Optimization of Subtractive Color Dyes for Dye-Based Color Inkjet Printer

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Abstract

In general, subtractive color dyes used for current inkjet printers (IJs) are selected from among many potential dyes. However, such trial-and-error approaches are inefficient, and there remain questions as to how to guarantee a truly optimum dye set. Thus, development of a computer simulation system to choose the optimum subtractive color dyes is an important goal.

In a previous study, the Cellular Neugebauer model (CNM) was shown to achieve sufficient prediction accuracy. However, prediction by CNM requires knowledge of the spectral reflectances of the secondary colors included in the Neugebauer primary set, and hence it is very difficult to use for evaluating the hypothetical subtractive color dyes.

Alternative models are available that rely only on the spectral reflectances of the primary colors. These include the Kubelka-Munk equation (KM) and the Williams and Clapper equation (WC). The drawback of these models is that they are most appropriately applied to prediction of color in photographic color paper. Fortunately, coated paper for dye-based color IJs has advanced to the point that there are now products available that are similar to that of a photographic color paper. The present study evaluates the prediction capability of KM and WC for high quality coated paper of dye-based color IJs.

Furthermore, a novel approach has been proposed by taking into account dot gain. The color gamuts of dye-based color IJs have been calculated by means of a computer simulation. These have been compared with the color gamuts obtained by CNM.

This study is an important step toward the development of simulations for use in improving image quality for dye-based IJ.

Introduction

Recently, IJs have been rapidly advancing. Among a variety of factors controlling image quality of dye-based color IJs, granularity and tone reproduction have been improved considerably by ink dilution and small droplet technology. Focused on subtractive color dyes, it will be important to increase the size of the color gamut. Development of the optimum subtractive color dyes will rely on the full understanding of the relationship between dye amounts placed on the paper and resultant colors.

In the field of printing, there are the models used to predict reproduced tristimulus values from dye amounts, such as the Neugebauer model (NM), the Yule-Nielsen Neugebauer model, and the KM.[1-4] Besides, the optimum subtractive color dyes in a color film have previously been studied by means of a computer simulation.[5-7]

In previous studies,[8,9] the authors verified predicting models for a dye-based color IJ, and calculated stability of gray balance and color gamut by means of a computer simulation. Among predicting models, the CNM resulted in the target prediction accuracy of $\Delta E_{94} \cong 1.0$, when the set of primaries was more than 4^N (N is the number of colorants). However, prediction by CNM requires knowledge of the spectral reflectances of the secondary colors as the Neugebauer primaries, and hence it is very difficult to use for evaluating hypothetical dyes.

On the other hand, quality of a coated paper for current dye-based color IJs has been improved considerably. As a result of improvement of gloss, sharpness, and ink absorption speed, the structure of a coated paper has become very similar to that of a photographic color paper.

The present study has focused on models that can predict reproduced tristimulus values only from the primary colors. The KM, WC, and modified KM have been evaluated. Further, color gamuts have been calculated by means of a computer simulation, and these have been compared with the color gamuts obtained by CNM.

Predicting Models

The KM,[10] 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, the KM for transparent film on opaque support is written as follows:

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

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

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.

In a photographic color paper, Williams and Clapper proposed a transformation formula considering the multiple internal reflections in a gelatin layer (the relative index of refraction of gelatin was taken as 1.53).[11,12] Then Ohta verified their transformation formula experimentally in a photographic color paper.[13] The WC is written as follows:

$$R = 0.193T^{2.13}\left[\frac{1}{2R_B} - \int_0^{\pi/2} T^{2\sec\theta} r_\theta \sin\theta\cos\theta d\theta\right]^{-1} \quad (3)$$

where

$T =$ transmittance of the gelatin layer
$R_B =$ reflectance of the paper base
$\theta =$ angle of reflection of the light from the paper base
$r_\theta =$ internal Fresnel reflectance of the interface θ
$R =$ reflectance when that of the paper base

Experimental Results

A CANON S900 was used as a color dye-based IJ. Its spatial addressability is $1200dpi \times 1200dpi$. In this present study, three inks: cyan (C), magenta (M), and yellow (Y), and a typical coated paper were used. A GretagMacbeth SpectroScan spectrophotometer was used to make all the spectral measurements. The predicting models described above were used and compared.

Prediction Accuracy by KM and WC

The WC is the predicting model for a photographic color paper, and hence it is necessary to modify for use in a dye-based color IJ. It is assumed in Fig. 1 that the gelatin layer in a photographic color paper corresponds to the ink absorption layer in a coated paper. In an attempt to obtain the value of R_B in Eq. 3, three base papers with different thickness of ink absorption layer were produced. The spectral reflectances of these three base papers are shown in Fig. 2. Figure 2 shows that the spectral reflectances of these three base papers are approximately the same, so transmittance of an ink absorption layer is close to 1.0 ($T = 1.0$). Then equation 3 can be written as follows:

$$R_B \cong 0.5\left(\frac{0.193}{R_0} + 0.307\right) \quad (4)$$

where R_0 is the spectral reflectance of $T = 1.0$, and R_B is easily obtained form Eq. 4. Transmittance of the ink absorption layer T can be obtained by the Simplex method from R_B and the measured spectral reflectances of C, M, and Y. Then the predicted spectral reflectance can be calculated by deciding ink volumes through minimizing RMS spectral error. Predicted spectral transmittance curves of 12-step ramps of cyan (C) are shown in Fig. 3. Spectral density curves of C, M, and Y that are used by a dye-based IJ are shown in Fig. 4 after normalizing peak density to 1.0.

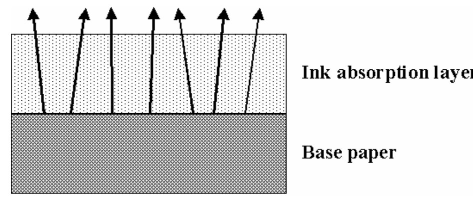

Figure 1. Illustration of the structure of a coated paper in a dye-based color IJ

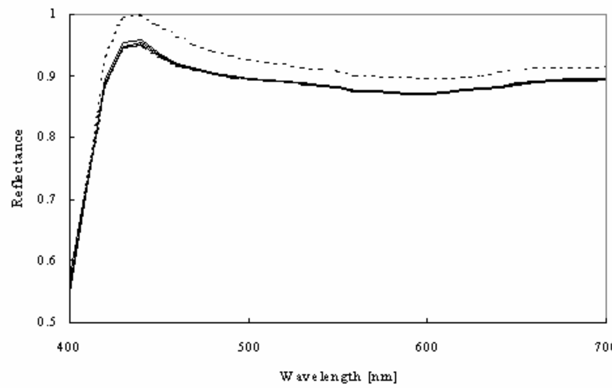

Figure 2. Spectral reflectances of base paper (dotted line) and base paper with ink layers of different thickness (solid lines) in a dye-based color IJ

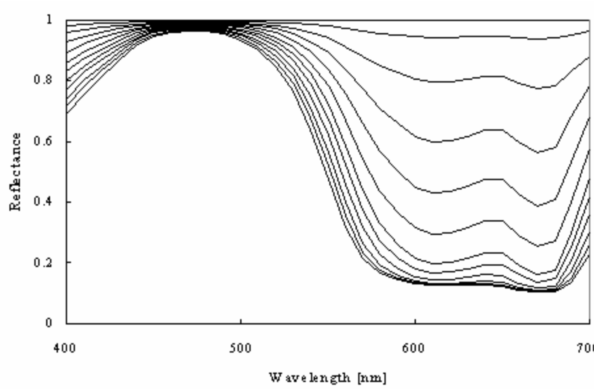

Figure 3. Spectral transmittances of 12 examples out of 33-step ramps of cyan (C) obtained by the Simplex method

99 (33×3) printed samples that composed of 33-step ramps of C, M, and Y were used for evaluation of each predicting model. It can be seen in Tables 1 and 2 that the KM and WC could not achieve sufficient prediction accuracy for cyan and yellow as $\Delta E_{94} \geq 1.0$ and $RMS \geq 0.015$.

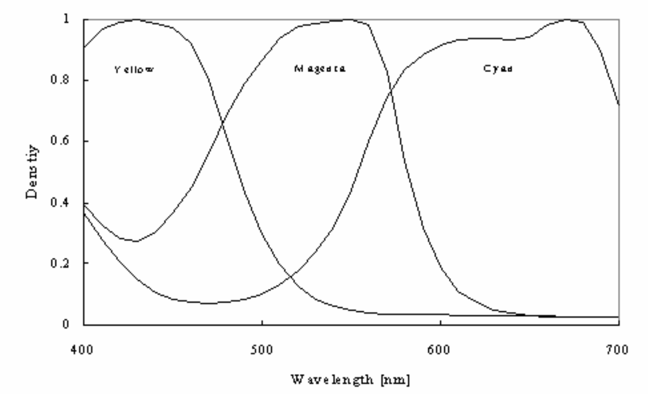

Figure 4. Spectral density distributions of C, M, and Y dyes for a dye-based color IJ after normalizing to 1.0 peak density

Table 1. Prediction accuracy by KM

	Cyan	Magenta	Yellow
Average ΔE_{94} D65	1.97	0.80	1.11
Standard deviation	1.45	0.60	0.60
Maximum	4.76	2.07	1.98
Minimum	0.00	0. 00	0. 00
Average ΔE_{94} A	1.81	0.81	1.02
RMS spectral error	0.015	0.012	0.020

Table 2. Prediction accuracy by WC

	Cyan	Magenta	Yellow
Average ΔE_{94} D65	1.85	1.07	0.61
Standard deviation	1.17	0.73	0.25
Maximum	3.53	2.42	1.04
Minimum	0.00	0.00	0.04
Average ΔE_{94} A	1.93	0.92	0.50
RMS spectral error	0.015	0.012	0.016

The color gamuts by C, M, and Y of Fig. 4 when they were used in a coated paper have been studied by means of a computer simulation. A color gamut can be calculated at four lightness levels of $L^* = 40$, 50, 60, and 70 by using the Newton-Raphson technique. The numerical integration was done with the Simpson's rule together with Newton's 3/8 rule,[13] and all code was written in C.

One aspect of this study is to verify whether the models can be used to accurately predict the colorimetric gamut by a hypothetical dye set. The color gamuts obtained by KM and WC were compared with those obtained by CNM.

The results are shown in Figs. 5-8 for the KM, WC, and CNM. It can be seen in Figs. 5-8 that the cyan-yellow areas of color gamuts obtained by KM and WC are a little smaller than those of color gamuts obtained by CNM. The yellow-magenta areas of color gamuts obtained by KM have a tendency to become a little bigger than those of color gamuts obtained by CNM when lightness level is less than 50. However, both equations can roughly predict the color gamuts for dye-based IJs.

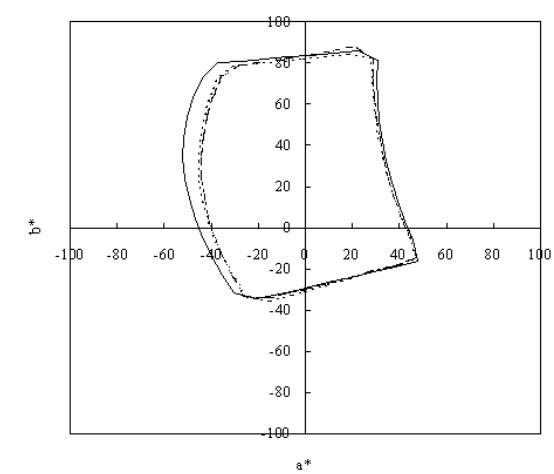

Figure 5. Color gamuts in a dye-based color IJ obtained by KM (broken line), WC (dotted line), and CNM (solid line) at L = 70*

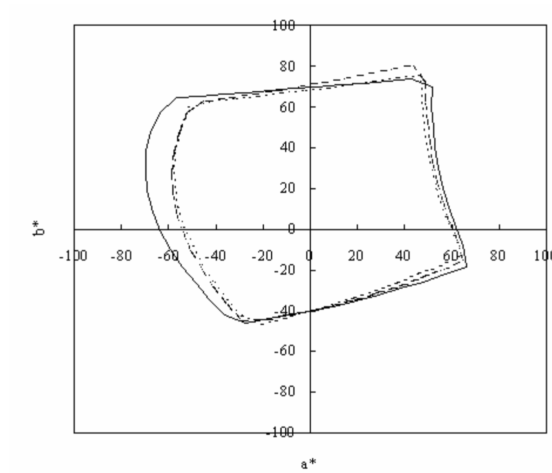

Figure 6. Color gamuts in a dye-based color IJ obtained by KM (broken line), WC (dotted line), and CNM (solid line) at L = 60*

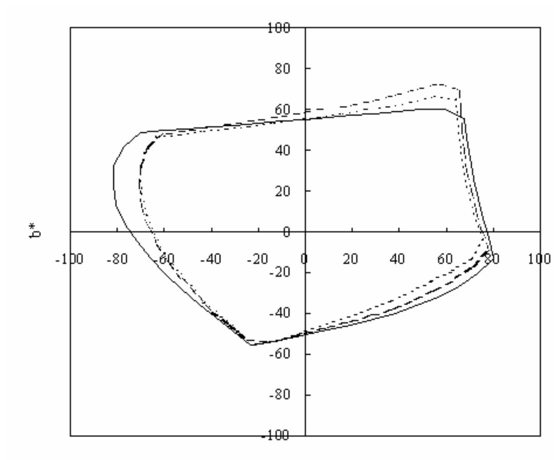

Figure 7. Color gamuts in a dye-based color IJ obtained by KM (broken line), WC (dotted line), and CNM (solid line) at L = 50*

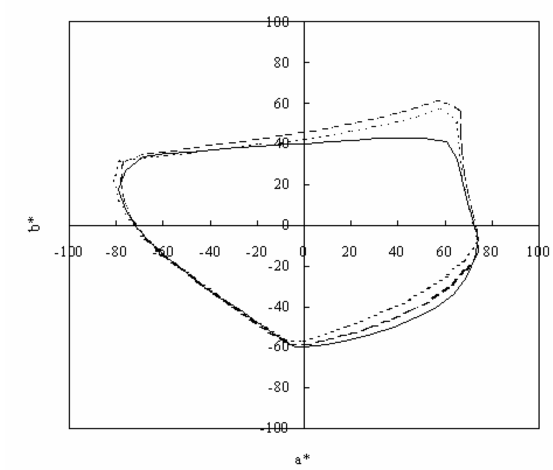

Figure 8. Color gamuts in a dye-based color IJ obtained by KM (broken line), WC (dotted line), and CNM (solid line) at L = 40*

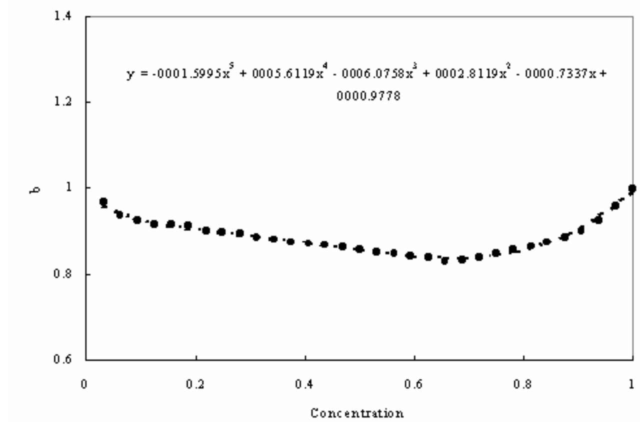

Figure 9. The value of b *obtained by the Simplex method*

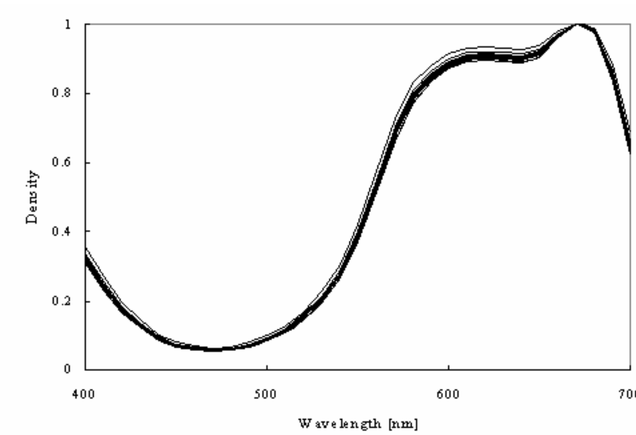

Figure 10. Modified spectral density $D'_{\lambda,i}(\lambda)$ *of 12 examples out of 33-step ramps of cyan (C) after normalizing to 1.0 peak density*

Prediction Accuracy by Modified KM

In a previous study,[9] the author proposed a modified NM that takes into account dot gain. From its equation, we can obtain Eqs. 5, 6, and 7.

$$D'_{\lambda,i}(\lambda) = 1.0 - (1.0 - D_{\lambda,i}(\lambda))^b \quad (5)$$

$$b = f(c) \quad (6)$$

$$R'_{\lambda,i}(\lambda) = 10^{-t}, t = D'_{\lambda,i}(\lambda) \quad (7)$$

where $D_{\lambda,i}(\lambda)$ is the measured spectral density of primary, $D'_{\lambda,i}(\lambda)$ is the modified spectral density of primary, and $R'_{\lambda,i}(\lambda)$ is the modified spectral reflectance of primary. The author applied the same modification to the KM. The value of b for the modified KM can be obtained by the Simplex method through minimizing RMS spectral error, and the same value is used for each colorant unless dye concentration is greatly different. The values of b and $D'_{\lambda,i}(\lambda)$ after normalizing to 1.0 peak density are shown in Figs. 9 and 10. Then, the predicted spectral reflectance $\hat{R}_{\lambda}(\lambda)$ is easily calculated from Eqs. 1 and 2 by using $R_{\lambda,i}(\lambda)$.

99 (33×3) printed samples that composed of 33-step ramps of C, M, and Y were used for evaluation. As shown in Table 3 and Fig. 11, the modified KM resulted in the achievement of sufficient prediction accuracy as $\Delta E_{94} < 1.0$ and $RMS < 0.015$.

Table 3. Prediction accuracy by modified KM

	Cyan	Magenta	Yellow
Average ΔE_{94} D65	0.76	0.53	0.58
Standard deviation	0.38	0.24	0.25
Maximum	1.37	0.92	0.88
Minimum	0.00	0. 12	0. 05
Average ΔE_{94} A	0.79	0.46	0.62
RMS spectral error	0.009	0.008	0.013

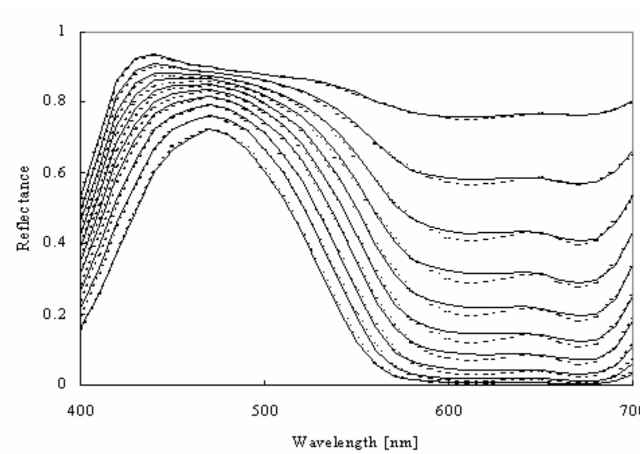

Figure 11. Measured spectral reflectances (dotted lines) and predicted spectral reflectances obtained by modified KM (solid lines) for 10 examples out of 33-step ramps of cyan (C)

As before, the color gamut was calculated at four lightness levels of $L^* = 40$, 50, 60, and 70 and is shown in Figs. 12-15. It can be seen in Figs. 12-15 that the yellow-magenta color gamuts obtained by modified KM have slightly bigger area than those obtained by CNM. This is due to insufficient accuracy for 3-colorant prediction by modified KM. However, the modified KM can exactly reproduce color gamuts except the yellow-magenta areas.

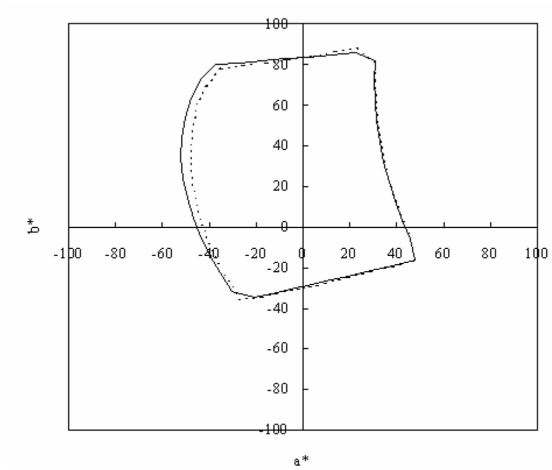

Figure 12. Color gamuts in a dye-based color IJ obtained by modified KM (solid line) and CNM (dotted line) at L = 70*

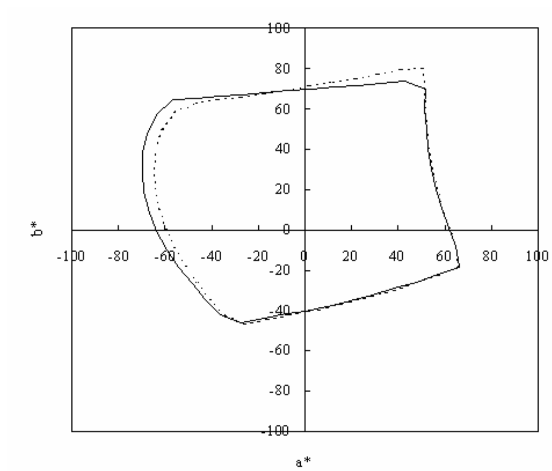

Figure 13. Color gamuts in a dye-based color IJ obtained by modified KM (solid line) and CNM (dotted line) at L = 60*

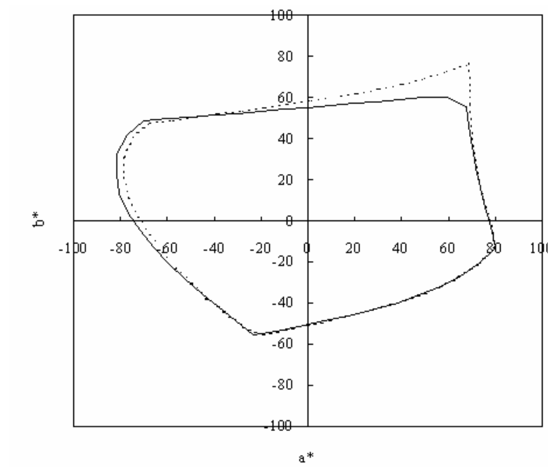

Figure 14. Color gamuts in a dye-based color IJ obtained by modified KM (solid line) and CNM (dotted line) at L = 50*

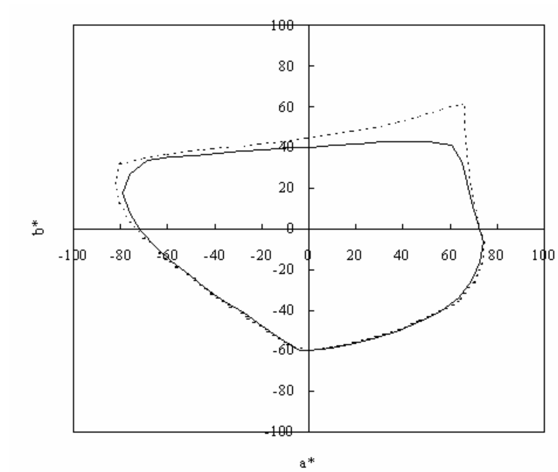

Figure 15. Color gamuts in a dye-based color IJ obtained by modified KM (solid line) and CNM (dotted line) at L = 40*

Conclusion

The KM and WC were evaluated by ΔE_{94} and RMS for spectral prediction accuracy. 33-step ramps of C, M and Y showed that both equations could not achieve sufficient prediction accuracy as $\Delta E_{94} > 1.0$ and $RMS > 0.015$. However, the color gamuts obtained by both equations roughly corresponded to those obtained by CNM.

However a modified KM accounting for dot gain achieved sufficient prediction accuracy as $\Delta E_{94} < 1.0$ and $RMS < 0.015$ for evaluation of 33-step ramps of C, M and Y. Furthermore, the color gamuts obtained by modified KM exactly corresponded to those obtained by CNM except the yellow-magenta areas.

The areas that are composed of three-colorant combinations of C, M, and Y in the boundaries of color gamuts have a tendency to increase when lightness level is less than 50. In particular, the areas have become larger in the yellow-magenta areas of color gamuts. Therefore, the modified KM does not achieve sufficient accuracy for 3-colorant prediction where $\Delta E_{94} \cong 3.0$, so the modified KM cannot exactly reproduce the yellow-magenta areas of color gamuts.

In a future study, the author will improve 3-colorant prediction accuracy by modified KM, and the optimum subtractive color dyes for a dye-based color IJ will be developed by means of a computer simulation.

Acknowledgement

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Biography

Takayuki Ogasahara received his BS and MS degrees in nuclear engineering from Nagoya University in 1994 and 1996. Since then, he has been employed at CANON INC. in VITD Lab. His work has primarily focused on the development of image processing, including optimization of subtractive color dyes, halftoning, and image quality issues. He has developed some inkjet printers such as S900 and S9000. He is a member of the IS&T, and a visiting scientist at Rochester Institute of Technology. E-mail: Takayuki0513@aol.com