Optimization of Color Dyes for Spectral and Colorimetric Color Reproduction Ⅱ

Takayuki Ogasahara, Visual Information Technology Development Laboratory, CANON INC. 30-2, Shimomaruko 3-chome, Ohta-ku, Tokyo 146-8501, Japan, E-mail: Ogasahara.takayuki@canon.co.jp, Takayuki0513@aol.com

Abstract

In the previous study, the author showed that it is difficult to obtain the optimum combination of color dyes satisfying both spectral and colorimetric color reproduction. The current ink jet printers have solved this problem by a multi-color ink jet system. However, the system above makes color separation process converting RGB to CMYK complicated. The purpose of this study is to reveal the characteristics of the optimum color dyes for spectral and colorimetric color reproduction by means of a computer simulation, and it gives direction in order to design subtractive color dyes. In this paper, spectral RMS error and the size of the color gamut were calculated between the optimum dye sets for spectral and colorimetric color reproduction. Then, the relationship between spectral RMS error and the size of color gamut was evaluated by the peak wavelengths and widths of absorption bands composing the optimum three dyes for colorimetric color reproduction. The result above shows that it is an effective way to make an absorption band at long wavelength broader for satisfying both spectral and colorimetric color reproduction.

Introduction

Development for the optimum subtractive color dyes will rely on the full understanding of the relationship between dye amount placed on the paper and resultant color. The optimum subtractive color dyes in a photographic subtractive color dyes have previously been studied by means of a computer simulation [1][2]. The obtained results have showed that it is very effective to use computer simulation for development of the optimum subtractive color dyes. In the previous studies [3]-[6], the authors verified predicting models for dye-based color IJs. Among the predicting models, KM approximately reproduced the color gamut of the coated paper used in a dye-based color IJ. Then, the optimum combinations of subtractive color dyes for colorimetric color reproduction were obtained by means of a computer simulation [7]-[9].

The purpose of this study is to search for the optimum dye sets for spectral and colorimetric color reproduction, and to give direction to design subtractive color dyes. Then, it is assumed that the relationship between dye amount placed on the coated paper and resultant color is based on a simple model. Considering the condition above, KM has been used for prediction of the resultant color reproduced by subtractive color dyes. The previous study was solved the optimum combinations of subtractive color dyes for spectral and colorimetric color reproduction by means of a computer simulation. Then, it is a very effective way to increase the number of dyes for spectral and colorimetric color reproduction; however, it is a large difference between the wavelengths and widths of absorption bands for spectral and colorimetric color reproduction.

Based on the previous result, the optimum dye sets between spectral and colorimetric color reproduction have been compared by spectral RMS error and the size of the color gamut. Then, focused on the optimum combination of three dyes for colorimetric color reproduction, the relationship between spectral RMS error and the size of color gamut has been evaluated by the peak wavelengths and widths of absorption bands. The result above shows that it is an effective way to make an absorption band at long wavelength broader for satisfying both spectral and colorimetric color reproduction.

Predicting Models

In the previous study [6], some models were studied from the viewpoint of prediction accuracy for the reproducible color gamut of the coated paper in a dye-based color IJ. Among the models, KM that relies only on the reflectances of the primary colors approximately reproduced the color gamut. KM [10]-[13], which was developed as a series of equations useful for predicting reflectance in many types of colorant systems, is often used as an approach for translucent and opaque media. In particular, KM for transparent film on opaque support is written as follows:

$$\hat{R}_{\lambda}(\lambda) = R_{\lambda,paper}(\lambda)\exp\left\{-2\left(\sum_i c_i k_{\lambda,i}\right)\right\} \qquad (1)$$

$$k_{\lambda,i} = -0.5\ln\{R_{\lambda,i}(\lambda)/R_{\lambda,paper}(\lambda)\} \qquad (2)$$

where $\hat{R}_{\lambda}(\lambda)$ is the predicted spectral reflectance, $R_{\lambda,i}(\lambda)$ is the measured spectral reflectance of primaries, and $R_{\lambda,paper}$ is the spectral reflectance of the paper. c_i represents concentration, and $k_{\lambda,i}$ defines the absorption coefficient of the i-th colorant.

It can be seen in Eq. 1 that KM takes into consideration absorption coefficient only. However, the actual reflection includes the scattering coefficient and surface reflection also in the colorant layer. In this study, it is important to give direction in order to design subtractive color dyes, so it is assumed that the relationship between dye amount placed on the coated paper and resultant color is based on a simple model: there are little scattering coefficient and no surface reflection. The previous study [6] also shows that the absorption coefficient $k_{\lambda,i}$ in Eq.1 works well as a fitting parameter. Then, this study has used KM for prediction of resultant color reproduced by subtractive color dyes.

Experimental Results

In this paper, hypothetical absorption bands are used by numerically fitting suitable functions to actual absorption bands. An absorption band is based on symmetric cubic spline function (SCSF) by using the two primary parameters of the peak wavelength and width [14], and its cubic spline function is written as follows:

$$C(\lambda)=\begin{cases}\dfrac{w^3+3w^2\left(w-|\lambda-\lambda_0|\right)+3w\left(w-|\lambda-\lambda_0|\right)^2+3\left(w-|\lambda-\lambda_0|\right)^3}{6w^3}, \\ |\lambda-\lambda_0|\le w \\ \dfrac{\left(2w-|\lambda-\lambda_0|\right)^3}{6w^3}, w\le|\lambda-\lambda_0|\le 2w \\ 0, otherwise\end{cases}$$

(3)

which λ_0 is the peak wavelength of absorption band, w is the width of absorption band, and the peak densities are normalized to 1.0 for $C(\lambda)$.

The absorption band that is defined by symmetric cubic spline function in Eq. 3 has been studied by means of a computer simulation. Spectral RMS error for 24 samples of Macbeth Color Checker was calculated in steps of 10 nm in the ranges between 400 nm and 700 nm. The size of the color gamut was also calculated at nine lightness levels of $L^*=$ 10, 20, 30, 40, 50, 60, 70, 80 and 90 under illuminant D50 and $2°$ observer [1]. The dye-based color IJ simulation was built from the use of KM. The Simplex method [14] was employed to depict color gamut.

Then it needs to select the optimum dye set satisfying both spectral and colorimetric color reproduction. This problem is classified as a constrained nonlinear optimization, and is solved by the direction-set method [15]-[18].

Based on the previous study [9], table 1 shows the peak wavelengths and widths of absorption bands composing the optimum dye sets for minimizing spectral RMS error of 24 samples of Macbeth Color Checker. Figure 1 shows the spectral reflectances of the optimum combinations of three dyes and six dyes for minimizing spectral RMS error. It can be seen in Table 1 that all peak wavelengths of absorption bands are scattered over the wavelength region between 400 nm and 700 nm.

Table 2 shows the peak wavelengths and widths of absorption bands composing the optimum dye sets for maximizing the size of the color gamut. Figure 2 shows the spectral reflectances of the optimum combinations of three dyes and six dyes for maximizing the size of the color gamut. It can be seen in Fig. 2 that all peak wavelengths of absorption bands exist at less than 620 nm.

Table 1. Peak wavelengths and widths of absorption bands for minimizing spectral RMS error

	Peak wavelength [nm]	Widths [-]
3 dyes	420,540,660	90,70,100
4 dyes	410,530,620,690	90,70,90,100
5 dyes	410,510,540,630,690	90,50,70,80,100
6 dyes	400,480,530,550,630, 690	70,50,120,60,80,110

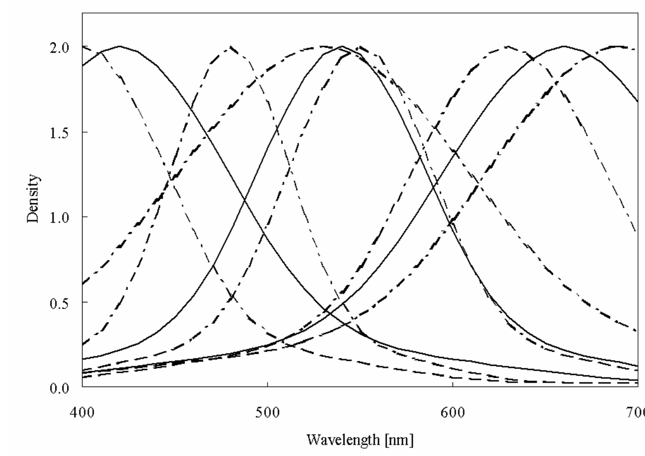

Figure 1. Spectral reflectances of the optimum combinations of three dyes (solid lines) and six dyes (dotted lines) for minimizing spectral RMS error.

Table 2. Peak wavelengths and widths of absorption bands for maximizing color gamut

	Peak wavelength [nm]	Widths [-]
3 dyes	440,530,610	50,40,60
4 dyes	430,510,570,640	70,40,40,50
5 dyes	440,460,530,610,670	50,100,50,50,60
6 dyes	410,430,480,520,570, 620	60,130,80,40,50,40

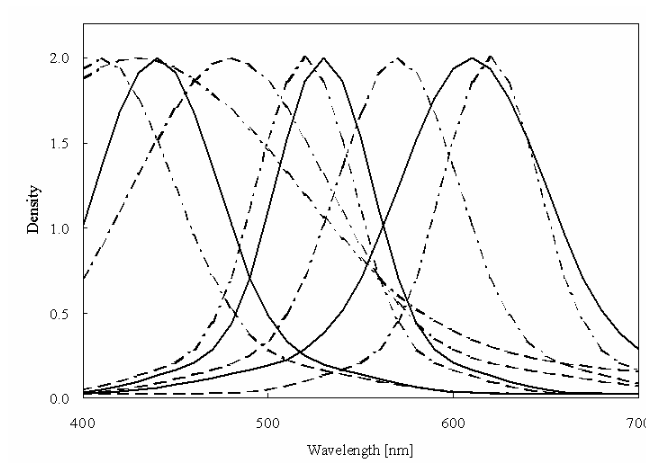

Figure 2. Spectral reflectances of the optimum combinations of three dyes (solid lines) and six dyes (dotted lines) for maximizing the color gamut.

Comparison between The Optimum Dye Sets for Spectral and Colorimetric Color Reproduction

In comparison between the optimum dye sets for spectral and colorimetric color reproduction, the widths of absorption bands for spectral color reproduction are broader than those for colorimetric color reproduction. It can be considered that the narrower band gives an increase of the color gamut because of few unwanted secondary absorptions that lead to a reduced color gamut [19].

Figure 3 shows a comparison of the size of the color gamuts obtained by the optimum dye sets for spectral and colorimetric color reproduction. It can be seen in Fig. 3 that both of them expand the size of the color gamuts by increasing the number of dyes. However, the size of the color gamut obtained by the optimum combination of three dyes for colorimetric is almost the same as that of six dyes for spectral color reproduction.

Figure 4 shows a comparison of spectral RMS error for 24 samples of Macbeth Color Checker calculated by the optimum dye sets for spectral and colorimetric color reproduction. The optimum dye sets for colorimetric color reproduction could not improve spectral RMS error by increasing the number of dyes. The result above shows that there is a large difference between the wavelengths and widths of absorption bands for spectral and colorimetric color reproduction.

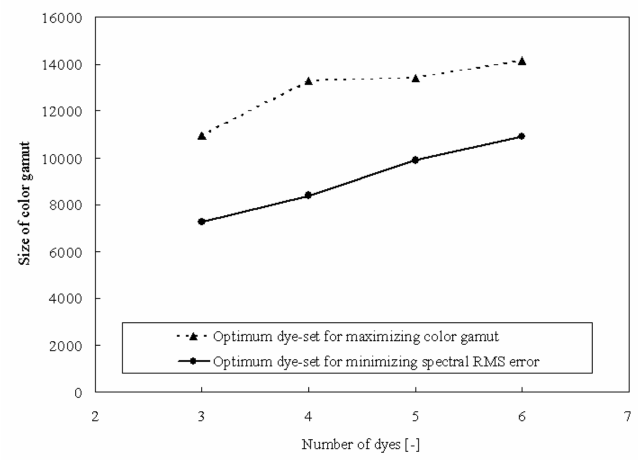

Figure 3. Comparison of the size of the color gamuts obtained by the optimum dye sets for spectral color reproduction (solid line), and that for colorimetric color reproduction (dotted line) under illuminant D50 and 2° observer.

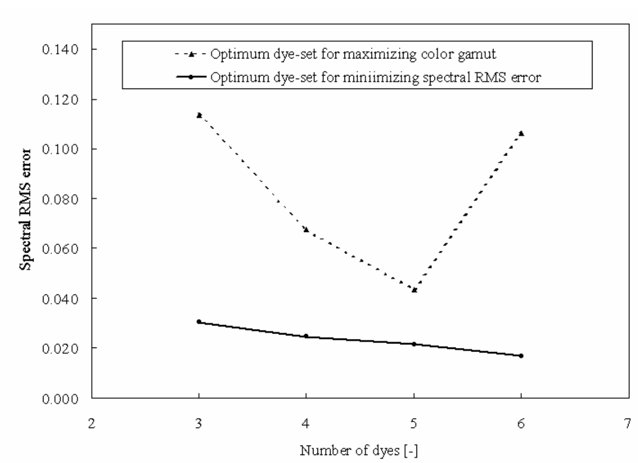

***Figure 4.** Comparison of spectral RMS error for 24 samples of Macbeth Color Checker calculated by the optimum dye sets for spectral color reproduction (solid line), and that for colorimetric color reproduction (dotted line).*

The Combination of Three Dyes Satisfying both Spectral and Colorimetric Color Reproduction

Focused on the optimum combination of three dyes for maximizing the size of the color gamut, the relationship between spectral RMS error and the size of color gamut was evaluated by the peak wavelengths and widths of absorption bands.

Table 3 shows the peak wavelengths and widths of absorption bands for expanding the size of the color gamut based on the optimum combination of three dyes for minimizing spectral RMS error. Figure 5 shows that the optimum absorption bands of yellow and cyan for minimizing spectral RMS error give the size of the color gamut a small decrease, and that of magenta gives it a large decrease. It can be seen in Fig 6 that the optimum absorption band of cyan for minimizing spectral RMS error improves color inconstancy index (CII) [20] and metamerism index (MI) largely. MI is calculated as the CIE94 color difference between measured and reproduced tristimulus values for 18 examples (Nos. 1-18) out of 24 samples of Macbeth Color Checker under illuminants D50, A and F11 respectively. CII is calculated as the CIE94 color difference of reproduced tristimulus values for 6 examples (Nos. 19-24) out of 24 samples of Macbeth Color Checker between illuminant D50 and some illuminants. Then, it is an effective way to make an absorption band at long wavelength broader for satisfying both spectral and colorimetric color reproduction.

Table 3. Peak wavelengths and widths of absorption bands for maximizing color gamut

	Peak wavelength [nm]	Widths [-]
Yellow	**420**,540,660	**110**,70,100
Magenta	420,**590**,660	90,**110**,100
Cyan	420,540,**650**	90,70,**110**

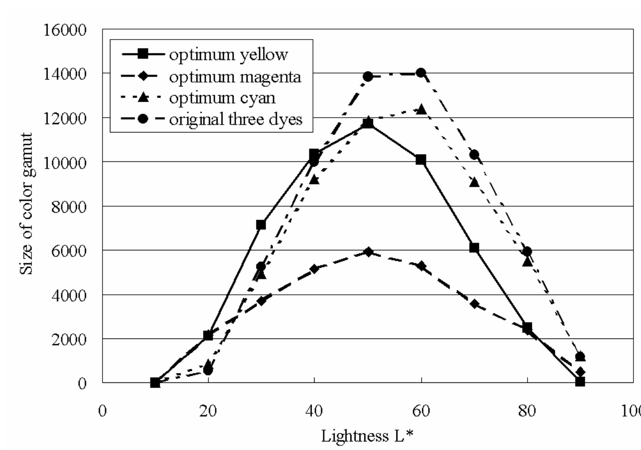

Figure 5. The relationship between lightness L and the size of the color gamuts obtained by the combinations of three dyes for maximizing the color gamut under illuminant D50 and 2° observer.*

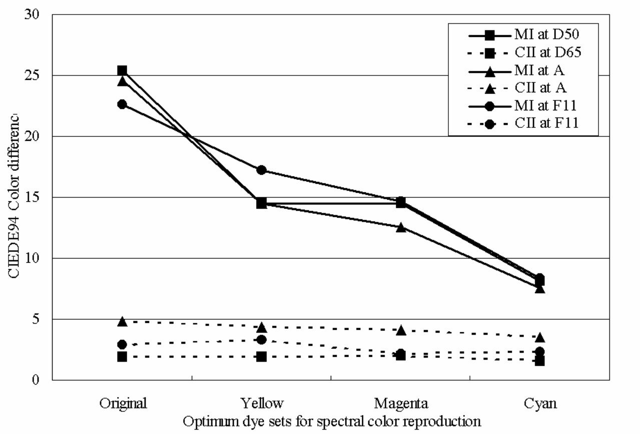

Figure 6. The relationship between CIEDE94 color difference and the size of the color gamuts obtained by the combinations of three dyes for maximizing the color gamut under illuminant D50 and 2° observer.

Conclusion

The results obtained by means of a computer simulation showed that it is a very effective way to increase the number of dyes for spectral and colorimetric color reproduction. In comparison between the optimum dye sets for spectral and colorimetric color reproduction, the widths of absorption bands for spectral color reproduction are broader than those for colorimetric color reproduction. For the optimum combination of six dyes, the peak wavelengths of absorption bands for spectral color reproduction are scattered over the wavelength region between 400 nm and 700 nm, and those for colorimetric color reproduction exist at less than 620 nm. Then, it is a large difference between the wavelengths and widths of absorption bands for spectral and colorimetric color reproduction.

Focused on the optimum combination of three dyes for colorimetric color reproduction, the relationship between spectral RMS error and the size of color gamut was evaluated by the peak wavelengths and widths of absorption bands. The result above shows that it is an effective way to make an absorption band at long wavelength broader for satisfying both spectral and colorimetric color reproduction.

In a future study, the author will solve the relationship between dye amount placed on the paper and resultant color, and develop the dye set satisfying both spectral and colorimetric color reproduction.

Acknowledgement

The author would like to thank Dr. N. Ohta and Dr. M. Inui for their helpful suggestions, and Dr. N. Kawamura, Mr. T. Makita and Mr. A. Ushiroda for their interest and permission to publish this paper.

References

[1] N. Ohta, "The Color Gamut Obtainable by the Combination of Subtractive Color Dyes. I. Actual Dyes in Color Film. (1) Optimum Peak Wavelengths and Breadths of Cyan, Magenta, and Yellow," *Photogr. Sci. Eng.*, **15**(5), 399-422 (1971).

[2] N. Ohta, "The Color Gamut Obtainable by the Combination of Subtractive Color Dyes. I. Actual Dyes in Color Film. (3) Stability of Gray Balance," *Photogr. Sci Eng.*, **16**(3), 203-207 (1972).

[3] T. Ogasahara and N. Ohta, "Verification of the Optimum Prediction Model for Dye-Based Inkjet Printer," *Proc. of the IS&T PICS 2003 Conference,* Rochester, NY, 429-434 (2003).

[4] T. Ogasahara, "Optimization of the Printing Model for Dye-Based Inkjet Printer," *Proc. of the IS&T NIP19 Conference,* New Orleans, LA, 785-788 (2003).

[5] T. Ogasahara, "Verification of the Predicting Model and Characteristics of Dye-Based Inkjet Printer," *J. Imaging Sci Tech.,* **48**(2), 136-143 (2004).

[6] T. Ogasahara, "Optimization of Subtractive Color Dyes for Dye-Based Color Inkjet Printer," *Proc. of the 11th Color Imaging Conference,* Scottsdale, *AZ*, 218-223 (2003).

[7] T. Ogasahara, "Optimization of Subtractive Three Color Dyes for Dye-Based Color Inkjet Printer", *J. Imaging Sci Tech.,* **48**(2), 502-510 (2004).

[8] T. Ogasahara, "Optimization of Subtractive Four Color Dyes for Dye-Based Color Inkjet Printer", *J. Imaging Sci Tech.,* **48**(2), 511-518 (2004).

[9] T. Ogasahara, "Optimization of Color Dyes for Spectral and Colorimetric Color Reproduction," *Proc. of the IS&T NIP21 Conference,* Baltimore, ML, 372-375 (2005).

[10] A. Beer, "Bestimmung der absorption des rothen lichts in farbigen flussigkeiten," *Ann. Phys. Chem.,* **86**(2), 78(1852).

[11] G. Wyszechki and W. S. Stiles, "Color Science: Concepts and Methods," Quantitative Data and Formulae"2nd edition. New York: John Wiley & Sons, 30(1982).

[12] P. Kubelka and F. Munk, "Ein Beitrag zur Optik der Farbanstriche," *Z. Tech Phys.* **12,** 593-601 (1931).

[13] H. R. Kang, "Kubelka-Munk Modeling of Ink Jet Mixing," *J. Imaging Sci Tech.,* **17**(2), 76-83(1992).

[14] N. Ohta, Introduction to Color Reproduction Technology, Corona Publishing Co., Ltd., (1997).

[15] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, Numerical Recipes in C [Japanese version], Gijutsu-Hyohron Co., Ltd., 282-338 (1993).

[16] R. P. Brent, Algorithms for Minimization without Derivatives, Prentice-Hall Inc., **7,** (1973).

[17] F. S. Acton, Numerical Methods That Work, Harper and Row, 464-467 (1970).

[18] D. A. H. Jacobs, The State of the Art in Numerical Analysis, Academic Press, 259-262 (1977).

[19] Y. Chen R. S. Berns and L. A. Taplin, "Improving the Color Constancy of Prints by Ink Design," *Proc. of the 13th Color Imaging Conference,* Scottsdale, *AZ*, 159-164 (2005).

[20] N. Ohta, "The Color Gamut Obtainable by the Combination of Subtractive Color Dyes I. Actual Dyes in Color Film. (2) Influence of Unwanted Secondary Absorption Peak," *Photogr. Sci. Eng.*, **15**(5), 416-422 (1971).

Author Biography

Takayuki Ogasahara received his B.S. and M.S. degrees in nuclear engineering from Nagoya University, Japan in 1994 and 1996. Since then, he has been employed at CANON INC. His work has primarily focused on the optimization of subtractive color dyes, development of image processing and image quality issues. Between 2002 and 2004, he was a visiting scientist at Munsell Color Science Laboratory of Rochester Institute of Technology. He is a member of the IS&T.