Application of image-based skin chromophore analysis to cosmetics

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Abstract

The spatial distributions of melanin and hemoglobin in human skin can be determined by image-based skin chromophore analysis including independent component analysis (ICA) of a skin color image. The separation is based on the skin color model in the optical density domain to quantify the change in the chromophores. In this paper, the analysis technique developed by Tsumura et al. was applied to many skin images, and the distribution of skin chromophores, such as melanin and hemoglobin, agreed well with the physiological knowledge. The effectiveness of cosmetic products was also evaluated by observing the changes in the amount of each chromophore. Finally a simulation to synthesize the changes in skin chromophores was performed to demonstrate its validity.

Keywords

skin color image, independent component analysis, melanin, hemoglobin, cosmetics

1. Introduction

With the recent progress of various imaging systems such as multi-media, computer graphics and telemedicine systems, skin color has become increasingly important for communication, image reproduction on hardcopy and softcopy, medical diagnosis and so on[1-4]. In the cosmetics industry[5-7] also, skin color is very important because skin color

shows not only facial impression but also body and skin conditions. For this reason, in order to develop and provide cosmetics which suit skin conditions for each person, skin diagnosis and the evaluation of efficacy of skin care products have been very important. However, in case of skin tone lightening essence, which limits the production of melanin chromophore, it was very difficult to evaluate the effectiveness for each chromophore only by colorimetric values, because the values contain information of various skin chromophores such as melanin and hemoglobin at the same time. Therefore it is necessary to extract the information of each skin chromophore independently as density information, especially 2-dimensional density distribution.

Techniques to separate melanin and hemoglobin chromophores are being developed currently. Shimada[8] and Nakai[9] estimated chromophore density from spectral reflectance of skin. Image processing techniques to estimate distribution of melanin, oxy-hemoglobin and dioxy-hemoglobin are also being developed using inverse Monte Carlo simulation by Okuyama et al. [10]. However, since these techniques need absolute reflectance, specific lighting conditions, such as diffused lighting with integrated sphere or spatio-temporal modulation of lighting, are required.

Tsumura et al. [11] proposed a technique in which hemoglobin and melanin chromophores are extracted from a single skin color image using independent component analysis (ICA[12-15]) without special geometrical lighting conditions. The technique proposes a model to remove shading by a simple inverse lighting technique. Skin color distribution without shading is searched for from the entire face, and the shading factor is removed by projecting the observed color onto a skin color distribution plane. Since the technique allows us to use various geometric lighting conditions, it has the capacity to expand the scope of applications to other fields such as telemedicine under various illuminations, skin-care check at cosmetic shops, facial image processing on TV commercials.

In this paper, we apply image-based skin chromophore analysis to cosmetics. The

validity of this method for cosmetics was examined and given an explanation from several points of view of skin diagnosis and usefulness in evaluating the efficacy of cosmetic products. The beginning of the experiments in this paper was already introduced in the paper by Tsumura et al. [11]; however, in this paper we will show the experiment on the above aspects of cosmetics mentioned above. At first, skin of artificially generated chromophores was captured and analyzed by the Tsumura technique to confirm the physiological validity. Secondly, it was applied to actual facial skin color images to diagnose the skin condition, such as acnes. Thirdly, the efficacy of cosmetic products, especially lightening essence, was evaluated by the technique. The relative amount of melanin reduction by the lightening product was calculated, and was compared with the result of a placebo sample. Finally, with the reference of the actual change in each chromophore density by the lightening product, a woman's facial skin images were synthesized in various density of melanin or hemoglobin chromophore.

The schematic flow in the image-based skin color analysis is shown in Figure 1. The original photo was separated into the images of surface and body reflection [16] by using polarized light[17]. The body reflection image was analyzed by the ICA technique to isolate both melanin and hemoglobin component images. By using these images, the relative density of each chromophore component was measured.

2. Modeling of skin color for ICA

In this session, we outline the technique proposed by Tsumura et al.[11]. Modeling of skin color for independent component analysis (ICA) and shading removal technique by a simple inverse lighting technique are outlined step by step.

ICA is a technique that extracts the original signals from mixtures of many independent sources without *a priori* information on the sources and the process of the mixture.

Observed vector ***v***(x,y), whose elements are not mutually independent, is shown as follows:

$$\boldsymbol{v}(x,y) = \mathbf{A}\,\boldsymbol{s}(x,y) \qquad (1)$$

where ***s***(x,y) is the source signal vector, and **A** is a *2*x*2* mixing matrix. By applying the ICA to the observed vector, the relative source signals are extracted without ***a priori*** information on these items, by assuming that original source signals are mutually independent. In performing ICA, the following equation was defined by using a separating matrix **H** and an extracted independent vector ***e***(x,y) as follows;

$$\boldsymbol{e}(x,y) = \mathbf{H}\,\boldsymbol{v}(x,y) \qquad (2)$$

Many methods for finding the separation matrix ***H*** have been proposed. In this paper, optimization techniques based on the fixed-point method [I-L] are used to find the separation matrix ***H***. Tsumura et al. described the details of the theory [18].

A two-layered skin model is used in the imaging process shown in Figure 2. Part of the incident light is reflected on the surface as a Fresnel reflection, and other parts penetrate into the epidermis layer and dermis layers and are diffusely reflected from the surface. The body reflection can be written as Equation (3), assuming that the modified Lambert-Beer law is applicable in the skin layer for incident light. The modified Lambert-Beer law is assumed in Equation (3):

$$L(x,y,l) = \exp\{-r_m(x,y)s_m(l)l_e(l) - r_h(x,y)s_h(l)l_d(l)\}E(x,y,l) \qquad (3)$$

where l is the wavelength, $E(x, y, l)$ and $L(x, y, l)$ are the spectral irradiance and spectral radiance to imaging devices, respectively, at the position (x, y) on the surface, and $r_m(x, y)$, $r_h(x, y)$, $s_m(l)$, $s_h(l)$ are the pigment densities and spectral cross-sections of melanin and hemoglobin, respectively. For the modified Lambert-Beer law [19], $l_e(l)$ and $l_d(l)$ are the mean path lengths of photons in the dermis and epidermis layers, respectively. The surface reflection is removed by polarization filters in front of both the camera and the light source by using the algorithm proposed by Ojima et al.[17]. Sensor response $v_i \quad (i = R, G, B)$ from the digital camera can be obtained as follows.

$$v_i(x, y) = c\int L(x, y, l)s_i(l)dl \qquad (4)$$

$$= c\int \exp\{-r_m(x, y)s_m(l)l_e(l) - r_h(x, y)s_h(l)l_d(l)\}E(x, y, l)s_i(l)dl,$$

where $s_i(l) \quad (i = R, G, B)$ is the spectral sensitivity of the digital camera, and c is a constant value determined from the gain of the camera. If we assume the spectral sensitivity is a narrow band and can be approximated by the delta function [20] as $s_i(l) = d(l - l_i)$, and if we assume that the skin is illuminated by a single color of illuminant, the spectral radiance of illuminant is separable as $E(x, y, l) = p(x, y)\bar{E}(l)$, and we can obtain the following equation from Equation (4):

$$v_i(x, y) = c\exp\{-r_m(x, y)s_m(l_i)l_e(l_i) - r_h(x, y)s_h(l_i)l_d(l_i)\}p(x, y)\bar{E}(l_i) \qquad (5)$$

If we take the logarithm of Equation (5), we obtain the following equation by vector and matrix formulation:

$$\boldsymbol{v}^{\log}(x,y) = -r_m(x,y)\boldsymbol{s}_m - r_h(x,y)\boldsymbol{s}_h + p^{\log}(x,y)\boldsymbol{1} + \boldsymbol{e}^{\log}, \quad (6)$$

where,

$$\mathbf{v}^{\log} = \left[\log(v_R(x,y)), \log(v_G(x,y)), \log(v_B(x,y))\right]^t,$$

$$\boldsymbol{s}_m = \left[s_m(l_R)l_e(l_R), s_m(l_G)l_e(l_G), s_m(l_B)l_e(l_B)\right]^t,$$

$$\boldsymbol{s}_h = \left[s_h(l_R)l_d(l_R), s_h(l_G)l_d(l_G), s_h(l_B)l_d(l_B)\right]^t,$$

$$\boldsymbol{1} = [1,1,1]^t,$$

$$\boldsymbol{e}^{\log} = \left[\log(E(l_R)), \log(E(l_G)), \log(E(l_B))\right]^t,$$

$$p^{\log}(x,y) = \log(p(x,y)) + \log(c),$$

Therefore, the observed signals $v^{\log}$ can be represented by the weighted linear combination of the three vectors $s_m, s_h, 1$ with the bias vector $e^{\log}$, as shown in Figure 3.

In practical application, shading on the face is caused by directional light, and this results in a wrong estimate for the density of pigment on the shaded area. Since the skin texture of color is homogeneous in the local area, the strength of shading is added to each value of skin color in 3D configuration. In order to remove shading, it is necessary to find the appropriate 2D skin color plane spanned by the absorbance vectors s_m, s_h and to decompose the observed skin color vector from shading directed to the vector $\boldsymbol{1}$. The appropriate 2D skin plane is obtained by principal component analysis (PCA) in the range of flat portion of skin. Since the strength of shading is directed to the vector 1 for any device and illuminant, the observed skin color vector $\boldsymbol{v}^{log}$(x,y) can be decomposed by

projecting it onto 2D skin plane along the vector $\mathbf{1}$ (Fig.4). The projected skin color vector $\mathbf{v}^{\log}_{projection}$ is obtained as follows;

$$\mathbf{v}^{\log} = [\mathbf{s}_m \quad \mathbf{s}_h \quad \mathbf{1}] \left[-r_m, -r_h, p^{\log}\right]^t + \mathbf{e}^{\log} \qquad (7)$$

Rewriting, we arrive at:,

$$\left[-r_m, -r_h, p^{\log}\right]^t = [\mathbf{s}_m \quad \mathbf{s}_h \quad \mathbf{1}]^{-1}(\mathbf{v}^{\log} - \mathbf{e}^{\log})$$

The bias vector $\boldsymbol{e}^{\log}$ is unknown. Therefore, if we assume that the smallest value of each pigment in the skin image is zero, then $\boldsymbol{e}^{\log}$ is calculated by $e_i^{\log} = \min_{x,y}(v_i^{\log}(x,y))$ for each band of color. Based on the above decomposition, the shading term $p^{\log}\mathbf{1}$ is removed as follows:

$$\mathbf{v}^{\log}_{projection} = [\mathbf{s}_m \quad \mathbf{s}_h \quad \mathbf{0}][\mathbf{s}_m \quad \mathbf{s}_h \quad \mathbf{1}]^{-1}(\mathbf{v}^{\log} - \mathbf{e}^{\log}) + \mathbf{e}^{\log}. \qquad (8)$$

The components (Fig.5 (d), (e)) extracted with the shading removal technique are compared with the components without the shading removal (Fig.5 (b),(c)). Shading caused by the shape of the nose was removed in Fig.5 (d), (e).

3. Experimental results

3.1 Analysis of artificially generated chromophores

In order to confirm the physiological validity of the image-based skin chromophore technique, two practical experiments were performed on 4 volunteers: One was ultra violet

B (UV-B) irradiation on the arms of volunteers to identify the melanin component. The other was the application of methyl nicotinate, which is known to increase blood circulation, to the other arms for the hemoglobin component. A typical example of a volunteer has already been introduced [11], but we show the results of 4 volunteers to confirm the validity and the repeatability of the technique.

A typical example is shown below. An image of the arm, where UV-B (1.5 Minimum Erythema Dose) was irradiated in local rectangular areas, was taken after two weeks by a digital camera (Nikon D1, 2,000 by 1,312 pixels). An image of the arm, where methyl nicotinate (1mg/ml solution) was applied in a local round area, was also taken by a digital camera 30 minutes after application. These images were analyzed by the proposed method. Figures 6(a), (b), and (c) show the original skin image and the images of the densities for the melanin and hemoglobin components, respectively. On the other hand, Figures 6(d), (e), and (f) show the original skin image for methyl nicotinate and the images of the densities for the melanin and hemoglobin components, respectively. Figure 6(b) shows the square patterns caused the by melanin component, but the patterns did not appear in the hemoglobin component in Figure 6(c). Figure 6(f) also shows the round patterns, which indicate the biological response of hemoglobin to methyl nicotinate, but there was not any response in the melanin component in Figure 6(e). These practical experiments were performed on 4 Japanese volunteers (males) to confirm the repeatability. Though their arms are different in shape and skin color, it was found in common that the shading of each chromophore component image was reduced and that physiological feedback of each chromophore against UV-B irradiation or application of methyl nicotinate was the same as a typical example (Figure 6). We can also indirectly conclude that the approximation for the imaging model in Section 2 is also valid in our applications.

Additionally, the difference of melanin density at the two regions indicated as no.1 and no. 2 in Figure 7(a), which are corresponding to the area of with and without UV-B irradiation, was compared with the colorimetric values (CIE 1976L*a*b*). It was indicated

that an increase of only melanin had a strong effect on the decrease of L* and some effect on the increase of a*, b* (Figure 7(c)). For this reason, L* was historically used as an indicator for degree of skin tanning in the cosmetic field. However, since a change in hemoglobin density also has an effect on the change of L*, it is not good enough to quantify the change in melanin density only. We introduce the result measuring the change of melanin density by using the proposed analyzing technique in later session (3.3).

3.2 Analysis of facial skin

The proposed analysis was applied to actual facial images. The first example is a skin congested with blood (Figure 8). The congestion of blood appeared clearly in the hemoglobin component (Figure 8(b)) by separating melanin pigmentation around pores shown in the melanin component image (Figure 8(a)).

As another example, an image of facial skin with acnes was taken and analyzed (Figure 9). Both square and circular area in Figure 9 indicate acnes. In the original image (Figure 9(a)), both acnes are similar to each other. The extracted hemoglobin component image (Figure 9(c)) shows there were rashes in both areas, but only melanin pigmentation was in the square area (Figure 9(b)). In consequence, the acne in the square area was found to be an acne scar. This result shows that two acnes which are similar in the original image can be identified by comparing the chromophore component, especially the melanin component in this case.

As described above, it was found that the proposed analysis showed the skin condition clearly and identified the condition. The analysis is expected to be useful for diagnosis in the fields of cosmetics, dermatology, telemedicine and others.

3.3 Evaluating efficacy of cosmetic products

In order to evaluate the effectiveness of cosmetic products such as lightening essence, facial skin color images of 39 female subjects were captured periodically and analyzed. A cosmetic product, which is useful for lightening skin color, was applied to their faces everyday for 9 weeks. Subjects were separated into 2 groups. One was a sample group and the other was a placebo group, and each group used a sample with or without lightening essence, respectively. Figure 10 shows the change in melanin densities from the beginning (0 week). It was confirmed that the average change of the sample group (19 females) decreased more and faster than that of the placebo group (10 females). The change in melanin density decreased during the 9 weeks, down to about minus 0.1.

3.4 Skin color synthesis

In order to understand and experience the changes of each chromophore component, we made a simulator to synthesize the various facial skin color images by changing the extracted chromophore components. A simulation was performed by reversing the analyzing process shown in Figure 1. As examples, synthesized images of a woman's face were made by uniformly decreasing and increasing the hemoglobin and melanin components, shown in Figure 11. The center image is of the original skin color. Each column of images indicates the decrease and increase of the amount of hemoglobin. From left to right, the amount of hemoglobin is decreased or increased by $-0.2, 0.0, 0.2$. These values are relative values since the absorbance vector is normalized in the process. Each row of the images indicates the decrease and increase of the amount of melanin. From left to right, the amount of melanin is decreased or increased by $-0.2, 0.0, 0.2$. The step of variation in melanin densities are set at the maximum of measured density, that is triple the average amount measured after 9 weeks (section 3.3). Since the amount can be easily changed with a graphical user interface (GUI) with our simulation system, we can see

realistic changes of facial color in real time. Though physiological feedback data from the application of a lightening essence was used for simulation, it will be necessary to collect various data of physiological feedback from external and internal stimuli.

4. Conclusions

The practical image-based skin color analysis technique worked very well to separate skin chromophore components from a facial skin image.

The physiological validity of the technique was confirmed by analyzing skin of artificially generated melanin or hemoglobin.

It was indicated that the chromophore component images were very useful to classify skin conditions, such as acnes which seem to be similar to the original images. There are several skin conditions in which the main cause of skin color pattern are very difficult to determine, such as dark circles around the eyes. The image-based skin color analysis technique will be very useful, because it extracts melanin, hemoglobin and shading information at the same time.

The effectiveness of a cosmetic product was quantitatively evaluated by observing the changes in the amount of extracted melanin chromophores. A woman's facial image was simulated by using the measured physiological feedback of melanin. In order to achieve sufficient physiological simulations, we have to collect much more physiological feedback data.

However, physiological reality is more complex in the skin [21]. Hemoglobin has two types of state: oxy-hemoglobin and dioxy-hemoglobin. The spectral absorbance is different for each, and the ratio between them will change spatially on a large area of skin image or in an area of skin disease. It is also known that there are at least two common varieties of melanin. There are also other pigments in the skin. These will cause errors in the analysis of skin images by the proposed technique.

Further research should be conducted to clarify the limitation and robustness of the techniques.

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Figure 1. Schematic flow of imaging process in the image-based skin color analysis.

Figure 2. Schematic expression of a two-layered skin model.

Figure 3. Schematic expression of skin color distribution in the optical density domain of three channels.

Figure 4. Projection onto the skin color plane to remove shading.

Figure 5. The result of independent component analysis with and without shading .

Figure 6. Analysis of chromophore patterns generated by artificial treatments. UV-B irradiation:(a)original, (b)melanin component, (c)hemoglobin component. Application of methyl nicotinate: (d)original, (e)melanin component, (f)hemoglobin component.

Figure 7. Changes of relative chromophores density in accordance with UV-B irradiation. (a) Analyzed two regions of a forearm with and with out irradiation of UV-B (no.1 , no.2 respectively). (b) Deference of chromophores density between two regions. (c) Deference of colorimetric values in CIEL*a*b* between two regions.

Figure 8. Analysis of blood congestion on actual facial skin. (a)original image, (b)melanin component, (c)hemoglobin component.

Figure 9. Analysis of acnes on actual facial skin. (a)original image, (b)melanin component, (c)hemoglobin component.

Figure 10. Relative changes in melanin density during the 9 weeks the lightening essence was applied. Dotted line: placebo group, Solid line: sample group

Figure 11. Skin color synthesis with changes in melanin and hemoglobin densities (color images).