inner forearm. Our measured results (e.g., $\beta = 9.8 \text{ mm}^{-1} \text{ at } \lambda = 650 \text{ nm}$) are within the range of previous studies (e.g., $\beta = 7.3-11.1 \text{ mm}^{-1} \text{ at } \lambda = 650 \text{ nm}$) [11,12]. Dispersions of the measured extinction coefficient at all wavelengths are much bigger than simulated percentage error of the instrument; for example, the dispersion before soaking in water at $\lambda = 650 \text{ nm}$ is 2.2%. This shows that the instrument has a high degree of accuracy in measuring the extinction coefficient.
Two moisture meters for the epidermis (Skin Moisture Sensor MY-808S, Scalar Corporation) and dermis (Moisture Meter D Compact, Delfin Technologies Ltd.) were used to measure the moisture levels of the subject's skin. It was previously reported that changes in the temperature of the skin could change the optical properties [18]. Therefore, the arm was soaked in water at a temperature approaching the surface temperature of the body (34 to 35°C). The results of the moisture level measurements according to the two moisture meters are shown in Table 2. These measured results show that the values of the moisture levels of the epidermis and dermis of skin, albedo, and extinction coefficient all increased after soaking the forearm in water. Through the increase in albedo, the skin becomes “brighter” and appears whiter. Through the increase in the extinction coefficient, it becomes difficult for light to penetrate the skin, and transparency decreases. Although further study will be necessary to make a correlation between the skin optical properties and the skin appearance described as “Toumeikan-no-aru” or “Mizumizushii,” it was possible to measure the slight differences in the appearance of the skin caused by changes in the moisture content by using the developed measurement instrument.

### 6. CONCLUSION

A measurement instrument with the capacity to simply and promptly measure the optical properties of human skin in vivo was developed. The influence of the optical performance of the developed instrument on the estimated extinction coefficient was clarified by simulation. The results showed that the developed instrument could measure the extinction coefficient with a high degree of accuracy and only −0.4% error caused by aberrations in the optical system.

The optical properties of human skin were measured using the developed measurement instrument. The dispersion of the measured extinction coefficient was 2.2%. This demonstrates that the simulated percentage error of the instrument is very small compared to the dispersion of the measured data. In addition, the change in optical properties with changes in the moisture levels of skin was measured. The slight difference in the appearance of skin caused by changing the moisture content could be measured using the instrument as differences in optical properties. This developed instrument could a candidate for a standard apparatus to measure the optical properties of human skin in vivo. The apparatus enables detailed investigations of the connection between radiation propagated in skin and the evaluation of skin appearance, and assessments of the effects of skincare products on skin appearance using not qualitative words, but standard indices.

### NOMENCLATURE

- $g$: asymmetry factor, -
- $I$: intensity, $W/(m^2 \cdot sr \cdot nm)$
- $L_{ep}$: line spread function for extended projection part, -
- $L_{ss}$: line spread function for spectroscopic part, -
- $n$: refractive index, -
- $p$: scattering phase function, -
- $P_e$: percentage error, -
- $s$: position in a direction, m
- $U$: radiation profile function, -
- $y$: position, m
- $\beta$: extinction coefficient, $mm^{-1}$
- $\theta$: scattering angle, °
- $\lambda$: wavelength, nm
- $\omega$: albedo, -
- $\Omega$: directional vector, -

| Subscripts | Description |
|------------|-------------|
| $a$ | true value of extinction coefficient assigned to numerical model |
| $e$ | estimated extinction coefficient with aberration |
| $in$ | incident |
| $pre$ | present |
| $refl$ | reflected |

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