Optimization of spectral sensitivities of mosaic 5-band camera to estimate chromophore densities from skin images including shading and surface reflections

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In this paper, spectral sensitivities of mosaic 5-band camera are designed by using numerical skin phantom for separation of chromophore densities, shading and surface reflection. To make the numerical skin phantom, spectral reflectance of skin various was calculated by Monte Carlo simulation for photon migration from the values of melanin, blood volume and oxygen saturation. In the numerical skin phantom, melanin and hemoglobin concentration distribution were obtained by separating from actual skin image by independent components analysis and the calculated components were assigned to concentration distribution. Utilizing this numerical skin phantom, spectral sensitivities of mosaic 5-band camera were optimized by using nonlinear optimization technique to estimate spectral reflectance for skin separation. In this optimization, the spectral sensitivities are assumed as normal distribution and sensor arrangement is set as same as that of conventional mosaic 5 band camera. From the results of optimization, we found that the optimized spectral sensitivities can improve the spectral estimation significantly.

Introduction

Skin is multi-layered tissue composed of epidermis, dermis and subcutaneous tissues and has chromophores such as melanin, oxy-hemoglobin and deoxy-hemoglobin. Since diffuse reflectance of human skin is changed depending on the concentration of these chromophores, the analysis of diffuse reflectance provides us the information on tissue activities related to chromophores. These information can be applied to early detection of skin disease and monitoring health.

Tsumura et al. discussed the method of extracting melanin and hemoglobin by applying independent component analysis to skin color image [1]. Kikuchi et al. proposed imaging of hemoglobin oxygen saturation ratio in the face by spectral camera based on multi regression analysis [2]. A lot of studies have been performed as above methods for estimating chromophore concentrations linearly from skin color image and spectral image. On the other hand, Kobayashi et al. analyzed nonlinear relation between absorbance and concentration of chromophores in the skin based on Monte Carlo simulation of photon migration [3] and reported a method of estimating optical path length at each layer [4]. By using the estimated optical path length, the concentration of chromophores can be obtained based on modified Lambert Beer's law. These techniques are expected to be used in the practical use by using conventional mosaic 5-band camera [5]. However, spectral sensitivities of conventional mosaic 5-band camera are not designed for separating reflectance and pigment components.

In this paper, spectral sensitivities of mosaic 5-band camera are designed by using numerical skin phantom for separation of chromophore densities, shading and surface reflection. In building the numerical skin phantom, spectral reflectance of skin various was calculated by Monte Carlo simulation for photon migration from the values of melanin, blood volume and oxygen saturation. In the numerical skin phantom, melanin and hemoglobin concentration distributions were separated from actual skin image by independent components analysis (ICA) and calculated components were assigned to concentration distribution used in Monte Carlo simulation of photon migration. Utilizing this numerical skin phantom, spectral sensitivities of mosaic 5-band camera are optimized by using nonlinear optimization technique to achieve the spectral estimation for separating chromophore densities, shading and surface reflection.

Generating Numerical Phantom for Spectral Reflectance Map of Skin

To design the spectral sensitivities of mosaic color filter, numerical phantom is required since the chromophore concentrations are unknown in the actual skin spectral reflectance. In this research, we build numerical phantom by generating spectral reflectance map by Monte Carlo simulation of Multi-Layered tissue (MCML) [3]. In this paper, various spectral reflectance for various melanin, various blood volume and various oxygen saturation was calculated as was performed in the previous work [6,7]. The outline of generating spectral reflectance map is shown in Fig. 1.

First, in order to obtain the distribution of chromophores close to real skin, we extract chromophore component by applying independent component analysis on actual skin color image without surface reflection by setting polarization filters in front of the camera the light sources with crossed nicol arrangement [1]. Then, the patterns of melanin and blood volume are given by the results of this independent component analysis for real skin image. The pattern of oxygenation is given by our hand to represent dark shadows under the eyes as is described below. The detail to assign the distributions for Monte Carlo simulation of photon migration (MCML) are described after the explanation of MCML in the next paragraph..

In the MCML, we assumed two-layered skin model composed of epidermis and dermis. The five optical parameters are set at each layer such as thickness t, reflectance index n, anisotropy factor g, scattering coefficient μ_s and absorption coefficient μ_a. The thickness t of epidermis and dermis are 0.006 and 0.40 cm respectively in this research. The reflectance index n, scattering coefficient μ_s and anisotropy factor g of two layers are the same value, n = 1.4, the data of μ_s and g are used from [6,7]. The absorption coefficient μ_a is calculated by the absorption coefficients of chromophores such as melanin, oxy-hemoglobin and deoxy-hemoglobin as follows.

$$\begin{aligned} \mu_{a.epi}(\lambda) &= [Mel]\mu_{a.mel}(\lambda), \\ \mu_{a.der}(\lambda) &= [Ohb]\mu_{a.ohb}(\lambda) + [Hb]\mu_{a.hb}(\lambda) \\ &= [Thb][StO]\mu_{a.ohb}(\lambda) + [Thb](1-[StO])\mu_{a.hb}(\lambda), \end{aligned} \quad (1)$$

where λ is wavelength and the subscript of absorption coefficient *epi*, *der*, *mel*, *ohb* and *hb* indicate epidermis, dermis, melanin, oxy-hemoglobin and deoxy-hemoglobin respectively. The absorption coefficients of chromophores are used from [5,6]. The percentage of melanin, oxy-hemoglobin and deoxy-hemoglobin are expressed by [*Mel*], [*Ohb*] and [*Hb*] respectively. We input these percentage of chromophores to MCML and acquire diffuse reflectance of skin. The percentage of oxy-hemoglobin and deoxy-hemoglobin are calculated by blood volume [*Thb*] and oxygen saturation [*StO*]. The blood volume is defined by the sum of oxy-hemoglobin and deoxy-hemoglobin, [*Ohb*] + [*Hb*]. The oxygen saturation indicates the ratio of oxy-hemoglobin in the blood and expressed by [*Ohb*]/([*Ohb*]+[*Hb*]).

To assign the distributions of melanin, hemoglobin and oxygen-saturation, as shown in Fig. 1, the obtained melanin concentration by ICA is divided into 10 and allocated into input melanin concentration of [Mel] = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10%. Similarly, the obtained hemoglobin concentration by ICA is divided into 5 and allocated into input blood volume [Thb] = 0.2, 0.4, 0.6, 0.8, 1.0%. We also consider two oxygen saturations [StO] = 60, 80% and set lower oxygen saturation in the center of map. It is noted that this region intends to represent dark shadows under the eyes. To generate diffuse reflectance map, we obtained diffuse reflectance from the results of MCML corresponding to the combination of melanin concentration, blood volume and oxygen saturation at each pixel.

Finally, we multiply shading to the diffuse reflectance map for generating the images that is constructed from four components. By adding surface reflectance on this four components image, we can generate the images that are constructed from five components. The surface reflectance is calculated by the subtraction between skin color image with and without surface reflection by using the polarizing filters. It can be seen that the actual skin texture can be reproduced by our proposed numerical phantom that is obtained by MCML and independent component analysis.

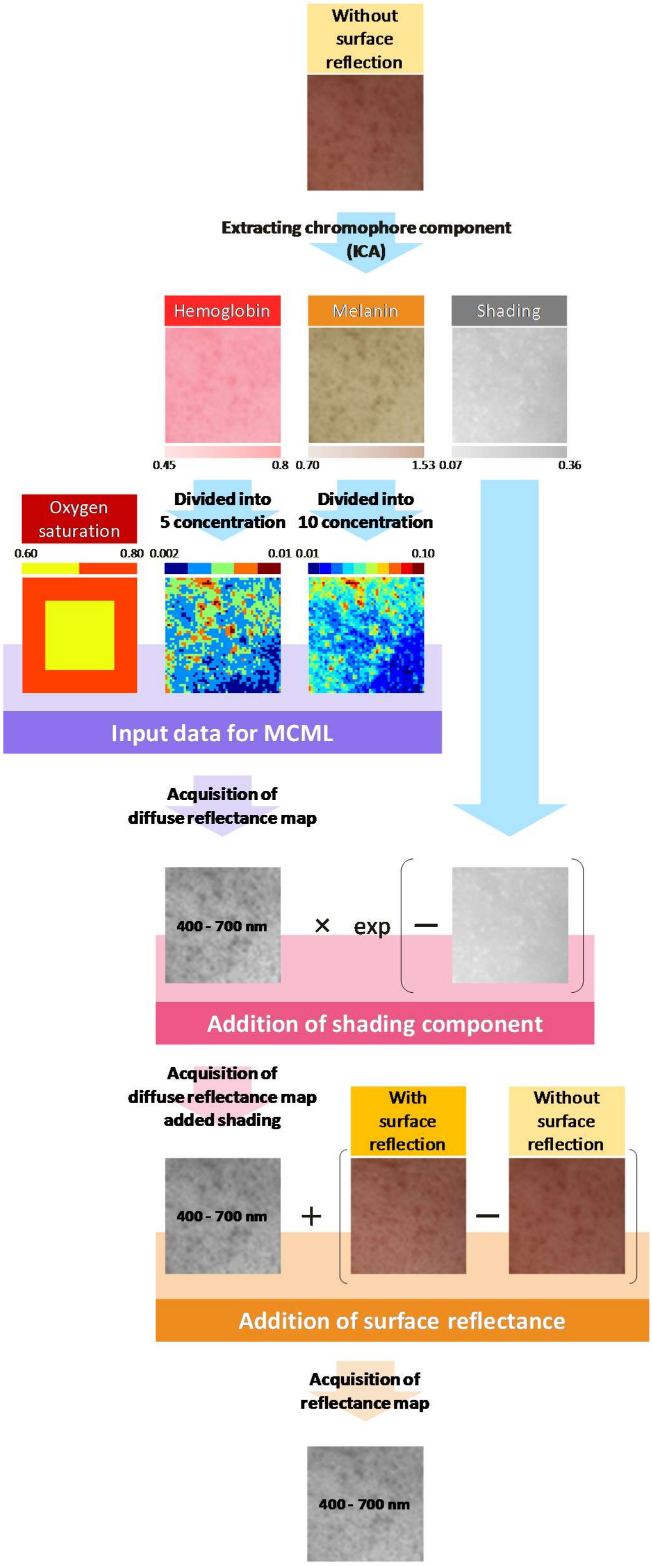


Figure 1 Outline of generating spectral reflectance map

Design of spectral sensitivities of mosaic 5 band color filter

Figure 2 shows the mosaic color filters on the imaging device considered in this paper. Figure 2(a) shows the conventional mosaic color filters that are Red, Green, Blue, Orange, and Cyan [5]. Figure 2(b) shows our mosaic color filters where we will design the spectral sensitivities of each filter; v_1, v_2, v_3, v_4, v_5.

In designing the spectral sensitivities of color filter, we approximately represent each peak shape of the spectral sensitivities as normal distribution function. Since each normal distribution function can be parameterized by average and standard deviation for wavelength, we will find the optimal 5 sets of average and standard deviation for wavelength. This means that we will optimize the 10 parameters in this paper.

By setting the 10 parameters in computer simulation of imaging process, we can calculate the sensor outputs for the numerical phantom for skin spectral map. At first, the demosaicing is performed for the sensor outputs. The linear interpolation is used in this research. The interpolated pixel values are converted to spectral reflectance at each pixel by using Wiener estimation method [8]. The optimization is performed by using the "fmincon" in MATLAB optimization tool box, which find minimum of constrained nonlinear multivariable function [9]. The error in the optimization was given by the RMSE (root mean square error) between the original spectral reflectance in the numerical phantom and estimated spectral reflectance at 560nm, 570nm, 590nm, 610nm, 700nm for the given 10 parameters. These five wavelengths are known to give a good separation of chromophore densities, shading and surface reflection. The detail of this was reported in another paper [10].

Figure 3 shows the original spectral sensitivities of 5-band camera. Figure 4 shows the optimized spectral sensitivities drawn by obtained 10 parameters. Table 1 shows the parameters of optimized spectral sensitivities. Figure 5(a) shows the original spectral reflectance in the numerical phantom. Figure 5(b) shows the estimated spectral reflectance from the optimized 10 parameters. The independent line means the spectral reflectance at each position of the image.

Spectral sensitivities were improved on the aspect of estimation on spectral reflectance at 560nm, 570nm, 590nm, 610nm and 700nm. The RMSE for the estimated spectral reflectance was 0.053 in the conventional spectral sensitivities. The RMSE was 0.036 in the optimized spectral sensitivities as shown in Table 1. We can say that the accuracy of spectral estimation is significantly improved in the optimized spectral sensitivities.

Conclusion

In this paper, spectral sensitivities of mosaic 5-band camera were designed by using numerical skin phantom for separation of chromophore densities, shading and surface reflection. By using the numerical skin phantom, spectral sensitivities of mosaic 5-band camera were optimized by using nonlinear optimization technique to estimate spectral reflectance accurately at 560nm, 570nm, 590nm, 610nm, 700nm whose wavelengths are known to give a good separation of chromophore densities, shading and surface reflection. The RMSE was 0.036 in the optimized spectral sensitivities. We need to deeply discuss why these sensitivities are selected as optimal solution in our future work.

R	G	Or	G	R
G	Cy	G	B	G
Or	G	R	G	Or
G	B	G	Cy	G
R	G	Or	G	R

(a)Conventional arrangement

V_1	V_3	V_2	V_3	V_1
V_3	V_4	V_3	V_5	V_3
V_2	V_3	V_1	V_3	V_2
V_3	V_5	V_3	V_4	V_3
V_1	V_3	V_2	V_3	V_1

(b)Arrangement used in the optimization of spectral sensitivisies

Figure 2 Sensor array of 5-band camera

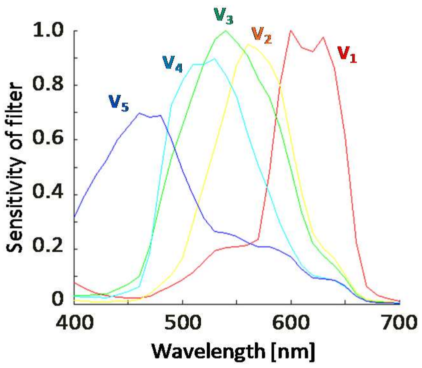


Figure 3 Sensitivites of conventional filters

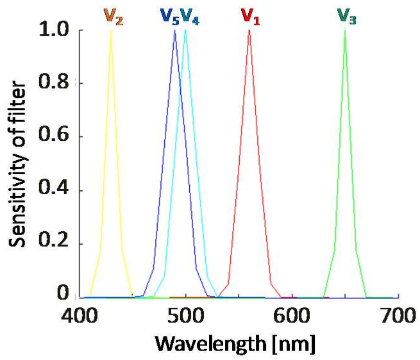
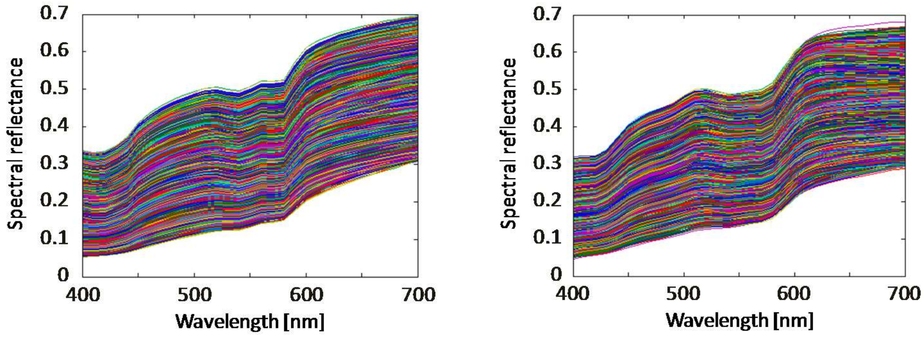


Figure 4 Sensitivities of optimized filters

Table 1 Parameters of optimized spectral sensitivities

Filter	V_1	V_2	V_3	V_4	V_5
Standard deviation	8	5	5	9	10
Average value [nm]	560	433	648	501	488
RMSE	0.036				



(a) Original values (b) Estimated values

Figure 5 Spectral reflectance in the numerical phantom

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