Principal Component Analysis of Skin Color and Its Application to Colorimetric Color Reproduction on CRT Display and Hardcopy

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We propose a new method to predict the images on a CRT and a hardcopy of skin color under various illuminants. Spectral reflectance of human skin is analyzed by principal component analysis and it is shown that the spectral reflectance can be estimated by three basis functions. The estimation allows colorimetric color reproduction without colorimetric measurements for each illuminant. The proposed method is verified by several skin color patches taken by a calibrated HDTV camera. The method is also applied to practical facial pattern images.

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Introduction

The appearance of skin color depends on the illuminants in the environment. In the development of cosmetics and their sales promotion, the color of skin images must be predicted under various illuminants. Practically, it would be convenient if the skin color images taken under only one illuminant could be transformed to the correct skin color images taken under various illuminants. In conventional color reproduction techniques,[1] however, it is difficult to reproduce a skin color under various illuminants.

In conventional color reproduction, color patches under the illuminants are measured colorimetrically to match the color between an illuminated object and an image reproduced by an output device. The result of colorimetric measurements should be analyzed to make a LUT (look-up table) or transform operation for each illuminant. The repetition of such a process for each illuminant would be a restraint for the development of cosmetics and their sales promotion.

Previous work shows that the spectral reflectance of human skin can be represented by three basis functions based on principal component analysis.[2] Then the two-dimensional distribution of spectral reflectance can be estimated from the values of three color channels and the spectral radiance of the illuminant, as is performed in electronic endoscope images.[3]

In this report, we propose a new skin color reproduction method to predict skin color images under various illuminants. The proposed method uses estimated spectral reflectance. The estimation will allow colorimetric reproduction without colorimetric measurements for each illuminant. These processed skin colors are reproduced colorimetrically both on a CRT display and a hardcopy.

The principal component analysis of the spectral reflectance and a method to estimate the spectral reflectance are described. The proposed method is verified by several skin color patches taken by a calibrated HDTV camera and the method is applied to a facial pattern image.

The proposed method matches colorimetrically the skin color images under various illuminants. However, this method can be improved to match color appearance, using chromatic adaptation models.

Principal Component Analysis of Spectral Reflectance of Human Skin

Ojima and coworkers[2] measured 108 reflectance spectra of skin in faces of 54 Mongolians (Japanese women) between 20 and 50 years of age. The Munsell values of the samples have a range as follows: H = 2YR – 8YR, V = 5 – 7, C = 2 – 5, and the distribution of these skin colors in CIE 1976 L*a*b* color space is shown in Fig. 1. The spectral reflectance was measured at intervals of 5 nm between 400 and 700 nm. Therefore, the spectral reflectance is described as vectors $\boldsymbol{o}$ in 61-dimensional vector space. Figure 2 shows the averaged spectral reflectance of human skin, and these values are given in Table I. The covariance matrix of the spectral reflectance was calculated for the principal component analysis. The eigenvectors of the

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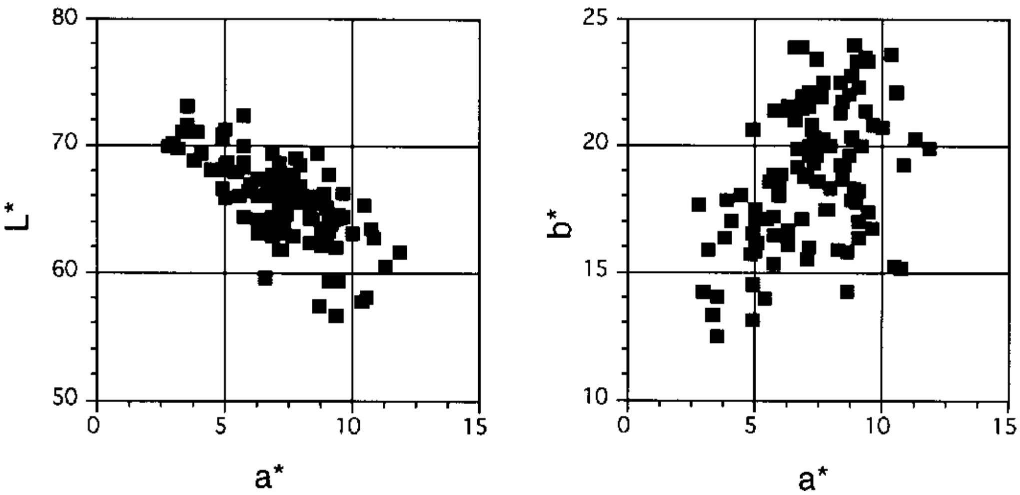


Figure 1. Distribution of skin colors used in principal component analysis.

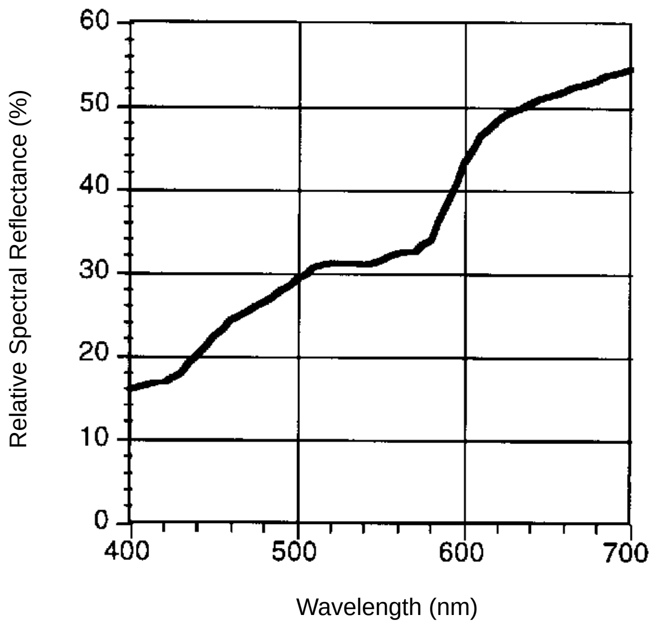


Figure 2. Averaged spectral reflectance of human skin.

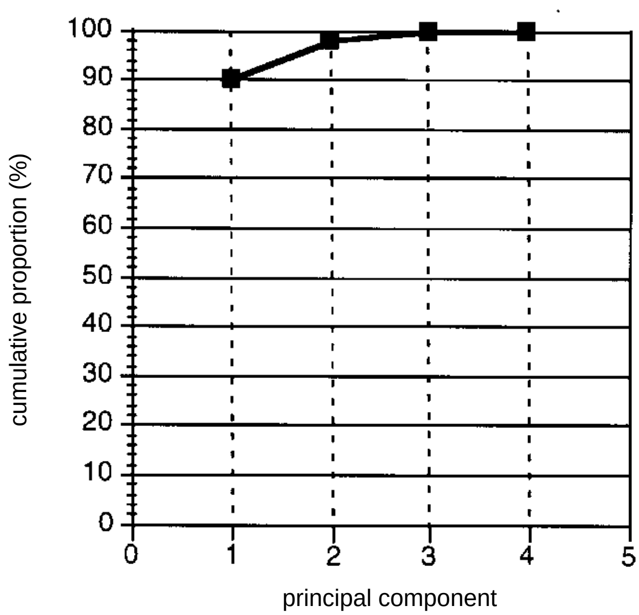


Figure 3. Cumulative contribution ratio of principal components of the spectral reflectance of skin.

TABLE I. Averaged Spectral Reflectance of the Sampled Human Skin

Wavelength (nm)	Relative spectral reflectance (%)	Wavelength (nm)	Relative spectral reflectance (%)
400	16.0	555	31.9
405	16.2	560	32.2
410	16.4	565	32.5
415	16.6	570	32.7
420	16.8	575	33.4
425	17.4	580	34.1
430	17.9	585	36.2
435	18.9	590	38.4
440	20.0	595	40.8
445	21.2	600	43.2
450	22.3	605	44.8
455	23.2	610	46.4
460	24.1	615	47.3
465	24.8	620	48.3
470	25.4	625	48.8
475	25.9	630	49.4
480	26.5	635	49.9
485	27.1	640	50.4
490	27.7	645	50.8
495	28.4	650	51.2
500	29.2	655	51.5
505	29.9	660	51.8
510	30.6	665	52.2
515	30.9	670	52.5
520	31.2	675	52.9
525	31.1	680	53.2
530	31.1	685	53.5
535	31.0	690	53.9
540	31.0	695	54.1
545	31.3	700	54.4
550	31.5		

covariance matrix are named as principal component vectors. Then the spectral reflectance of human skin can be expressed as a linear combination of the principal component vectors as follows:

$$\boldsymbol{o} = \bar{\boldsymbol{o}} + \sum_{i=1}^{n} \alpha_i \boldsymbol{u}_i, \tag{1}$$

where $\bar{\mathbf{o}}$ is the averaged spectral reflectance, $\boldsymbol{u}_i$ $(i = 1, ...\ n)$ are the eigenvectors and $\alpha_i(I = 1, ..., n)$ are the eigenvalues. The eigenvectors are combined in order of the eigenvalues.

The cumulative proportion rates of the principal component vectors are shown in Fig. 3. From this figure, we can see that the cumulative proportion rate from the first to third components is about 99.5%. Thus, the spectral reflectance of human skin can be represented as ~99.5%

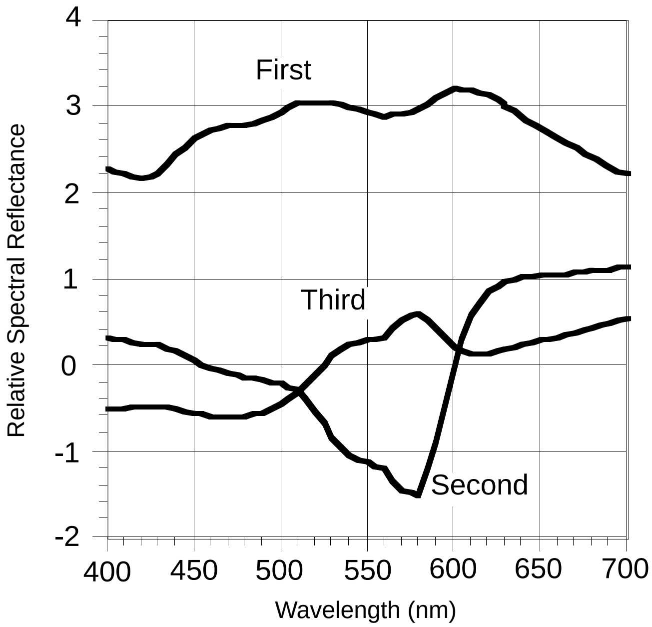


Figure 4. The first, second, and third principal components of the spectral reflectance of skin.

by using a linear combination of three principal components $\boldsymbol{u}_1, \boldsymbol{u}_2, \boldsymbol{u}_3$. The three principal components are shown in Fig. 4, and their values are given in Table II. Therefore, Eq. 1 can be represented approximately as follows:

$$\boldsymbol{o} \cong \bar{\boldsymbol{o}} + \sum_{i=1}^{3} \alpha_i \boldsymbol{u}_i = \bar{\boldsymbol{o}} + (\boldsymbol{u}_1 \boldsymbol{u}_2 \boldsymbol{u}_3) \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix}. \tag{2}$$

Estimation of the Spectral Reflectance of Human Skin

Considering the result of the above principal component analysis, we can estimate the spectral reflectance of skin, using the tristimulus values of the human skin. The tristimulus values can be easily measured by a colorimeter. The spectral reflectance of skin is estimated as follows. As is well known, the tristimulus values *X, Y, Z* can be calculated by Eq. 3:

$$\begin{aligned} X &= K \sum_{\lambda=400}^{700} E(\lambda)\bar{x}(\lambda)O(\lambda), \\ Y &= K \sum_{\lambda=400}^{700} E(\lambda)\bar{y}(\lambda)O(\lambda), \\ Z &= K \sum_{\lambda=400}^{700} E(\lambda)\bar{z}(\lambda)O(\lambda), \end{aligned} \tag{3}$$

where $O(\lambda)$ is the spectral reflectance, $E(\lambda)$ is the spectral radiance of the illuminant, $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ are color matching functions, and K is a constant. By vector notation, Eq. 3 can be expressed as follows:

$$\begin{aligned} X &= K\boldsymbol{e}^t \bar{\boldsymbol{X}} \boldsymbol{o}, \\ Y &= K\boldsymbol{e}^t \bar{\boldsymbol{Y}} \boldsymbol{o}, \\ Z &= K\boldsymbol{e}^t \bar{\boldsymbol{Z}} \boldsymbol{o}, \end{aligned} \tag{4}$$

where $[\cdot]^t$ represents the transpose of $[\cdot]$, the vectors $\boldsymbol{e}$ and $\boldsymbol{o}$ are vector notations of $E(\lambda)$ and $O(\lambda)$, respectively, and the matrices $\bar{\boldsymbol{X}}, \bar{\boldsymbol{Y}}, \bar{\boldsymbol{Z}}$ are represented as follows:

TABLE II. The First, Second, and Third Principal Components of the Spectral Reflectance of Human Skin

Wavelength (nm)	1st principal component	2nd principal component	3rd principal component
400	2.258	0.326	-0.514
405	2.232	0.306	-0.506
410	2.207	0.284	-0.497
415	2.177	0.267	-0.491
420	2.149	0.250	-0.486
425	2.184	0.242	-0.488
430	2.218	0.234	-0.488
435	2.326	0.198	-0.488
440	2.435	0.161	-0.510
445	2.527	0.102	-0.533
450	2.619	0.041	-0.557
455	2.665	0.000	-0.572
460	2.711	-0.040	-0.588
465	2.735	-0.064	-0.589
470	2.758	-0.086	-0.592
475	2.767	-0.112	-0.590
480	2.776	-0.138	-0.589
485	2.800	-0.158	-0.572
490	2.824	-0.177	-0.554
495	2.878	-0.192	-0.508
500	2.933	-0.208	-0.461
505	2.983	-0.251	-0.390
510	3.033	-0.294	-0.321
515	3.044	-0.410	-0.225
520	3.056	-0.526	-0.130
525	3.045	-0.682	-0.018
530	3.035	-0.837	0.094
535	3.019	-0.942	0.172
540	3.003	-1.047	0.250
545	2.971	-1.087	0.266
550	2.940	-1.129	0.283
555	2.915	-1.173	0.307
560	2.891	-1.213	0.330
565	2.897	-1.335	0.424
570	2.902	-1.453	0.517
575	2.927	-1.477	0.564
580	2.950	-1.500	0.611
585	3.028	-1.202	0.526
590	3.107	-0.903	0.441
595	3.154	-0.455	0.319
600	3.202	-0.006	0.199
605	3.195	0.285	0.158
610	3.188	0.576	0.117
615	3.152	0.711	0.130
620	3.117	0.846	0.142
625	3.062	0.899	0.165
630	3.006	0.952	0.186
635	2.944	0.978	0.209
640	2.882	1.004	0.231
645	2.816	1.019	0.257
650	2.751	1.034	0.284
655	2.694	1.040	0.307
660	2.639	1.046	0.331
665	2.585	1.057	0.359
670	2.530	1.069	0.386
675	2.469	1.083	0.416
680	2.407	1.098	0.445
685	2.354	1.106	0.471
690	2.302	1.114	0.497
695	2.253	1.119	0.524
700	2.202	1.124	0.550

$$\bar{x}(\lambda) \rightarrow \bar{\boldsymbol{X}} = \begin{pmatrix} \bar{x}_1 & & O \\ & \bar{x}_2 & \ddots \\ O & & \bar{x}_n \end{pmatrix}, \tag{5}$$

$$\bar{y}(\lambda) \rightarrow \bar{\boldsymbol{Y}} = \begin{pmatrix} \bar{y}_1 & & O \\ & \bar{y}_2 & \ddots \\ O & & \bar{y}_n \end{pmatrix}, \tag{6}$$

$$\bar{z}(\lambda) \rightarrow \bar{Z} = \begin{pmatrix} \bar{z}_1 & & O \\ & \bar{z}_2 & \ddots \\ O & & \bar{z}_n \end{pmatrix}, \tag{7}$$

From Eq. 2, Eq. 4 can be written as

$$X \cong Ke^t \bar{\boldsymbol{X}} \left[\bar{o} + (\boldsymbol{u}_1 \boldsymbol{u}_2 \boldsymbol{u}_3) \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix} \right], \tag{8a}$$

$$Y \cong Ke^t \bar{\boldsymbol{Y}} \left[\bar{o} + (\boldsymbol{u}_1 \boldsymbol{u}_2 \boldsymbol{u}_3) \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix} \right], \tag{8b}$$

$$Z \cong Ke^t \bar{\boldsymbol{Z}} \left[\bar{o} + (\boldsymbol{u}_1 \boldsymbol{u}_2 \boldsymbol{u}_3) \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix} \right]. \tag{8c}$$

Equation 8 can be rewritten as follows:

$$X \cong K\boldsymbol{e}^t \bar{\boldsymbol{X}}\, \bar{\boldsymbol{o}} + K\boldsymbol{e}^t \left(\bar{\boldsymbol{X}}\boldsymbol{u}_1 \bar{\boldsymbol{X}}\boldsymbol{u}_2 \bar{\boldsymbol{X}}\boldsymbol{u}_3 \right) \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix}, \tag{9a}$$

$$Y \cong K\boldsymbol{e}^t \bar{\boldsymbol{Y}}\, \bar{\boldsymbol{o}} + K\boldsymbol{e}^t \left(\bar{\boldsymbol{Y}}\boldsymbol{u}_1 \bar{\boldsymbol{Y}}\boldsymbol{u}_2 \bar{\boldsymbol{Y}}\boldsymbol{u}_3 \right) \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix}, \tag{9b}$$

$$Z \cong K\boldsymbol{e}^t \bar{\boldsymbol{Z}}\, \bar{\boldsymbol{o}} + K\boldsymbol{e}^t \left(\bar{\boldsymbol{Z}}\boldsymbol{u}_1 \bar{\boldsymbol{Z}}\boldsymbol{u}_2 \bar{\boldsymbol{Z}}\boldsymbol{u}_3 \right) \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix}. \tag{9c}$$

We can consider the first term of Eq. 9 to be a contribution of the averaged spectral reflectance to the tristimulus values, and the second term as a contribution of three eigenvectors. Then we can rewrite Eq. 9 as follows:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \cong \begin{pmatrix} \bar{X} \\ \bar{Y} \\ \bar{Z} \end{pmatrix} + \begin{pmatrix} X_1 & X_2 & X_3 \\ Y_1 & Y_2 & Y_3 \\ Z_1 & Z_2 & Z_3 \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix}, \tag{10}$$

where $\bar{X}, \bar{Y}, \bar{Z}$ are the averaged tristimulus values and X_i, Y_i, Z_i ($i = 1, 2, 3$) are the tristimulus values corresponding to the three eigenvectors of spectral reflectance of skin.

The eigenvalues α_1, α_2, and α_3 are given by

$$\begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \end{pmatrix} \cong \begin{pmatrix} X_1 & X_2 & X_3 \\ Y_1 & Y_2 & Y_3 \\ Z_1 & Z_2 & Z_3 \end{pmatrix}^{-1} \left[\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} - \begin{pmatrix} \bar{X} \\ \bar{Y} \\ \bar{Z} \end{pmatrix} \right]. \tag{11}$$

The spectral reflectance of human skin can be estimated by the above eigenvalues and three principal components by Eq. 2.

Two-Dimensional Measurement of Spectral Reflectance by HDTV Camera

We measured the tristimulus values X, Y, Z of human skin in each pixel with an HDTV camera (Nikon HQ1500C). A two-dimensional distribution of spectral reflectances of the human face can be estimated from the measured tristimulus values as described above. Output values R, G, B of the HDTV camera were transformed to X, Y, Z as follows[2]:

$$\begin{aligned} R &= K_r \cdot f_r(R_o), \\ G &= K_g \cdot f_g(G_o), \\ B &= K_b \cdot f_b(B_o), \end{aligned} \tag{12}$$

$$\begin{aligned} R_o &= \sum_{\lambda=400}^{700} E(\lambda)\bar{r}(\lambda)O(\lambda), \\ G_o &= \sum_{\lambda=400}^{700} E(\lambda)\bar{g}(\lambda)O(\lambda), \\ B_o &= \sum_{\lambda=400}^{700} E(\lambda)\bar{b}(\lambda)O(\lambda), \end{aligned} \tag{13}$$

where $\bar{r}(\lambda), \bar{g}(\lambda), \bar{b}(\lambda)$ are the spectral sensitivity functions of the camera; f_r, f_g, f_b are nonlinear functions; and K_r, K_g, K_b are white balance constants. The nonlinearity between RGB level and luminance was compensated to be linear by using the following quadratic equations:

$$\begin{aligned} R' &= -5.50 + 4.26 \times 10^{-1} R + 2.04 \times 10^{-3} R^2, \\ G' &= -6.06 \times 10^{-1} + 2.90 \times 10^{-1} G + 2.66 \times 10^{-3} G^2, \\ B' &= -7.37 \times 10^{-1} + 2.31 \times 10^{-1} B + 3.11 \times 10^{-3} B^2, \end{aligned} \tag{14}$$

where R', G', B' are compensated values. The compensated values R', G', B' were transformed to the tristimulus values X, Y, Z by Eq. 15:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \boldsymbol{M}_1 \begin{pmatrix} R' \\ G' \\ B \\ 1 \end{pmatrix}, \tag{15}$$

where $\boldsymbol{M}_1$ is a 3×4 matrix. This matrix $\boldsymbol{M}_1$ can be determined by multiple regression analysis. Thirty-nine patches of Japanese skin color were used in the multiple regression analysis. The Munsell values of the patches have a range as follows; H = 0YR – 10YR, V = 5 – 8, C = 2 – 5. The pictures were taken under Metal halide lamp (RDS, with color temperature of 5,700 K) illumination at 2° field of view by the HDTV camera. The tristimulus values of the patches were measured by a spectrophotometer (Minolta CM1000). In CIE 1976 L*a*b* color space, the averaged color difference and the maximum

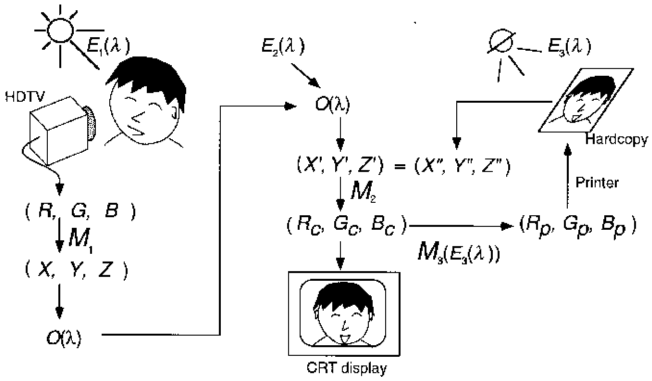


Figure 5. Diagram of the proposed color reproduction system for CRT and hardcopy to predict skin color image taken under various illuminants.

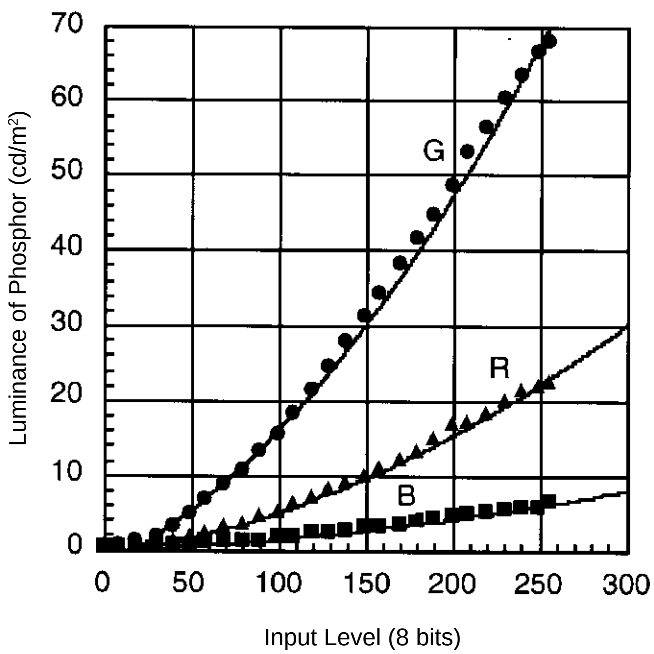


Figure 6. The relationship between input levels of CRT display and luminance of phosphor.

color difference were calculated between the measured and calculated tristimulus values. The averaged color difference $\overline{\Delta E^*ab}$ was 1.0, and the maximum color difference ΔE^*ab_{max} was 2.3. This result shows that the transformation has sufficient accuracy to estimate the spectral reflectance by Eq. 11.

Skin Color Reproduction Based on Spectral Reflectance

Figure 5 is a schematic diagram of color reproduction from an image taken by HDTV camera to CRT or hardcopy of skin color under various illuminants. The tristimulus values X', Y', Z' of skin color under a selected illuminant are easily calculated from the estimated spectral reflectances $O(\lambda)$ and the spectral radiance $E_2(\lambda)$ of the illuminant.

Color Reproduction on CRT Display. The tristimulus values X', Y', Z' are transformed to input levels R_c, G_c, B_c of the CRT display, using the transform operation $\boldsymbol{M}_2$. The transform operation $\boldsymbol{M}_2$ was measured as described below.[4]

First, the relationship between input level R_c, G_c, B_c and luminance of the display phosphors was analyzed. A CRT display (Nanao Flex Scan56T Monitor) with fixed luminance, contrast, white point, and gamma was used in the experiment. Twenty-six color patches were displayed on the monitor in a dark environment to avoid interference by external light sources. The luminance L and the chromaticity x, y of the displayed color patches in each channel were measured by a luminance colorimeter (Topcom BM-7). The relationship between the input level and luminance is plotted in Fig. 6. The relationship between the luminance and input levels is

$$\begin{aligned} L_R &= a_0 R_c^2 + a_1 R_c + a_2, \\ L_G &= b_0 G_c^2 + b_1 G_c + b_2, \\ L_B &= c_0 B_c^2 + c_1 B_c + c_2, \end{aligned} \tag{16}$$

where L_R, L_G, L_B are the luminance of red, green, and blue phosphors respectively, and a_i, b_i, c_i (i = 0 to 2) are coefficients.

The tristimulus values X, Y, Z on the display can be decomposed *to* R, G, B contribution terms as shown in the following equation:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} X_R + X_G + X_B \\ Y_R + Y_G + Y_B \\ Z_R + Z_G + Z_B \end{pmatrix}, \tag{17}$$

where X_i, Y_i, Z_i ($i = R, G, B$) are the tristimulus values corresponding to the emission of red, green, and blue phosphors, respectively. The tristimulus values corresponding to each phosphor are calculated from the measured L, x, and y. A relationship between X–Y, Z–Y for each phosphor is shown in Fig. 7. These relations can be represented by linear equations as follows:

$$\begin{aligned} X_R &= a_R Y_R + b_R \\ X_G &= a_G Y_G + b_G \\ X_B &= a_B Y_B + b_B \\ Z_R &= c_R Y_R + d_R\,, \\ Z_G &= c_G Y_G + d_G \\ Z_B &= c_B Y_B + d_B \end{aligned} \tag{18}$$

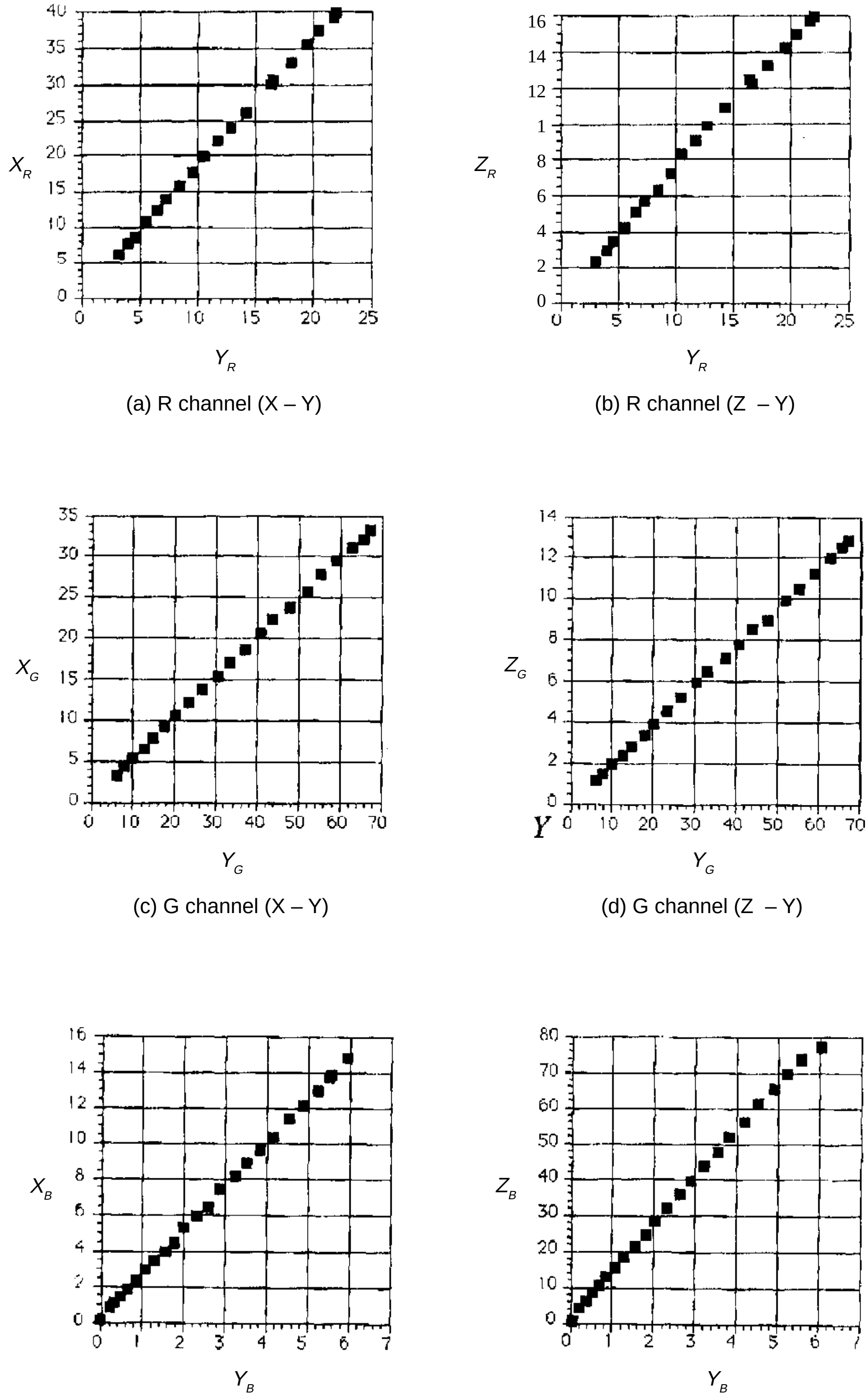
where a_i, b_i, c_i, d_i ($i = R, G, B$) are coefficients.

From Eqs. 17 and 18, the following equation is obtained.

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} a_R Y_R + a_G Y_G + a_B Y_B + b_R + b_G + b_B \\ Y_R + Y_G + Y_B \\ c_R Y_R + c_G Y_G + c_B Y_B + d_R + d_G + d_B \end{pmatrix} = \boldsymbol{A}\begin{pmatrix} Y_R \\ Y_G \\ Y_B \end{pmatrix} + \begin{pmatrix} b_R + b_G + b_B \\ 0.0 \\ d_R + d_G + d_B \end{pmatrix}, \quad \boldsymbol{A} = \begin{pmatrix} a_R & a_G & a_B \\ 1.0 & 1.0 & 1.0 \\ c_R & c_G & c_B \end{pmatrix}. \tag{19}$$

The luminance can be calculated from Eq. 19 as follows:

$$\begin{pmatrix} L_R \\ L_G \\ L_B \end{pmatrix} = \begin{pmatrix} Y_R \\ Y_G \\ Y_B \end{pmatrix} = \boldsymbol{A}^{-1}\begin{pmatrix} X - b_R - b_G - b_B \\ Y \\ Z - d_R - d_G - d_B \end{pmatrix}. \tag{20}$$



(a) R channel (X – Y)

(b) R channel (Z – Y)

(c) G channel (X – Y)

(d) G channel (Z – Y)

(e) B channel (X – Y)

(f) B channel (Z – Y)

Figure 7. *X–Y* and *Z–Y* relationship for each *RGB* channel of the CRT display.

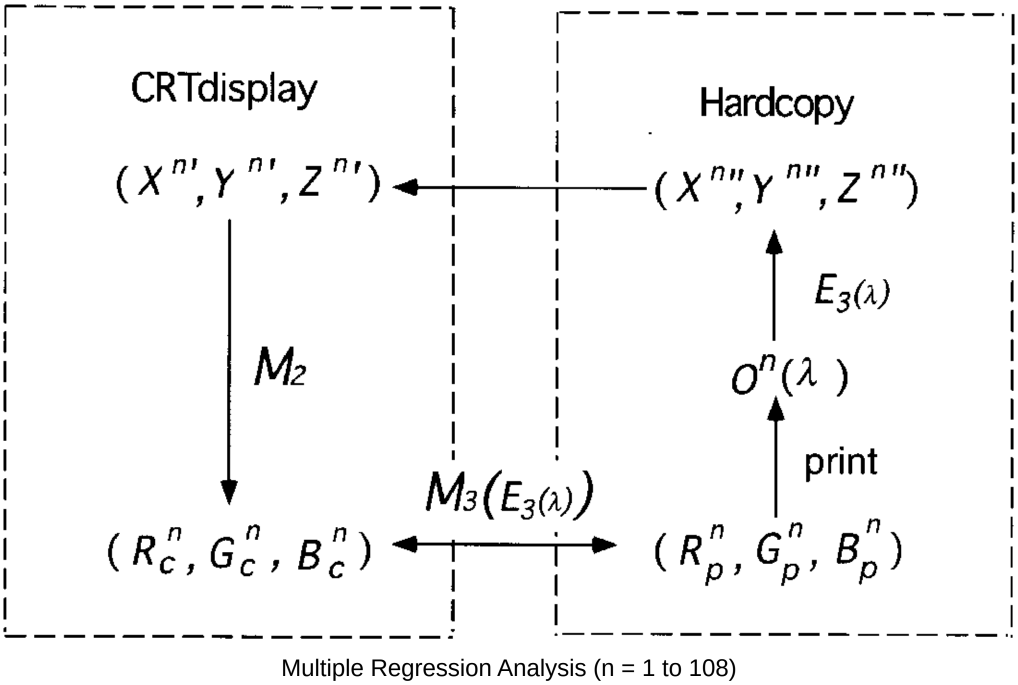


Figure 8. Diagram of the multiple regression analysis to reproduce skin color on hardcopy.

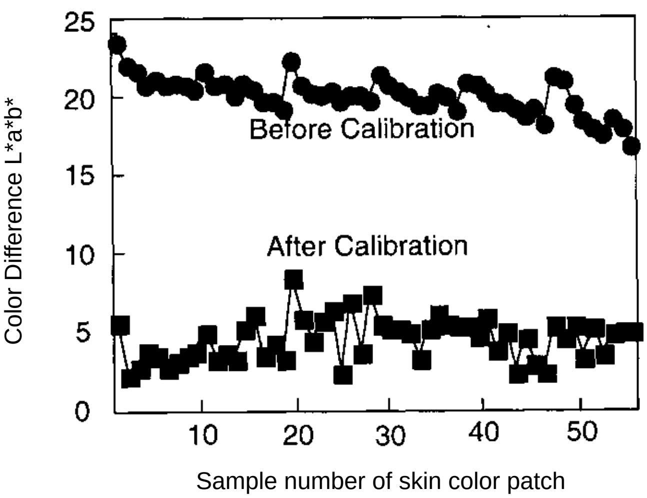


Figure 9. Color differences in LAB color space between skin color patches displayed on a monitor and the corresponding hardcopies viewed in an illumination booth, before and after color transformation.

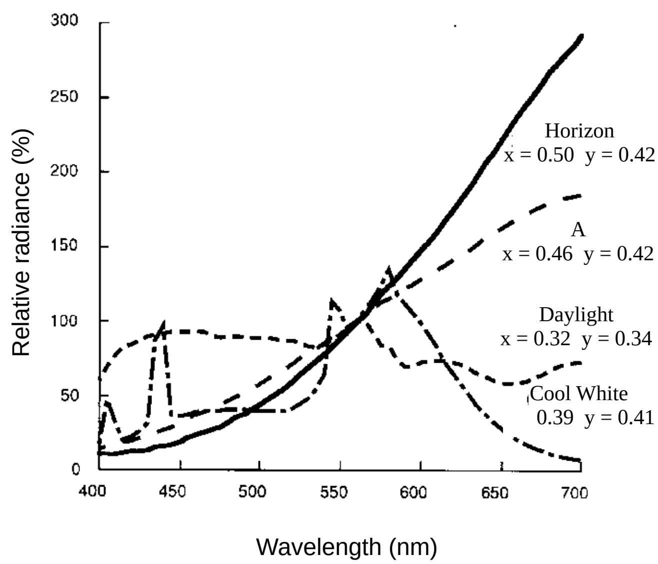


Figure 10. Measured relative spectral radiance of the illumination lamps in the experimental booth.

Then, using Eqs. 16 and 20, the transformation from the tristimulus values X, Y, Z to the input levels R_c, G_c, B_c can be achieved.

Color Reproduction in Hardcopy. As shown in Fig. 5, the tristimulus values X'', Y'', Z'' of a printed skin image under a certain illuminant were matched to the tristimulus values X', Y', Z' of the same skin image on a CRT display. To achieve the above matching, the matrix $\boldsymbol{M}_3$ was used to transform the CRT input levels R_c, G_c, B_c to printer input levels R_p, G_p, B_p. The matrix $\boldsymbol{M}_3$ depends on the spectral radiance $E_3(\lambda)$ of the illuminant on the hardcopy. As shown in Fig. 8, the matrix $\boldsymbol{M}_3$ was calculated by multiple regression analysis, using the measured spectral radiance $E_3(\lambda)$ and the spectral reflectances of color patches. Note that we need not measure the tristimulus values of the color patches under each illuminant.

One hundred eight skin color patches with printer input level R_p^n, G_p^n, B_p^n were printed, using Fujix Pictrography 3000. The spectral reflectance $O_n(\lambda)$ of each patch was measured by a spectrophotometer (Datacolor Spectraflash 500).

In printing, the tristimulus values $X^{n\prime\prime}$, $Y^{n\prime\prime}$, $Z^{n\prime\prime}$ are calculated under a selected illuminant $E_3(\lambda)$, using the available spectral reflectances $O^n(\lambda)$ by the transformation matrix $\boldsymbol{M}_2$. The tristimulus values $X^{n\prime\prime}$, $Y^{n\prime\prime}$, $Z^{n\prime\prime}$ for each patch were transformed to R_c^n, G_c^n, B_c^n, which are input levels of the CRT. In Eq. 21, the coefficients $(a_{i,j})$ ($i = 1, ..., 3, j = 1, ..., 11$) of the transformation matrix $\boldsymbol{M}_3$ were determined by multiple regression analysis.

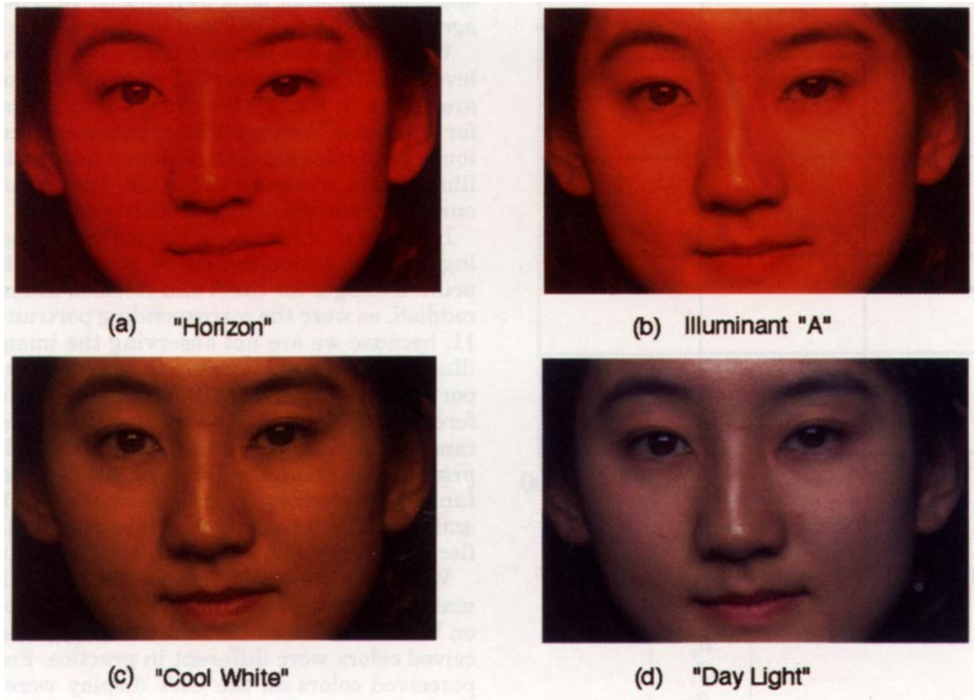


Figure 11. Portrait reproduced on CRT display under four different illuminants. (a) Horizon, (b) A, (c) Cool White, and (d) Daylight.

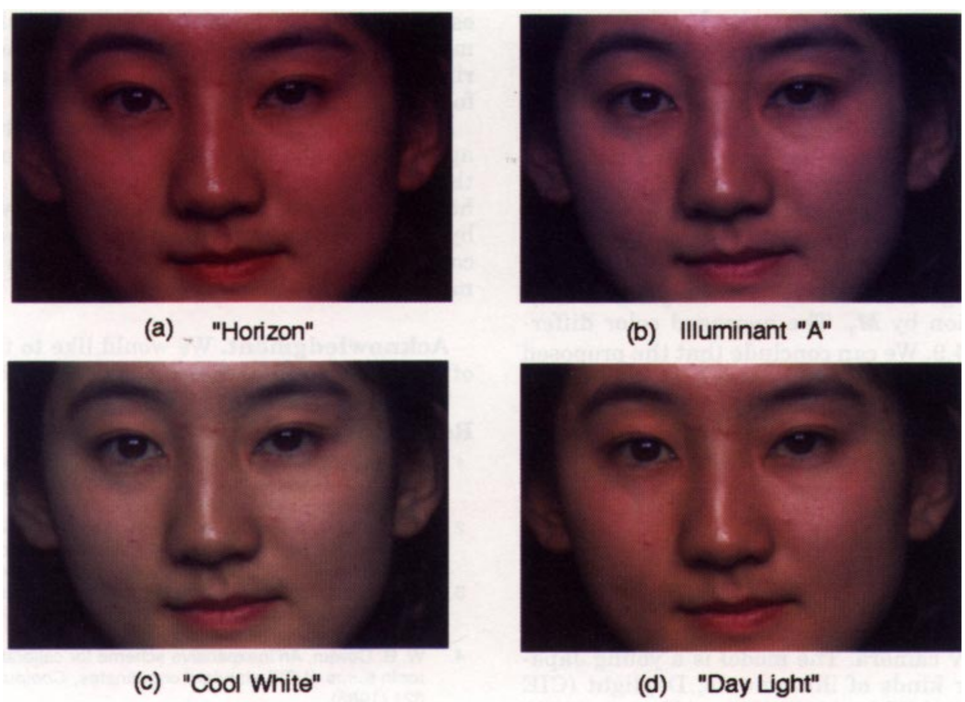


Figure 12. Predicted portrait hardcopy for four different illuminants. (a) Horizon, (b) A, (c) Cool White, and (d) Daylight.

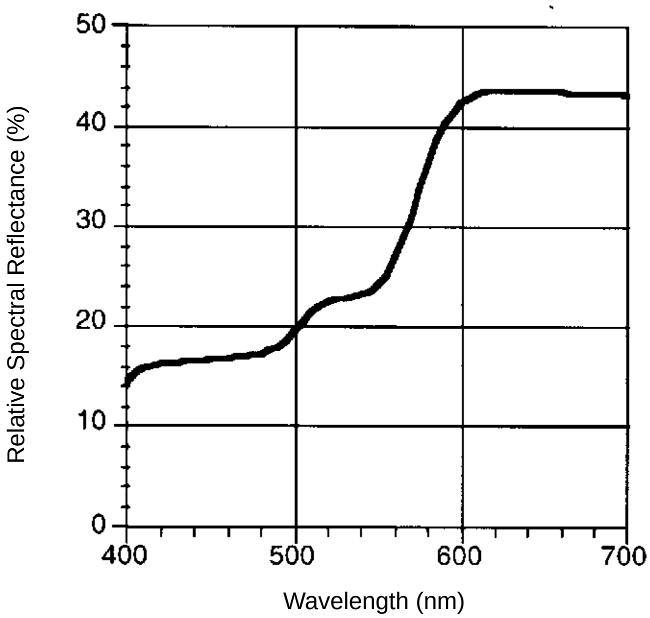


Figure 13. Averaged spectral reflectance of printed skin color.

$$\begin{pmatrix} R_P \\ G_P \\ B_P \end{pmatrix} = \begin{pmatrix} a_{1,1} & a_{1,2} & \dots & a_{1,11} \\ a_{2,1} & a_{2,2} & \dots & a_{2,11} \\ a_{3,1} & a_{3,2} & \cdots & a_{3,11} \end{pmatrix} \begin{pmatrix} R_c \\ G_c \\ B_c \\ R_c^2 \\ G_c^2 \\ B_c^2 \\ R_cG_c \\ G_cB_c \\ R_cB_c \\ R_cG_cB_c \\ 1 \end{pmatrix} \tag{21}$$

The accuracy of this colorimetric color reproduction was evaluated by average color differences of 55 skin color patches used in the multiple regression analysis. Color difference between CRT and hardcopy was calculated with and without color transformation by $\boldsymbol{M}_3$. As shown in Fig. 9, the averaged color difference $\overline{\Delta E^*ab}$ was 19.9 without the color transformation, and 4.5 with the color transformation. Thereafter, 55 skin color patches not used in the multiple regression analysis were printed with color transformation by $\boldsymbol{M}_3$. The averaged color difference $\overline{\Delta E^*ab}$ was 4.9. We can conclude that the proposed color transformation is effective to match the skin color between displayed image and hardcopy. The average calculation time of multiple regression analysis for matrix $\boldsymbol{M}_3$ was 25 seconds in a workstation (SPARC Station II; Sun Micro Systems, Inc.).

Experiments and Discussion

Five portrait images with 1920×1035 pixels were taken by the HDTV camera under the same conditions we used for the two-dimensional measurement of spectral reflectance by the HDTV camera. The model is a young Japanese woman. Four kinds of illuminants; Daylight (CIE D65), A (2856 K), Cool White (4150 K), and Horizon (2300 K) in a standard illumination booth (Macbeth Spectralight II) were used in the experiment. The spectral radiance from 400 to 700 nm of each illuminant was measured by a spectroradiometer as shown in Fig. 10. The predicted images displayed on CRT and hardcopy were observed.

We printed the portrait image directly with the input levels R_c, G_c, B_c of the CRT display. The printed images are shown in Fig. 11. We can see that the portrait images for the A and Horizon illuminants seem reddish, because longer wavelength components predominate in these illuminants, as shown in Fig. 10. These images show that our color reproduction system works well.

In the case of hardcopy, the portrait images printed using transformation matrix $\mathbf{M}_3$ are shown in Fig. 12. The printed images for the A and Horizon illuminants are not reddish, as were the corresponding portrait images in Fig. 11, because we are not observing the images under each illuminant. Here it is noted that the colors of the printed portrait images in Fig. 12 are slightly different. The differences are explained by the fact that the spectral reflectance of human skin and the spectral reflectance of the printed skin color are different. Averaged spectral reflectance of printed skin color is shown in Fig. 13. From Fig. 2 and Fig. 13, we can see the differences of the spectral reflectance between human skin color and printed skin color.

We can conclude that our color reproduction system can make a colorimetric color reproduction of portrait images on both a CRT monitor and hardcopy. However, the perceived colors were different in practice. For example, the perceived colors on the CRT display were more reddish than perceived skin color, because we are not considering chromatic adaptation in the reproduction of portrait images on the CRT monitor.

Conclusion and Future Work

In this work, we colorimetrically predicted skin color images under various illuminants on both the CRT display and hardcopy. The color reproduction is based on the estimation of the spectral reflectance of skin. The two-dimensional estimation of spectral reflectance allowed colorimetric reproduction without colorimetric measurements for each illuminant.

The color reproduction described in this paper is not applicable to the lips, hair, eyes, and so on, because only the spectral reflectance of human skin was considered here. The proposed reproduction method will be improved by using their spectral reflectances. Furthermore research considering color appearance models, such as the von Kries model,[5] should also be performed.

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