Evaluating a Multi-Spectral Imaging System for Mapping Pigments in Human Skin

Masahiro OKUYAMA*, Norimichi TSUMURA and Yoichi MIYAKE

Department of Information and Imaging Sciences, Chiba University,
1-33, Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

(Received ; Accepted)

A multi-spectral imaging system is evaluated for mapping melanin density, total-hemoglobin density, and oxygen saturation in human skin. In this system, the distribution of pigments in human skin is estimated and displayed from digital video signals using three pre-computed "look-up" tables for color conversions. The accuracy of the system is analyzed based on computer simulation by changing the number of bands, quantization levels of the camera system, and dimensions of approximation for spectral reflectance. The optimal system is examined based on the results of computer simulation.

Keywords: melanin, oxy-hemoglobin, deoxy-hemoglobin, oxygen saturation, pigment, human skin, system evaluation

*E-mail address: okuyama@graduate.chiba-u.jp

1. Introduction

Mapping pigments in human skin is expected to provide useful information about human health condition. The obtained information will also be used for skin diagnosis. We have already proposed a technique to obtain a map of skin pigments from multi-channel visible spectral imaging by an inverse optical scattering technique [1)]. The Monte Carlo simulation of photon migration [2)] is used as a forward model of optical scattering, where the spectral reflectance in skin is obtained from the density of skin pigments. The forward model is inversely used to obtain the density of pigments from spectral reflectance in skin. This inverse process, called inverse optical scattering technique, is based on a non-linear optimization technique using the forward model iteratively. A long period is required to iterate the forward model for this optimization and obtain the results. However, rapid processing is required in measuring changes of human health condition.

We earlier introduced the technique of real-time mapping pigments in human skin using three pre-computed "look up" tables for color conversions [3)]. Using these tables, achieved a real-time estimation of a pigment map. The first table converts Red Green Blue (RGB) values from a digital video camera into three scores for three principal components of spectral reflectances. The second table converts the principal scores into values of melanin, total-hemoglobin, and oxygen saturation, and the table is made using the inverse optical scattering technique. The third table converts the values into RGB values to display on a monitor. The first and third tables depend on devices and environments, while the second table is independent of them. An experiment was performed to show the effectiveness of the proposed system by occlusion and release of a finger, and change in the map was observed in real-time. Although we could observe the change, the observed map was noisy and accuracy of the measurements was not discussed in the previous paper.[3)]

In this paper, the multi-spectral imaging system is evaluated for mapping melanin density, total-hemoglobin density, and oxygen saturation in human skin. The accuracy of the system is analyzed based on computer simulation by changing the number of bands,

quantization levels, and number of principal scores. The optimal system is also examined at the point of feasibility of the system. In the next section, the previous system for real-time mapping pigments[3] is briefly described, and the quality of obtained results is discussed. In section 3, the multi-spectral imaging system is evaluated by changing the number of bands, quantization level, and number of principal scores in the computer simulation.

2. Real-Time Spectral Imaging System for Mapping Pigments in Human Skin[3]

Figure 1 shows a schematic diagram of the system. The system consists of a halogen-light source (Luminar Ace 1500UE, HAYASHI), integrating sphere, digital video camera (DFW-VL400, SONY) whose number of bands is 3 and quantization level is 8 bits for each band, personal computer (Pentium III, 1GHz), and a monitor. An IEEE 1394 cable connects the camera with the computer. The light is diffused by the 120 cm diameter integrating sphere to remove shading on an object. The digital camera captures the images of the object and transfers them to the personal computer in real-time.

2.1 Real-time estimation of maps for pigments

Figure 2 shows the flow of the real-time estimation process for pigments. At first, the RGB values captured by the digital video camera are converted into the scores for 3 principal components C_1 C_2 C_3 by the first look-up table, which we call the principal component table. The scores C_1 C_2 C_3 are converted into pigment values melanin (M), hemoglobin (H), oxygen saturation (S) by the second table, which we call the pigmentation table. Finally, using the third table called the color visualization table, the pigment values are converted into other RGB values R', G', B' to display their distribution of the pigments on the monitor. The principal component and color visualization table are dependent on devices and environments, and it takes a short time to reconstruct these tables. The pigmentation table, however, is not dependent on devices and environments, but, it takes about 10 days to reconstruct this table by the Monte Carlo simulation of photon migration in the human skin model. By dividing the

process from input RGB to output R', G', B' into these three look-up tables, the system can be easily reconfigured by changing camera devices and environments such as illuminants.

Preparation of the principal table is based on two steps. RGB values from the camera are first converted into the spectral reflectance based on the multiple regression analysis. Thirty three skin color patches whose spectral characteristics are similar to human skin are prepared and their spectral reflectances are measured by a spectral photometer. The color patches are also captured by the camera and the obtained RGB values and the corresponding spectral reflectance are used for the multiple regression analysis. In the second step, the spectral reflectance is projected to the principal component scores based on the principal component analysis. Four thousand four hundred and three skin spectral reflectances in Standard Object Color Spectra Database [4)] (SOCS) are used for this principal component analysis. All combinations of RGB value from the camera are computed to make the principal table.

Preparation of pigmentation table is based on three steps. A table that converts pigment values into spectral reflectance is first obtained by the Monte Carlo simulation of skin spectral reflectance. In the second step, the obtained spectral reflectance is converted into scores for the principal component. In the third step, the required table from the scores to pigment values is constructed by inversely arranging the table from pigment values to scores.

2.2 Experimental results

The occlusion and release of a blood vessel in the middle finger was observed by the system with 3 bands, 8 bits per pixel in each band, and 3 principal scores which give 3 dimensions of tables.[3)] The root of the middle finger was bound tightly with a string, and after 20 seconds the string was cut off. During the occlusion, hemoglobin density did not change, however, oxygen saturation was decreased because oxygen was consumed in the middle of the finger. After the string was cut, both hemoglobin and oxygen saturation were increased by the afflux of arterial blood. Finally, the amount of pigment returned to an equilibrium condition of blood supply and demand. We were able to observe the change, however, the observed map was noisy and accuracy of the measurements was not discussed in the previous paper[3)]. In the next section, this is discussed based on computer simulation.

3. System Evaluation by Computer Simulation

3.1 The process of computer simulation

We constructed a simulator of the system to map the pigments in order to evaluate the accuracy of its estimation. Figure 3 shows the process of the simulator. The spectral reflectance is calculated from the original pigment values using Monte Carlo simulation of photon migration in this skin. The spectral reflectance is converted into the camera responses based on the camera model with *N* bands and *Q* quantization level per pixel in each band. The camera response v_i is expressed as

$$v_i = \int T_i(\lambda)E(\lambda)S(\lambda)d\lambda, \qquad i = 1,...,N \quad (1)$$

where $T_i(\lambda), E(\lambda),$ and $S(\lambda)$ are the spectral transmittance of the *i*th filter, the spectral radiance of the illuminant and the spectral reflectance of the skin, respectively. Each response is quantized at *Q* bits per sample. It is assumed that the camera response is linear and the influence of the dark current can be neglected. Sensitivity of the sensor is not considered in the simulation for simplicity.

The obtained *N* camera responses are converted into the *P* principal scores for *P* principal vectors. This conversion should be implemented by the *N* dimension to *P* dimension look up table in the practical system for real-time processing. Because of the limited memory in the computer for the simulator, however, we cannot simulate this look up table for high dimensional signals. Therefore, the obtained *N* camera responses are directly converted into the *P* principal scores by applying the conversion matrix which will be used to make the look up table in the practical system. As was mentioned in the previous section, the conversion matrix from camera response to principal score is made from two conversions. First is the conversion from camera response to spectral reflectance based on the multiple regression analysis for skin patches, and second is the conversion from spectral reflectance to principal score based on principal component analysis for SOCS data[4)].

The obtained *P* principal scores are converted into the three pigment values M, H, S. This conversion also should be implemented by the *P* dimension to 3-dimension look up table in the practical system for real-time processing. However, we cannot simulate this look up table for high dimensional signals in the computer for the simulator. The conversion is performed by inverse Monte Carlo simulation of photon migration in the skin, which will also be used to make the look up table in the practical system. In the inverse Monte Carlo simulation, a simplex optimization method is used to find the pigment values from principal scores by iterating the forward model of photon migration.

The estimated pigment values obtained above are compared with the original values. The accuracy of the estimation is evaluated by the following equation,

$$Accuracy(\%) = 100 \times \frac{1}{M} \sum_{i=1}^{M} (1 - \frac{\left| V_{original}(i) - V_{estimated}(i) \right|}{V_{original}(i)}) \qquad (2)$$

where $V_{original}(i)$ is the original pigment value, $V_{estimated}(i)$ is the estimated pigment value, and *M* denotes the total number of evaluated data. The accuracy of the estimation is evaluated in melanin density, hemoglobin density and oxygen saturation, respectively. In order to evaluate the values in the proper range of real skin pigments in the simulation, the range was *a priori* investigated using the simplex optimization method for SOCS data. Figure 4 shows the results of obtained range. Based on these results, melanin density is set at a range from 70 [10^{-5} mol/L] to 120 at 10 intervals, hemoglobin density is set at a range from 10 [10^{-5} mol/L] to 35 at 5 intervals, and oxygen saturation is set at a range from 0.5 to 1.0 at 0.1 intervals, respectively. Therefore, 216 data are used to evaluate of the accuracy.

3.2 Device characteristics used in the computer simulation

In this paper, the number of band *N* is changed from 3 to 8 in the simulation for evaluation. Figure 5 shows the spectral radiance of illuminant used in the simulation. Figure 6 shows the three spectral transmittances of color filters used in the previous digital video camera system. These three spectral transmittances are always used in the simulation for 3 or more bands.

Figure 7 shows the eight spectral transmittances of commercially available color filters, In the case of simulation for 4 and more filters, we choose the filters among these eight filters in addition to the original three filters in Fig. 7. The filters which give the best accuracy for pigment estimation are chosen in the simulation by evaluating all filter combinations. The quantization level Q at each pixel in the camera is changed from 8 to 16 bits with an interval of 2 bits in the simulation for evaluation. The number of principal scores P is changed from 3 to 8 in the simulation. The quantization level of principal scores is not taken into consideration for simplicity in this paper.

The noise in a CCD camera will reduce the accuracy of estimation of pigment values. There are many noise sources in a CCD camera, including dark current and read noise, both of which are signal independent, and shot noise which is signal dependent.[5)] In this paper, however, we do not consider CCD noise in this simulation but focus on the number of bands, quantization levels, and the number of principal scores. We consider that the dark current noise can be reduced by using a cooled CCD camera, and other noises can also be reduced by the averaging of pixel value in neighbor pixels or in multiple images. Therefore, in the next sub-section, we will evaluate the system without noise.

3.3 Evaluated results

As the first step in the evaluation, the accuracy of the estimation for hemoglobin density, melanin density, and oxygen saturation is evaluated for 3 bands, 8 bits for quantization, and 3 principal scores. The result of accuracy was 84.6% for hemoglobin density, 96.6% for melanin density, and 60.0% for oxygen saturation. We can see that the hemoglobin and melanin densities are estimated with good accuracy in the present system. However, the accuracy of the estimation for oxygen saturation is low, and this can also be seen from the experimental results in the previous paper.[3)] Since this tendency is the same for all combinations of number of bands, quantization levels, and number of principal scores, we will show only the accuracy of oxygen saturation for evaluating the system in this paper.

Figure 8 (a), (b), (c) show the results of oxygen saturation accuracy in the system for 3, 4, 5 principal scores, respectively. All combinations of the number of bands N and quantization

level Q are evaluated in each number of scores. In the 3 principal scores, the increase of the number of bands is very effective in improving the accuracy of the estimation as is shown in Fig. 8(a). As shown by comparing between Fig. 8(a) and (b), increase in the number of principal scores from 3 to 4 is also very effective in improving the accuracy of the estimation. Figure 8 (c) shows the interesting result in a small number of quantization levels, where the accuracy of estimation in 5 principal scores is lower than that in 4 principal scores. We believe the reason for this to be as follows. Principal vectors and eigenvalues by principal component analysis are shown in Fig. 9 (a) (b). As shown in Fig. 9(a), the 5th principal vector contributes to the reflectance in long wavelength. Figure 10 shows the typical change of spectral reflectance with the change of oxygen saturation in Monte Carlo simulation. This figure indicates that the change of oxygen saturation depends on the change of reflectance in long wavelength. From Fig. 9(b), it can be seen that the eigenvalue for the 5th principal component is small, and the 5th principal scores usually have small values in the process. Therefore, the error caused by quantization is influenced largely in the 5th principal score, and this error influences the estimation error in the oxygen saturation. Based on this consideration, we can say that it is advisable not to use the 5th principal score in a small number of quantization levels. We conclude that poor estimation accuracy in a small number of quantization levels is caused by the error of quantization which is magnified in the principal score for the 5th principal vector.

From our point of view, the system with a 12 bits quantization level, having 5 bands and 5 principal component vectors is considered the most practical with an oxygen saturation accuracy of 97.5%. The selected filters for the system are shown in Fig. 11.

4. Conclusion

We constructed a simulator of the system to map the pigments to evaluate the accuracy, and found that the accuracy in estimating oxygen saturation was inadequate. In the simulation, we also changed the number of bands, quantization level in the camera, and number of principal

scores in the estimation. We found the increase in number of bands to be effective for system. The optimal system was thus examined empirically. However, one drawback for this system is the high dimension of the look-up table requiring implementation in the personal computer which has limited memory. We are expecting that the tree type of search algorithm [6] will help in implementing this conversion in the personal computer. In this paper, we developed a simulator of the system and discussed the accuracy of its estimation; many combinations of practical devices will be evaluated using the proposed simulator as the next step of our research.

References

1) N.Tsumura, M.Kawabuchi, H.Haneishi and Y.Miyake: J.Imaging Sci.&Technol. 45 (2001) 444.

2) L.Wang and S.L.Jacques: University of Texas M. D. Anderson Cancer Center (1992).

3) D.Nakao, N.Tsumura and Y.Miyake: Med.Imaging Technol. 20 (2002) 123[in Japanese].

4) J.Tajima, M.Tsukada, Y.Miyake, H.Haneishi, N.Tsumura, M.Nakajima, Y.Azuma, T.Iga, M.Inui, N.Ohta, N.Ojima, S.Sanada: Proc. SPIE Conf. Electron. Imaging (1998) 42.

5) H.Haneishi, T.Hasegawa, A.Hosoi, Y.Yokoyama, N.Tsumura and Y.Miyake: Appl. Opt. 39 (2000) 6621.

6) J.L.Bentley: Commun. of the Assoc. Comp. Mach. 18 (1975) 509.

Captions of figures

Fig. 1. Present system for mapping the pigments in real-time.

Fig. 2. Flow of the estimation process for pigments

Fig. 3. Flow of the estimation process in the simulator

Fig. 4. The range of human skin by simplex optimization

Fig. 5. Spectral radiance of the light source in the present system

Fig. 6. Spectral transmittance of R, G, B channels in the present digital video camera

Fig. 7. Spectral transmittance of color filters used to increase the number of bands

Fig. 8. The result of estimation accuracy for oxygen saturation in the system

Fig. 9. The principal component of principal component analysis for SOCS data

Fig. 10. Typical change of spectral reflectance with the change of oxygen saturation in Monte Carlo simulation (melanin: 90 [10^{-5}mol/L], hemoglobin: 15 [10^{-5}mol/L])

Fig. 11. Spectral transmittances of the bands in the optimal system