Quantitative Analysis of Skin Pigmentation in a Nonlinear Density Space

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Abstract

In this paper, we propose a method for a quantitative analysis of melanin and hemoglobin pigments from the skin color images. In the previous paper, we proposed a method to extract the values of melanin and hemoglobin components assuming a modified Lambert-Beer law in a linear density space. However, these extracted components are not quantitative values, since the modified Lambert-Beer law is based on the strong approximation of optical scattering process. In the proposed method for the quantitative analysis, the optical scattering process is well approximated in a nonlinear density space. The skin colors are on the two dimensional plane in the nonlinear density space, which is spanned by melanin and hemoglobin vectors. It is found that the components for the melanin and hemoglobin vectors are related to density and root of density, respectively. The proposed method was applied to the skin color image of arm irradiated by UV-B, and the results show the effectiveness of the proposed method.

Introduction

Skin color contains information of various skin pigments such as melanin and hemoglobin. Slight changes of the pigments construction in the skin produce a rich variation of skin color. Freckles and suntan are caused by melanin pigments, and the enhancement or suppression of the appearance of blood circulation are caused by hemoglobin pigments. The analysis of skin color has become increasingly important for medical diagnosis, cosmetic evaluation, and so on. We have already proposed a technique[1,2] by which melanin and hemoglobin components are extracted from a skin image using independent component analysis.

In this technique, the diffuse reflectance can be written as Equation (1), assuming the two-layered skin model as shown in Figure 1, and also assuming that a modified Lambert-Beer law is hold in the skin layer f or an incident light.

$$\boldsymbol{R}^{\log}(x,y) = -c_m(x,y)\boldsymbol{\sigma}_m - c_h(x,y)\boldsymbol{\sigma}_h, \tag{1}$$

where

$$\boldsymbol{R}^{\log} = \left[R_r^{\log}, R_g^{\log}, R_b^{\log}\right]^t,$$
$$R_i^{\log} = \log(R_i), \qquad (i = r,g,b),$$
$$\boldsymbol{\sigma}_m = \left[\sigma_m(\lambda_r)l_e(\lambda_r), \sigma_m(\lambda_g)l_e(\lambda_g), \sigma_m(\lambda_b)l_e(\lambda_b)\right]^t,$$
$$\boldsymbol{\sigma}_h = \left[\sigma_h(\lambda_r)l_d(\lambda_r), \sigma_h(\lambda_g)l_d(\lambda_g), \sigma_h(\lambda_b)l_d(\lambda_b)\right]^t,$$

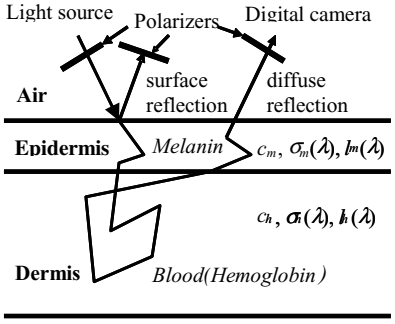


Figure 1. Schematic expression of a two-layered skin model

where λ is the wavelength, R_i is the skin diffuse reflectance, and $c_m(x,y)$, $c_h(x,y)$, $\sigma_m(\lambda)$, $\sigma_h(\lambda)$, $\boldsymbol{\sigma}_m$, $\boldsymbol{\sigma}_h$ are the pigment densities, the spectral absorption cross-sections and the vectors of melanin and hemoglobin, at the position (x,y) on the surface, respectively. The mean path length of photons in the dermis and epidermis layers are denoted by $l_e(\lambda)$ and $l_d(\lambda)$, respectively. Figure 2(a) shows the vectors of melanin and hemoglobin in the linear density space. The skin colors are assumed on the two dimensional plane in the linear density space, which is spanned by melanin and hemoglobin vectors. However, as shown in Figure 3, a result of plotting the skin colors in the linear density space are different from the description in Equation (1), since the modified Lambert-Beer law is the strong approximation of optical scattering process. Therefore, we introduced a bias vector to describe the skin color in the density space as shown in Figure 2(b). However, this addition of bias vector is quite *ad hoc* process in analyzing the skin color, and the extracted value for each component can not be guaranteed to be a quantitative value.

In this paper, we propose a method for the quantitative analysis of melanin and hemoglobin pigmentations from the skin color image. For extracting the quantitative values, we modeled the skin diffuse reflectance by approximating the optical scattering process with high accuracy. By using this model, the skin colors are on the two dimensional plane in the nonlinear density space spanned by only melanin and hemoglobin vectors. Based on the proposed model, we can show the relation between the extracted components and quantitative values. The proposed method was applied to the skin color image of arm irradiated by UV-B to show the effectiveness of the proposed method.

In the next section, we introduce an improved empirical model of skin diffuse spectral reflectance for skin color analysis.[3] The original empirical model was not optimized to model the skin

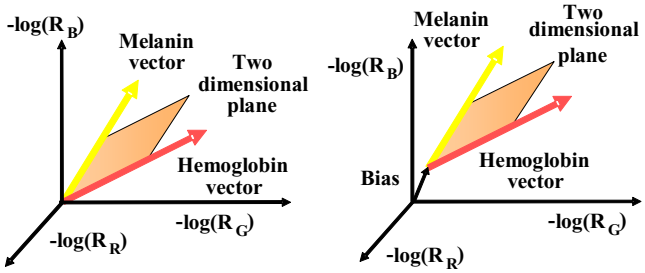
spectral reflectance. Therefore, we used the spectral characterizations of skin in building the improved empirical model. In the third section, we propose a method for the quantitative analysis of melanin and hemoglobin pigments from the skin color images based on the improved empirical model. Finally, the experiments of extracting melanin and hemoglobin components from the skin color images of arm irradiated by UV-B are performed to show the effectiveness of the proposed method.

Empirical Model of Skin Diffuse Reflectance for skin Color Analysis

Original Empirical Model for the Skin Reflectance[3] *(Our Previous Work)*

Figure 4 shows the two layered skin model for Monte Carlo simulation[4] of light transport in the skin, epidermis and dermis layer.[5] The depth of epidermis is set to be 0.07 mm in this paper. The depth of dermis is assumed large enough compared to the depth of epidermis. The reflective index in each layer is set to be 1.4 in this paper. We assumed that the pigment of epidermis is melanin, the pigment of dermis is hemoglobin.

The original empirical model for the skin is constructed based on the simulated data by Monte Carlo simulation of light transport in the skin model, and shown as



(a) Equation (1) (b)Addition of bias vector

Figure 2. Two dimensional plane in the linear density space

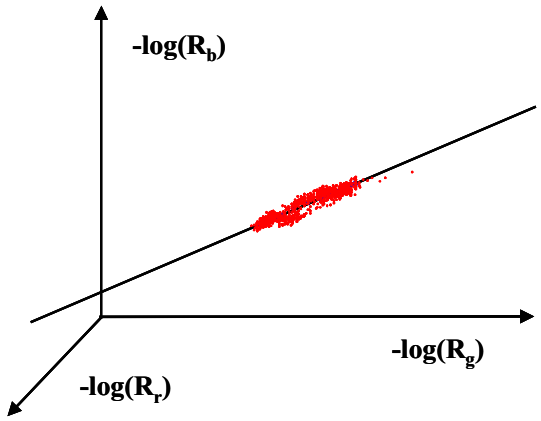


Figure 3. Measured skin color in the linear density space

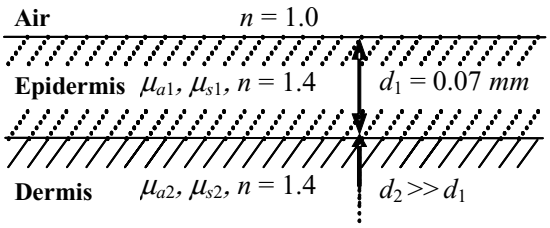


Figure 4. Two-layered skin model for Monte Carlo simulation to build the empirical model

$$\{-\log(R_0)\}^{N(\mu_{s1},\mu_{s2})} = \mu_{a1} l_1(\mu_{s1},\mu_{s2}) + \sqrt{\mu_{a2}}\, l_2(\mu_{s1},\mu_{s2}) - \log(1-R_{sp}), \quad (2)$$

where R_0 is the diffused reflectance of 0 degree angle for incident light, R_{sp} is the specular reflectance for 1.4 refractive index for the above incident light. The absorption coefficients for epidermis and dermis layers are denoted by μ_{a1}, μ_{a2}, scattering coefficients by μ_{s1}, μ_{s2}, respectively. The model parameters N, l_1, l_2 are function of scattering coefficients μ_{s1}, μ_{s2}.

These model parameters are obtained by fitting the model into the samples of reflectance obtained from Monte Carlo simulation of optical scattering. The accuracy of the fitting depends on the range of absorption coefficients where the samples are extracted. If the ranges of the absorption coefficients are narrower and narrower, the accuracy of the fitting for the empirical model is more accurate. However, the obtained model can be used only in that narrow range.

In our previous work, we set the value of absorption cross section at the decided value for every wave length, and define that the melanin density is ranged from 0 to 200 * 10^{-5} mol/L at the interval of 10 * 10^{-5} mol/L, the hemoglobin density is ranged from 0 to 30 * 10^{-5} mol/L at the interval of 5 * 10^{-5} mol/L, respectively. These ranges are wide enough to cover the pigment densities for Japanese normal skin in visible range. Figure 5 shows the skin spectral reflectance in the case of the worst and the best root mean square error (RMSE) for the original empirical model. The averaged RMSE of the skin spectral reflectance was 0.046 (4.6%). In the case of the worst approximation, RMSE of the skin spectral reflectance is 0.131 (13.1%) in Figure 5. It is clear that the original model is not enough to approximate the skin spectral reflectance.

Improved Empirical Model for the Skin Reflectance

The original empirical model may not be optimized to model the skin spectral reflectance. Therefore, we used the spectral characterizations of skin in building the improved empirical model. Figures 6(a) and (b) show the molar absorbance coefficient (extinction coefficient) of melanin and hemoglobin pigments. The scattering coefficient of the skin is illustrated in Figure 7.

The model parameters N, l_1, l_2 in Equation (2) are calculated from the ranges of absorption coefficients and the value of scattering coefficient.

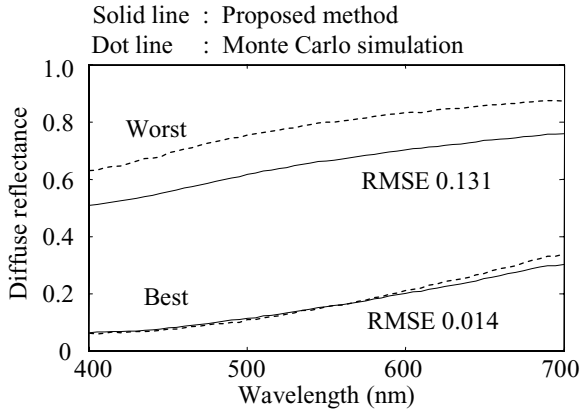
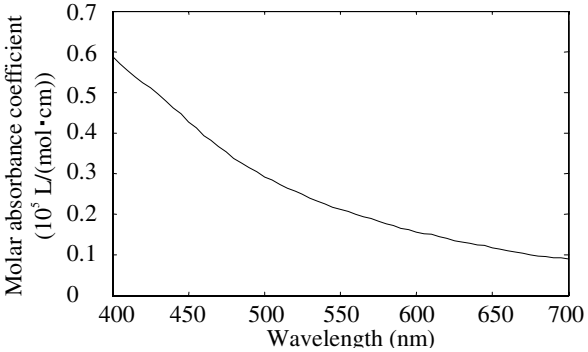
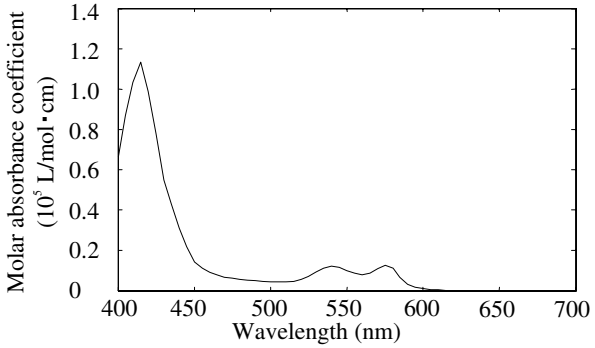


Figure 5. Skin spectral reflectance without considering the spectral characterization of skin



(a) Melanin



(b) Hemoglobin

Figure 6. Molar absorbance coefficient

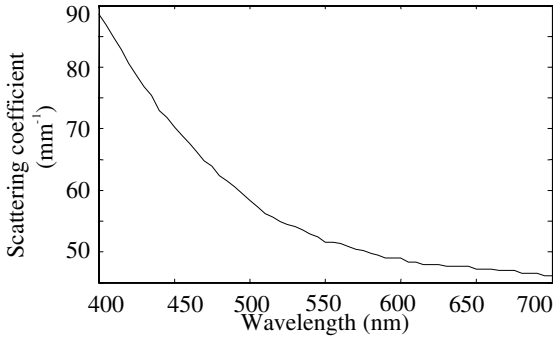


Figure 7. Scattering coefficient of skin

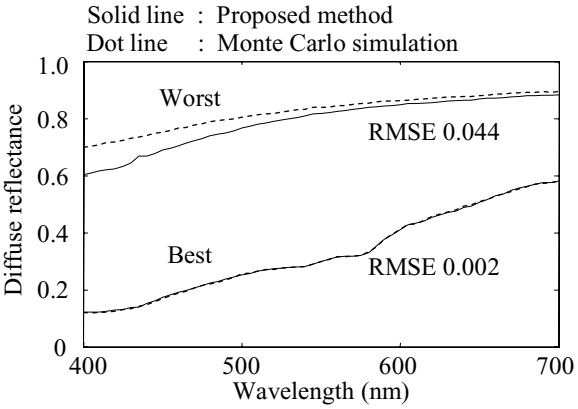


Figure 8. Spectral diffuse reflectance with considering the spectral characterization of skin

The absorption coefficients are calculated by multiplying the molar densities and the molar absorbance coefficients which changes at each wavelength as shown in Figure 6(a) and (b).Therefore, the range of absorption coefficients will change at each wavelength. Figure 7 also shows that scattering coefficient will also change at each wavelength.

In this paper, the diffuse reflectance at each wavelength is approximated by using model parameters with the consideration of the spectral characterization of skin. Figure 8 show the skin spectral reflectance in the case of the worst and the best root mean square error (RMSE) for the empirical model with considering the spectral characterization of skin. The averaged RMSE of the skin spectral reflectance was 0.0079 (0.79%) with considering the spectral characterization of skin. In the case of the worst approximation, RMSE of the skin spectral reflectance is 0.044 (4.4%) in Figure 8. It was found that the diffuse reflectance is well approximated by the improved empirical model with the consideration of spectral characteristic of skin.

Proposed Technique to Extract the Information of Densities

The improved empirical model is used as substitute for modified Lambert-Beer law. A formula for optical scattering process is shown as

$$(\boldsymbol{R}^{\log})^N(x,y) = -c_m(x,y)\boldsymbol{\varepsilon}_m - \sqrt{c_h(x,y)}\boldsymbol{\varepsilon}_h, \tag{3}$$

where

$$(\boldsymbol{R}^{\log})^N = \left[(R_r^{\log})^N, (R_g^{\log})^N, (R_b^{\log})^N\right]^t,$$
$$(R_i^{\log})^N = \{\log(R_i)\}^{N(\lambda_i)}, \qquad (i = r,g,b),$$
$$\boldsymbol{\varepsilon}_m = \left[\varepsilon_m(\lambda_r)l_1(\lambda_r), \varepsilon_m(\lambda_g)l_1(\lambda_g), \varepsilon_m(\lambda_b)l_1(\lambda_b)\right]^t,$$
$$\boldsymbol{\varepsilon}_h = \left[\sqrt{\varepsilon_h(\lambda_r)}l_2(\lambda_r), \sqrt{\varepsilon_h(\lambda_g)}l_2(\lambda_g), \sqrt{\varepsilon_h(\lambda_b)}l_2(\lambda_b)\right]^t.$$

where $c_m(x,y)$, $c_h(x,y)$, $\varepsilon_m(\lambda)$, $\varepsilon_h(\lambda)$ are the molar densities and molar absorbance coefficient for melanin and hemoglobin, respectively. $N(\lambda)$, $l_1(\lambda)$, $l_2(\lambda)$ are the model parameters of the empirical model. The skin surface reflection is removed by polarization filters in front of a camera and light source by using the algorithm proposed by Ojima et al.[6] The skin diffuse reflectance R_i of the wavelength i is defined that R_i=1 when there are not melanin and hemoglobin pigments in the skin. Figure 9 shows vectors of melanin and hemoglobin and a two dimensional plane which passes through an origin of the nonlinear density space. It is noted that the bias vector is not necessary in the proposed method.

Figure 10 shows the result of plotting the skin color in a nonlinear density space. The axes of the nonlinear density space are constructed by the Nth power of each axis of the linear density plane. The values N_i (i = r,g,b) are the model parameter $N(\lambda_i)$ of the empirical model, and different values at each axis.

The observed signals $(\boldsymbol{R}^{\log})^N$ can be represented by the weighted linear combination of the two vectors $\boldsymbol{\varepsilon}_m$, $\boldsymbol{\varepsilon}_h$. We can apply the independent component analysis to the two dimensional plane spanned by the melanin and hemoglobin vectors $\boldsymbol{\varepsilon}_m$, $\boldsymbol{\varepsilon}_h$. It is noted the components of melanin and hemoglobin vectors are related to density and root of density, respectively.

Experiment

We perform the experiment for extracting the quantitative values for melanin and hemoglobin components from the skin color image. The arm of a subject is irradiated by UV-B for melanin and hemoglobin components. An image of the arm, where UV-B was irradiated in local rectangular areas, was taken after one day and two weeks with a digital camera as shown in Figure 11(a) and (b), respectively. Figure 11(c) and (d) show the density scale bars and the density images for the melanin component. On the other hand, Figure 11(e) and (f) show the density scale bars and the density images for the hemoglobin component. Figure 11(c) and (e) are extracted from Figure 11(a), Figure 11(d) and (f) are extracted from Figure 11(b), respectively. The color of the density scale bars is expected to correspond with the quantitative value of densities. Since there is no any other instrument for measuring the quantitative value of pigmentation in the skin, we can not evaluate the accuracy of the extracted quantitative value. However, the obtained result for extracted quantitative value is valid from the physiological point of view.

Conclusion and Discussion

We proposed a method for the quantitative analysis of melanin and hemoglobin pigmentations extracted from the skin color images. Using the improved empirical model for skin diffuse reflectance for skin color analysis, by using the proposed method, it could extract the quantitative value of densities for melanin and hemoglobin components. This paper also proposed a technique that the skin spectral reflectance is approximated by the empirical model.

By using the proposed quantitative analysis, we are expecting that the quantitative value of melanin and hemoglobin densities are obtained on the two dimensional plane without using the bias vector.

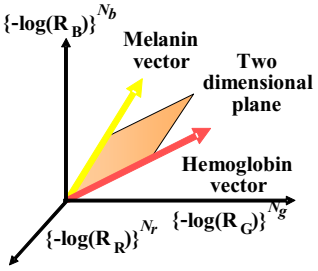


Figure 9. Two dimensional plane in the nonlinear density space

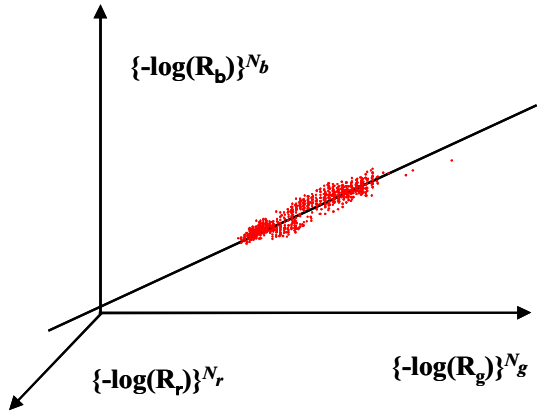


Figure 10. Measured skin color in the nonlinear density space

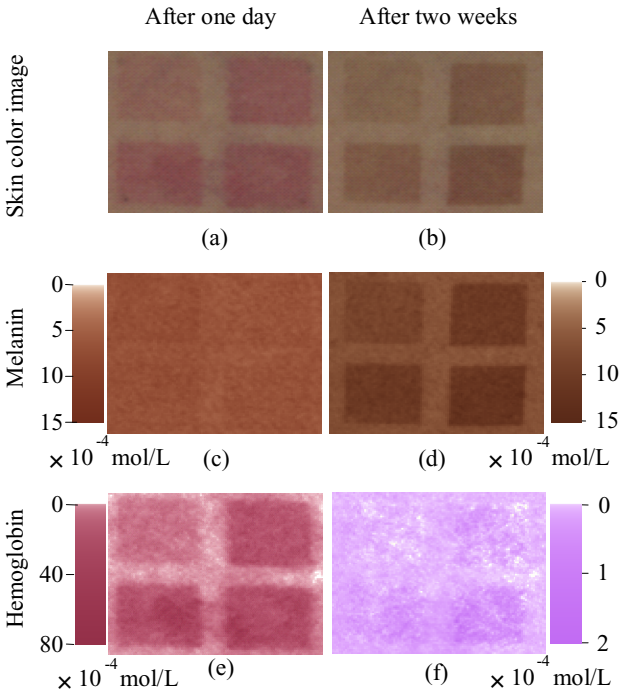


Figure 11. Skin color images and density images of melanin and hemoglobin components

The proposed quantitative analysis was evaluated by the density images of melanin and hemoglobin components which are extracted from skin color image of arm irradiated by UV-B, and the extracted results show the effectiveness of the proposed method. However, the extracted quantitative values are not evaluated by other instruments. Therefore, it is necessary to make the optical phantom of skin, and analyzed the captured image for the optical phantom to evaluate the accuracy of the quantitative analysis.

In the practical application, shading on the skin from directional light leads to an incorrect estimation for the density of components on the shaded area. The technique for shading removal has been already proposed in the previous paper.[2] However, this previously proposed technique can not be applied to analysis of shading removal in the nonlinear density space. In our future works, it is necessary to consider the technique for shading removal in the nonlinear density to be applied in the practical application.

Acknowledgement

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Author Biography

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