Regression-Based Model of Skin Diffuse Reflectance for Skin Color Analysis

Norimichi Tsumura[1], Daisuke Kawazoe[1], Toshiya Nakaguchi[1], Nobutoshi Ojima[1, 2], and Yoichi Miyake[1]

[1]Department of Information and Image Sciences, Chiba University,
1-33 Yayoi-cho, Inage-ku, Chiba 263-8522. Japan

[2]Kao Corporation ,
2-1-3 Bunka, Sumida-ku, Tokyo 131-8501 Japan

Abstract

A simple regression-based model of skin diffuse reflectance is developed based on reflectance samples calculated by Monte Carlo simulation of light transport in a two-layered skin model. This reflectance model includes the values of spectral reflectance in the visible spectra for Japanese women. The modified Lambert Beer law holds in the proposed model with a modified mean free path length in non-linear density space. The averaged RMS and maximum errors of the proposed model were 1.1 and 3.1%, respectively, in the above range.

Keywords: skin reflectance, regression, modified Lambert Beer law

In cosmetology and dermatology, analysis of human skin color is an important parameter for evaluating the current condition of the skin. Skin color is influenced by a variety of factors, including blood flow, melanin, optical scattering and, skin surface lipids. However, it is mainly determined by melanin in the epidermal layer and hemoglobin in the dermal layer. Skin color can therefore be approximated using a two-layered skin model, which is the fundamental model used in skin color analysis[1, 2].

We earlier proposed a technique for estimating the spatial distribution of melanin, hemoglobin and oxygen saturation from skin spectral reflectance images[1]. The two-layered skin model was used in that analysis and an inverse optical scattering technique was applied to the Monte Carlo simulation of photon migration[3] in the skin model. Quantitative analysis is possible for extracted pigmentation provided the optical parameters in the skin model such as the skin depth and scattering coefficient are accurately modeled for real skin. The earlier work of Lihong Wang and Steven L. Jacques produced an excellent standard C-code for Monte Carlo simulation of light transport in multi-layered tissue (MCML)[3], and we used this simulation in the previous paper, and also in this paper. The MCML program is constituted by the following operations for photons.(1) Photon launching,(2) Generating the propagation distance,(3) Moving the photon,(4) Internal reflection,(5) Photon absorption, (6) Changing photon direction by scattering, (7) Calculating observable quantities, many of these Monte Carlo simulations give the simulated diffuse reflectance. This forward model is iteratively used in the inverse optical scattering techniques to obtain the skin quantitative values of pigmentation from the measured diffuse reflectance. However, the analysis requires either a great deal of computation time to perform the inverse optical scattering

calculation or a huge memory to store pre-computed look-up tables. We have also proposed a technique for extracting melanin and hemoglobin components that is based on linear color space analysis for logarithmic values (optical densities) of skin color images[2, 4]. The spatial distributions of melanin and hemoglobin in human skin are separated by independent component analysis of skin color image. The analysis is based on the skin color model with assumptions, (1) spatial variation of color in the skin is caused by two pigments; melanin and hemoglobin, (2) their quantities are mutually independent spatially, (3) the linearity holds among the quantities and observed color signals in the optical density domain. The results of the separation agree well with the physiological knowledge. We have implemented a real-time processing system for separating the pigmentations using the basis vectors[5], since the analysis is a simple matrix-vector operation. However, the relationship between the extracted components and quantitative values was not clarified in that analysis, so that quantitative analysis could not be performed.

In this paper, we develop a simple regression-based model of skin diffuse reflectance based on reflectance samples calculated by Monte Carlo simulation of light transport in the two-layered skin model. This model can be used to improve linear color space analysis for quantitative measurement of skin pigmentations, and can also be used to reduce the computation time of the inverse optical scattering process calculation.

Firstly, a skin reflectance model is developed for a single-layered skin model. In this paper, the depth of the layer is assumed large enough to ignore the transmittance in the single-layered skin model. The analytical solution[6] for diffusion reflectance R_d in the diffusion equation is

$$R_d = \frac{1}{2}\exp\left(-\sqrt{\frac{3\mu_a}{\mu_a+\mu_s'}}\right)\left\{1+\exp\left(-4A\sqrt{\frac{\mu_a}{3(\mu_a+\mu')}}\right)\right\}, \quad (1)$$

where μ_a and μ_s' are the absorption and reduced scattering coefficients respectively, and A is the constant value calculated from the refractive index of media. On the other hand, the proposed regression-based model for the single-layered skin model was empirically written as

$$\{-\log_{10}(R_d)\}^{2.38} = \mu_a \frac{2.79}{\mu_s'}. \quad (2)$$

In developing this model, Monte Carlo simulation of photon migration was performed to obtain samples for multiple regression analysis. The reduced scattering coefficient μ_s' ranged from 20 to 100 cm^{-1} in the simulation; this is within the range of values for human skin in the visible region[7]. The absorption coefficient ranged from 0.9 to 7 cm^{-1}. This range was selected so as to cover the range of values for the spectral reflectance in the visible region for Japanese women[8], which is from 0.11 to 0.61. The anisotropy factor was set to 0.8, so that scattering coefficient μ_s for the simulation is calculated from the reduced scattering coefficient μ_s. The refractive index was set to 1.4 in the simulation. Figure 1 shows the difference between the reflectance obtained by the Monte Carlo simulation and the reflectance calculated from eq. (2). It demonstrates that the proposed model can approximate the diffuse reflectance obtained by the Monte Carlo simulation with an average accuracy of 0.0025 (0.25%) in the selected range. We propose that this model can be used as the Lambert Beer law in the non-linear space for optical density.

For example, the two-components model can be analyzed by performing a linear calculation in 2.38 power of optical density $\{-\log_{10}(R_d)\}^{2.38}$ as follows:

$$\{-\log_{10}(R_d)\}^{2.38} = (\mu_{a1} + \mu_{a2})l^*, \tag{3}$$

where μ_{a1} and μ_{a2} are the absorption coefficients for each component respectively and l^* is the modified mean free path length in the non-linear space which is written as

$$l^* = \frac{2.79}{\mu_s'}. \tag{4}$$

This property of eq. (3) in non-linear space is essential for applying color vector analysis to the spectral reflectance as was done in linear space in previous work[2, 4].

Figure 2 shows the two-layered model of skin that was used in this paper. An epidermis depth of 0.007 cm was used[1]. The analytical solution for diffusion reflectance in the diffusion equation is very complicated[9] and cannot be used in the skin color analysis in the color vector space[2, 4]. However, the proposed regression-based model for two-layered skin model is

$$\{-\log(R_d)\}^{N(\mu_{s1}',\mu_{s2}')} = \mu_{a1} l_1(\mu_{s1}', \mu_{s2}') + \sqrt{\mu_{a2}}\, l_2(\mu_{s1}', \mu_{s2}'), \tag{5}$$

where the absorption coefficients for epidermis and dermis layers are denoted by μ_{a1}, μ_{a2}, and reduced scattering coefficients by μ_{s1}', μ_{s2}', respectively. The samples for regression were arranged as follows. The reduced scattering coefficient in both layers ranged from 20 to 100 cm^{-1}, the same values that were used for deriving eq. (2). The absorption coefficient ranged from 5 to 100 cm^{-1} in the epidermis layer and from 0.3 to 100 cm^{-1} in the dermis layer. This range was selected to cover the range of values in the visible region for Japanese women[10]. The anisotropy factor was set to 0.8 and the

refractive index was 1.4 in the simulation. The model parameters of the skin were determined using 100,000 weighted photons in the Monte Carlo simulation for each reduced scattering coefficient. The number of simulated spectral diffuse reflectances were 16,200, and calculated in 36 hours. Figures 3(a)-3 (c) show the values of the model parameters N , l_1 and l_2 respectively as a function of the reduced scattering coefficients μ'_{s1}, μ'_{s2} . Figures 3(a) and 3(c) show that N and l_2 are affected by both reduced scattering coefficients. Figure 3(b) shows that the model parameter l_1 is slightly affected by reduced scattering coefficient in the dermis layer. Figures 4(a) and 4(b) show the root mean square (RMS) error and the maximum error of the proposed model for each scattering coefficient respectively. These figures show that the diffuse reflectance is approximately less than 0.016 (1.6%) of the root mean square error and the maximum error demonstrates that the proposed model can approximate the diffuse reflectance robustly in the selected range for skin color analysis. Equation (5) shows that the modified Lambert Beer law holds for μ_{a1} and $\sqrt{\mu_{a2}}$ with modified mean free path length l_1, l_2 in the non-linear density space which is spanned by the N-*th* power of density. It is noted that this holds for $\sqrt{\mu_{a2}}$ in the dermis layer. These properties in non-linear space are essential for applying the color vector analysis to the spectral reflectance as was done in linear space in previous work[2, 4]. The square root of μ_{a2} is empirically assigned in the process of multiple regression, since it is seen that the second layer acts as like the layer in the signal layer model with the value of 2.38 in eq. (2). We can conclude that the proposed model gives quantitative values for the absorption coefficients based on the skin color space analysis with known reduced scattering coefficients in the layer.

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Figure Captions

Figure 1. Difference between the reflectance for the Monte Carlo simulation and reflectance obtained from the proposed single-layer reflectance model.

Figure 2. Two-layered model of skin that was used to simulate the samples for regression analysis.

Figure 3. Values of model parameters (a) N, (b) l_1, and (c) l_2 as a function of the reduced scattering coefficients μ_{s1}', μ_{s2}'.

Figure 4. Accuracy of the proposed reflectance model: (a) root mean square error and (b) maximum error of the proposed model for each scattering coefficient.

“Color Print”

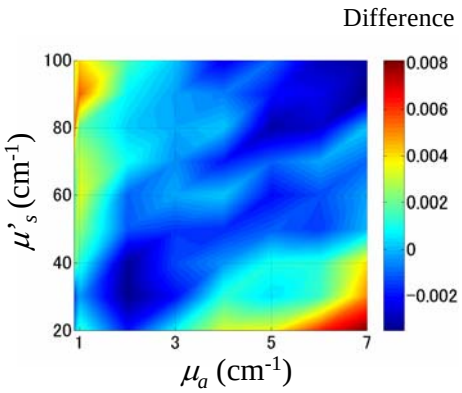

Fig. 1.

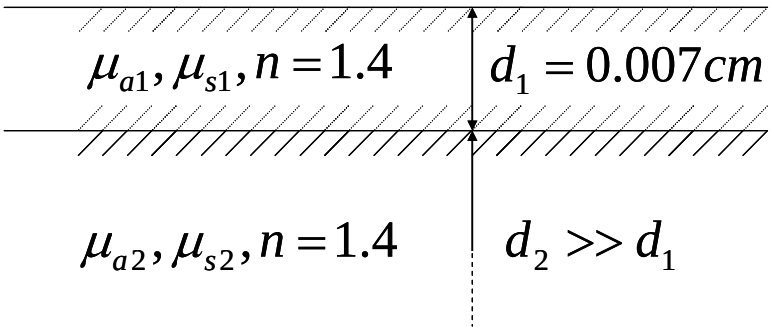

Fig. 2.

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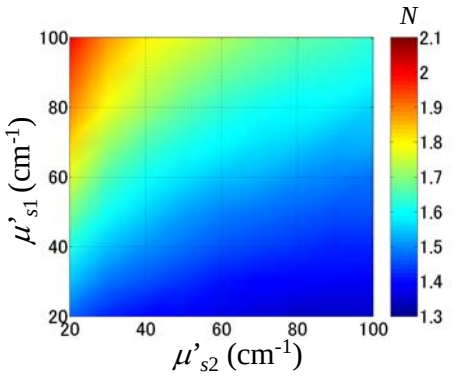
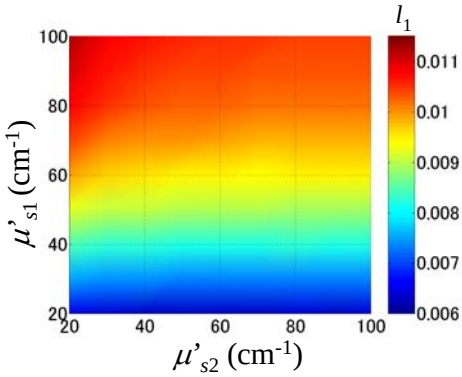
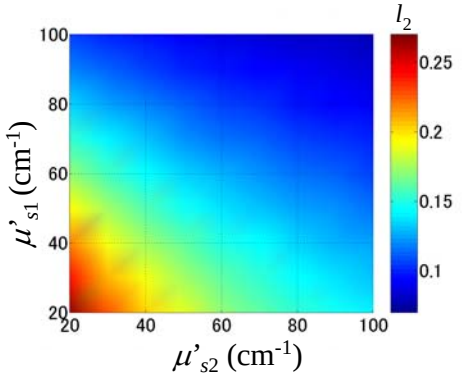


(a) values of model parameter N



(b) values of model parameter l_1



(c) values of model parameter l_2

Fig. 3.

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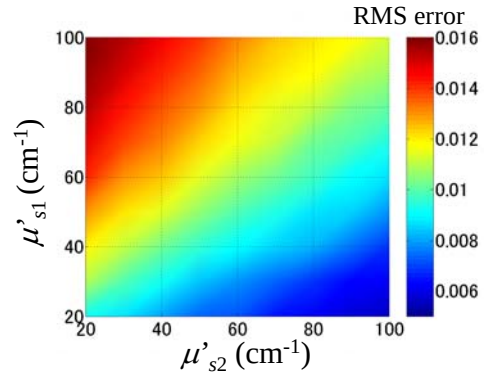
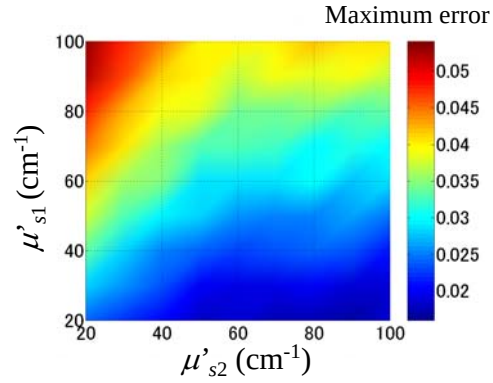


(a) root mean square error (RMS error)



(b) maximum error

Fig. 4..