Image Quality of Digital Photography Prints: I. Color Quality of Thermal Dye-Transfer Prints

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Color hardcopy derived from digital photography is produced using digital data supplied to a printer. The number of digital information levels is decided by image processing conditions and is manipulated using a personal computer. The typical number of levels for continuous-tone rendition of primary color images red (R), green (G) and blue (B) is 256 levels, equivalent to 8 bits (2^8 steps). To date, there have been few studies on the relationship of the number of levels of input image data and output image quality of prints.[1] This report discusses the relationship as it applies to thermal dye-transfer prints. Further, it discusses the appropriateness of thermal dye-transfer printing for continuous-tone pictorial image formation. The evaluations are based on both subjective human viewing and objective colorimetric measurements to discriminate between different patches printed in increments for 256-level data. The results show that a maximum 94% of the input 256-level image data, capable of being seen express different densities in the magenta and black samples under visual examination and about 10 million colors were estimated recognizable on the full-color print in a physical examination. Furthermore, the appropriateness of thermal dye-transfer printing is discussed. A digital data level of 8 bit for a hardcopy system was almost sufficient and reasonable to match human vision and to express continuous tone on the reproductions.

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Introduction

In current digital imaging systems, original picture information is carried by digital image data and manipulated by digital image processing methods using personal computers. Normally, the color information is carried by the additive primary color signals of R, G, and B from the object images captured by cameras, scanners, or images created by a computer. These digital imaging system signals are assigned as data. The R, G, and B image data when sent to a printer are converted into color hardcopy images on the same medium using the subtractive primary color materials, cyan (C), magenta (M), and yellow (Y). Thus, all printed color images are formed by a simple mixture of C, M, and Y colorants.

The color rendering of a hardcopy image is directly related to the tone of the C, M, and Y images on the print. On a print that produces its tone using the direct density method, color reproduction is done by quantitatively depositing C, M, and Y colorants on a substrate. Thermal dye-transfer printing is one of the best color hardcopy systems because the dyes are directly transferred from the donor to the print in direct proportion to the input signal intensity. Thus, this type of print makes a nice example for examining the response to input information versus the output printed image.

The examinations were done using sample prints (specimens) that had a special pattern printed using 256 levels of input image data under calibrated printing conditions. The samples were made using sublimation dye-transfer prints. The C, M, Y, and black patterns on the samples were printed by single and multiple transfers of color media. The main point of the examination was the discrimination recognition between individual density steps printed by serial image data. The evaluations included both subjective human viewing to measure just noticeable differences and objective colorimetric measurements to determine quantitative physical values changes.

Experiments

Specimens and Test Equipment. The specimens were produced using a model thermal dye-transfer media which is compatible with transparent and reflective outputs. Figure 1 shows the scheme of the model medium printing produced using multiple transfers of dyes and a reflector. Basically it is the same as the transparent medium used for an OHP (overhead projector), however, it has an additional white cover on the dye receiving layer.

The transparency was changed into the reflective medium by a white layer in the bottom. During the examinations, the deposition of the dye diffusion layer and a backing reflective layer on the receiving film was observed and analyzed from the reverse side. In this study, a transparent specimen (sample 1) was changed to a reflective specimen (sample 2) that retained the same transferred dye conditions. Sample 2 was thus equivalent to a hardcopy covered by a thick transparent film. This printing medium was a trial product of Sony and was named the “back light media.” The donor called an “ink ribbon,” consisted of serial three-color dye planes of Y, M, C, and a white backing. The receiving sheet was formed of transparent base film and coated with a receiving layer.

The formation of the receiving film after printing was as follows: the dyes were diffused into the surface receiving

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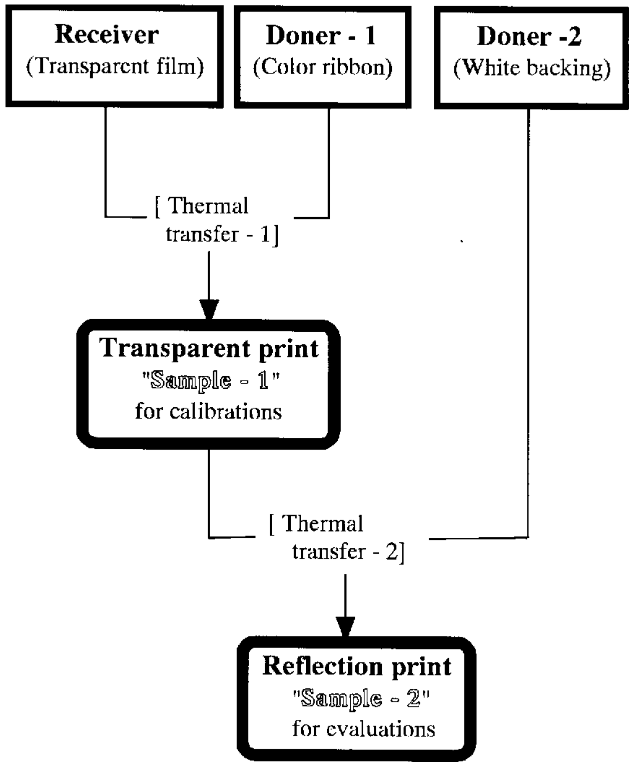

Figure 1. Procedures to produce transparent and reflective specimens sample 1 and sample 2, respectively.

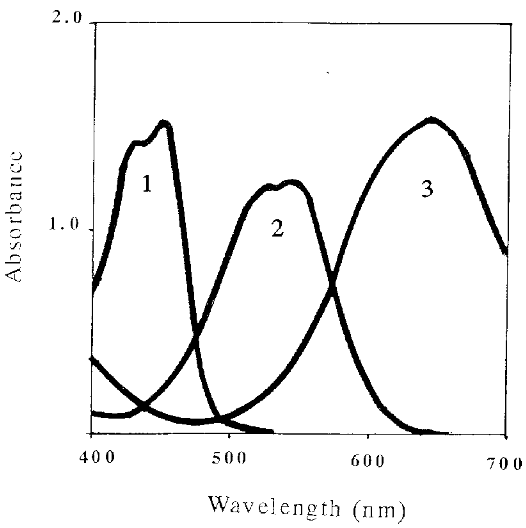

Figure 2. Absorption spectra of single-color transparent specimens (sample 1): 1—yellow, 2—magenta, 3—cyan.

layer and then a backing layer covered the receiving layer. The thicknesses of the base film receiver, dye receiving, and white cover layers were 130, 10, and 3 µm, respectively. The printer was a Sony UPD 8800, A4 printer.

The dyes in the donor ribbon were the normal thermal diffusion type compounds and tuned to diffuse in the receiving layer on the plastic film. The backing white layer consisted of titanium oxide powder dispersed in a plastic binder. Figure 2 shows the absorption spectra of three transfer dyes of C, M, and Y in the transparent specimens.

Measuring equipment included a spectrophotometer, a color spectrometer, a densitometer, and a microdensitometer. The absorption spectra and absorbance of transparent specimens were measured with a Hitachi 228 spectrophotometer. The color space values of L*, a*, and b* for the reflective specimen were measured using a Gretag SPM 100 spectrometer. The measuring angle was 2 deg. The transparent and reflective color densities of the specimens were measured by a Macbeth 924 densitometer. The measuring apertures of the densitometerwere 2 mm Φ and 4 mm Φ for transparency and reflectors, respectively. The fine structure of the reflective specimen was checked by a Konica PDM 100 microdensitometer.

The light box for subjective examination by specimen viewing was a stand type (Shinshin Kagaku DCM 460) and the illuminating conditions were 5500 K and 700 lx/cm^2.

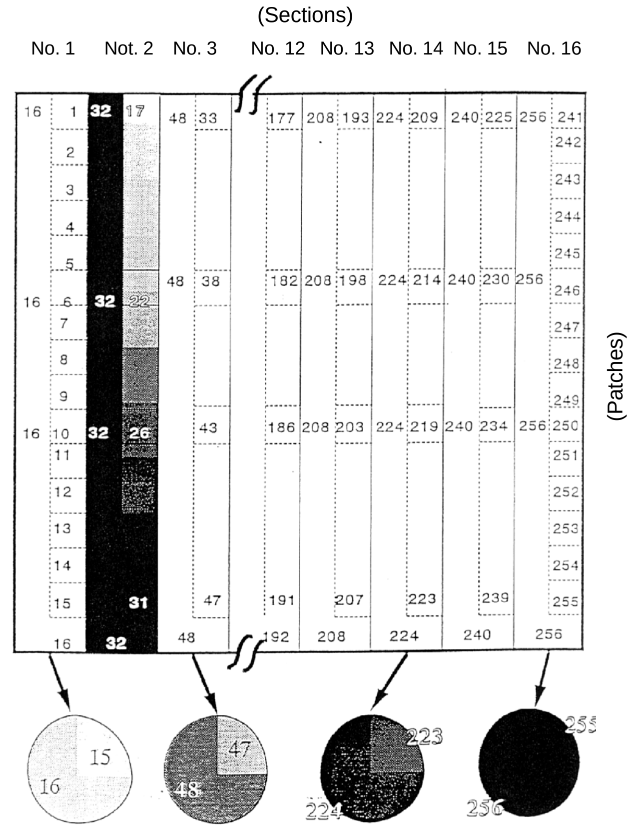

Figure 3. Printing pattern of 256 levels of imaging data.

Test Patterns for the Specimens. The configuration of the test pattern on a specimen and its reproduction of color specimen are shown[2,3] in Figs. 3 and 4. The arrangement of the pattern was as follows:

1. Divide a print into 16 sections and assign 16 groups of serial printing data levels individually. These sections were numbered No. 1 to No. 16 and the first No. 1 section was printed by stepwise 1st to 16th level image data and the last No. 16 section was assigned for printing of 241th to 256th level image data.
2. Divide each section into two parts, the left side was printed by constant ($16X$)th level datum and the rest of right side was vertically divided into 16 patches and printed by $16[16(X-1)+1]$th to 16th ($[16(X-1)+16]$) level data. The X was an integral number of 1 to 16. As the result in each section, stepwise 15 patches printed by $[16(X-1)+1]$th to $[16(X-1)+15]$th level data were surrounded by angle shape consolidated patches printed by constant $[16X]$th level.
3. Print size was 140×110 mm^2 and the area of each printed patch was 3.5×8 mm^2.

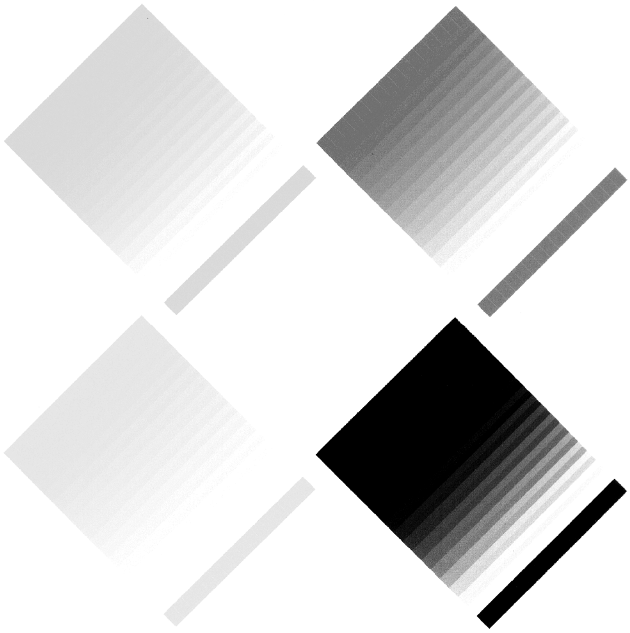

Figure 4. Reproductions of single-color and gray specimens.

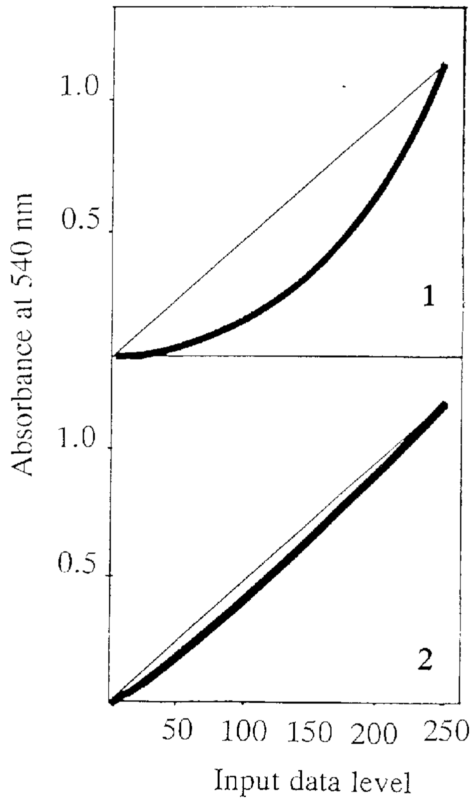

Figure 5. Relation of absorbance at 540 nm, green color density, and input data level of magenta specimen (sample 1): 1—linear input, 2—modulated input by particular gamma.

When printing the specimens, the electrical power supplied to the printing heater head was divided into 256 levels under special gamma characteristics as described later. The regulating of the supplied power was done by pulse width modulation and the maximum power to the printing head was 4×10^{-4} W (20 V). Thus, the highest 256th level data was supplied with the highest power, providing maximum print density. Conversely, the lowest 1st level was that of zero electricity showing no density change.

Calibration of Coloration and Dye-Transfer in the Specimen. The calibration of quantitative transfers of dye to the specimen was estimated by the relationship of absorbance and input image data level. The calibrations were done using specimens in the form of sample 1. Figure 5 shows the relation of absorbance and transparent color density and input data level on the magenta specimen film. The horizontal axis is plotted as an input data level equivalent to the supplied heat energy.

The curve for linear input of data shows a parabolic shape. Another curve was obtained by corrected input showing the specified gamma. The almost linear absorbance change was the result of the special gamma obtained from a product of the initial gamma and its inverse function. The approximate linear absorbance changes were shown in the three-color specimens. This result proved that the data level was equivalent to the amount of dyes in a patch printed by the above gamma characteristics.

In this study, the absorbance values of single-colored specimens of Y, M, and C, measured by a spectrophotometer, at the peak wavelengths of 452, 540, and 647 nm, respectively, were unexpectedly equivalent to the R, G, and B color densities measured by a transmission densitometer. Figure 6 shows the correlations of changes of absorbance at three wavelengths and that of the color densities. These two spectrophotometric features are linear with each other. Thus, in this discussion, density changes could be substituted conveniently for absorbance changes.

Evaluations. The subjective viewing examination was carried out under the following conditions: the sample prints were viewed in the light box, at a viewing distance with distinct vision of 300 mm and viewing angle of about 2 deg. The evaluations were done using specimens in the form of Sample 2.

In the objective examination, the colorimetric measurements were mainly to check color density and chromatic physical value change between adjacent [16*X*]th and [16(*X* – 1) + 15]th patches in every 16 sections on the reflective specimens.

Results and Discussion

Relation of Color Density and Mass of Printed Dye. The results of the calibration curve in Fig. 5 show that Beer's law was approximated in a single-colored specimen. While Beer's law was observed in the liquid phase in the diluted dye concentration, generally, it is not good in high concentrations and the disturbance of this law is thought to have occurred by coagulation of dye molecules in the concentrated phase. This phenomenon appeared in the change of the absorption spectrum and its peak wavelength shifts to the longer wavelength region.

Figure 7 shows the absorption spectra of transparent yellow specimens in the absorption peak wavelength region. The spectra show the specimen printed using different level data. No distinct wavelength changes toward the higher absorbance range occurred in the other two color specimens. The resembled dye concentration was maintained in the emulsion layer of color photographic film. It was also seen that this law was in operation if the solid emulsion layer of color film containing photographic color dyes in concentrated phase showed[5] a transmission density of over 1.0. Thus, it was concluded that the Beer's law was evident in the specimens of this work.

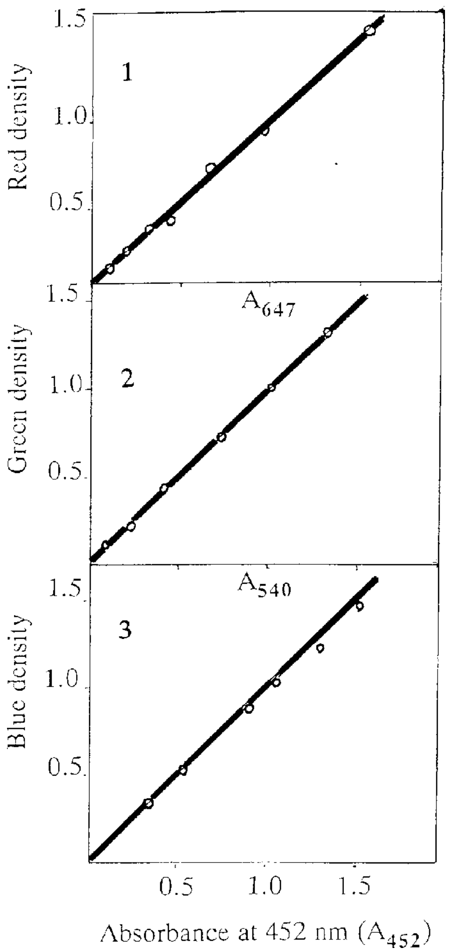

Figure 6. Correlation of changes of absorbances at peak wavelengths and three color transmission densities (sample 1): 1—cyan, 2—magenta, 3—yellow.

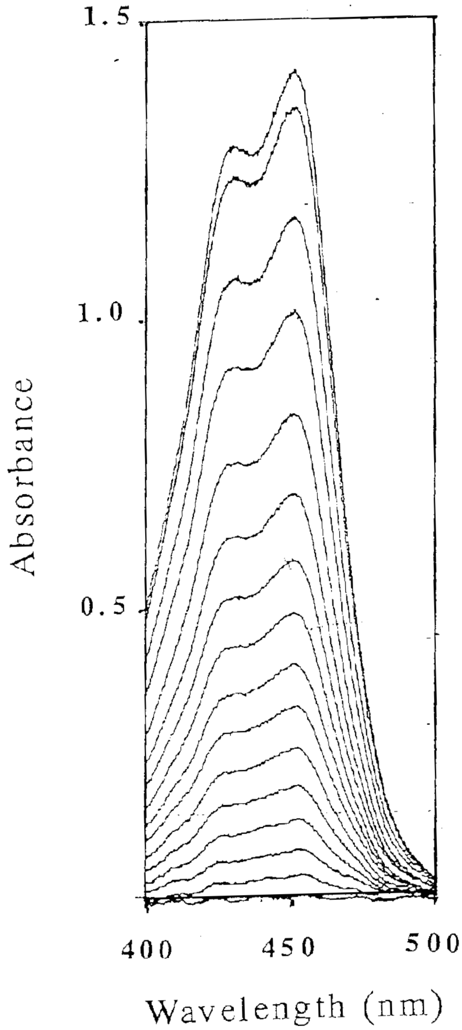

Figure 7. Absorption spectra of yellow specimens printed by different data levels.

Under the special printing condition using definite gamma characteristics, the absorbance change was near linear. According to the approximate completion of Beer's law, the data levels plotted in the horizontal axis of Fig. 5 were regarded as the amount of transferred dye to the specimen described previously. The maximum transparent color density of the three specimens were Dr = 1.20, Dg = 1.20, and Gb = 1.40 for cyan, magenta, and yellow single-color specimens, respectively. The results therefore show that the 256 patches in the pattern of the printed specimen consisted of different amounts of dyes.

Subjective and Objective Evaluation. During the evaluations, the specimens were covered by a white backing layer and then viewed and measured from the reverse side. Figure 8 shows the density changes between the original transparent sample 1 and the remodeled reflective sample 2. The density changes of a reflective specimen showed a distinctive difference from the transparencies. The slope of the specimen density curve was about twice that of the transparency, although the density change was not linear. This phenomenon was common to all three color specimens. The irregular conversion of linear to nonlinear was thought to be due to the reflection of the surface of the thick film.[5] Thus the reflective density changes on the individual patches in the examined specimen were not constant. The density difference in the high-numbered dark section were slightly suppressed.

Subjective Visual Examinations. Subjective examinations were carried out by viewing the sample prints in a light box. On viewing the specimen, the observer tried to recognize density changes at the boundaries of adjacent patches. Typical boundaries as located between the $[16(X-1)+15]$th and $[16X]$th levels in every 16 sections are shown in Fig. 3. On the examination, if the observer identified definite patch boundaries in adjacent sections, then all 16 patches around the appointed one were judged as discriminative.

Figure 9 shows the number of visually discriminative patches for each of the 16 sections of the three color samples. The results are the average of three observers. For the M specimen, 15 boundaries in the first No. 1 to No. 15 sections could be identified. In the case of the C specimen, 14 boundaries in the No. 1 to No. 14 sections were identified. The black specimen showed the same results as the M specimen.

In the above three specimens of C, M, and black, the observers could not discriminate boundaries in the No. 15 or No. 16 sections. Thus the rest of the 240 patches for M and black and 225 patches for C specimens were thought to be discriminative with each other. The nondiscriminate boundaries in the higher density regions of the No. 15 and No. 16 sections were thought to be due to a kind of black compression.

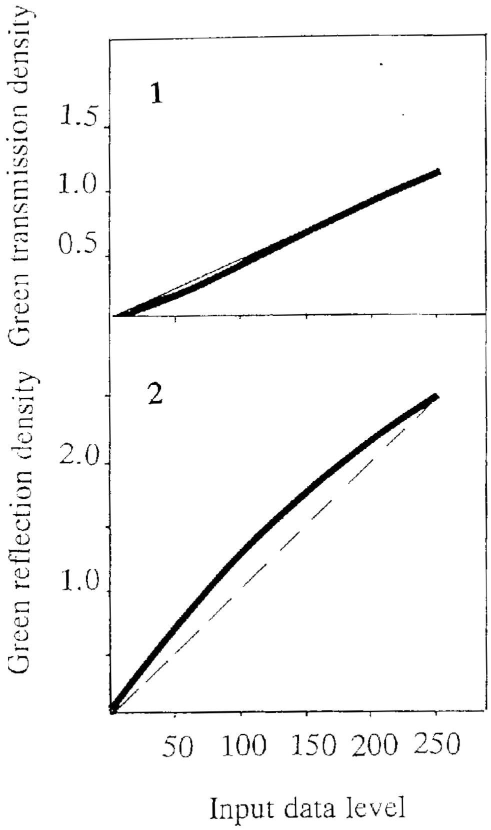

Figure 8. Transmission and reflective density changes of magenta printing in sample 1 and sample 2: 1—sample 1, 2—sample 2.

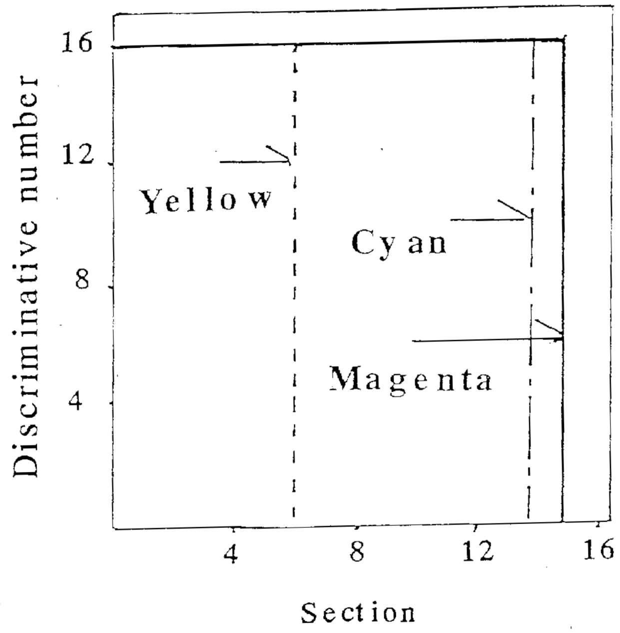

Figure 9. Visual discriminative numbers of patches in color specimens.

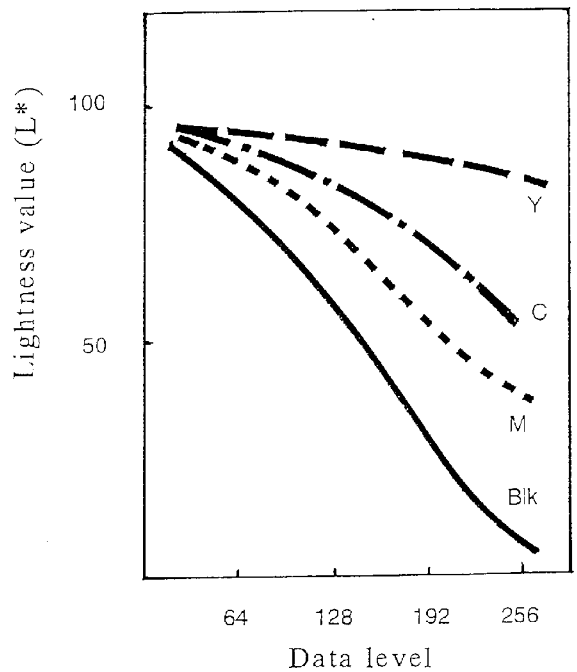

Figure 10. Relation of lightness and data level on color specimens.

In the case of the Y specimen, the boundaries after tne No. 8 sections were not distinct. Thus the numberof discriminative patches was thought to be 112.

In the specimens, if the individual patches contained different amounts of colorant, then the above numbers were equivalent to those of discriminative primary color numbers.

Objective Evaluations. There are two categories of objective physical examinations that can be used to check color: color density and color space values. On the microdensitometric traces of individual sections, the distinct step wise density changes could not be measured, even in the high numbered dark sections of the specimen. Of course, in the low-numbered light regions, the traces of density change showed very gentle slopes. The boundaries of patches printed by serial level data could not be recognized by density measurements.

The second colorimetric method was examinations using the color space values of L*, a*, and b* (CIE 1976) for each of the adjoined patches between the definite boundaries on the above color specimens measured by spectrometer.

The color space values of the appointed patches on the four color specimens first were measured on color specimens. These results are shown in Figs. 10 and 11.

Figure 10 shows the comparison of lightness values L* of the specimen and the input data level. The result of the black specimen was the combination of M, C, and Y images show a large change of L*, however the Y specimen shows only a small change in L*.

Figure 11 shows the specimen color gamut. The three bold lines show the mapping traces of the individual primary color specimens and the rest of the dots show the measured mapping points of 512 colors produced by a mixture of all the 32 level patches of C, M, and Y colors. In Fig. 11, the mapping trace of Y indicates large b* value changes, however small a* value changes. The C shows about equal changes for both a* and b* values. The trace of M shows large a* value changes and small b* value changes. This evaluation, using a* and b* values, is a good but not perfect way to examine the color changes on the three color specimens. The same also holds true for evaluations using individual color space values of L*, a*, and b*.

The final evaluation was the introduction of the color difference, *dE* obtained by operation of three color space

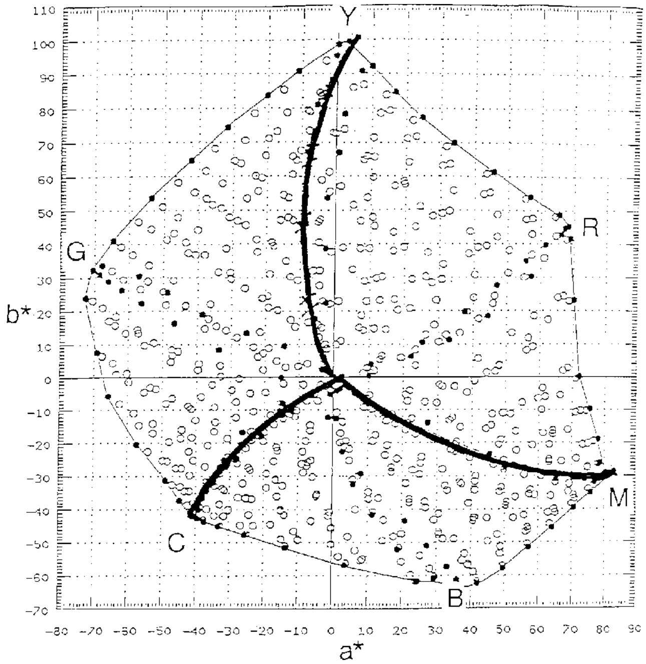

Figure 11. Color gamut of color specimens.

values of L*, a*, and b* on the adjacent patches as per the following equation:

$$dE = \{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2\}^{1/2}. \quad (1)$$

In Eq. 1, ΔL^*, Δa^*, and Δb^*, are the differences of L*, a* and b* values between those of the patches printed by [16(X – 1) + 15]th and [16X]th level data as in the case of our subjective examination.

Figure 12 shows a comparison between color difference value, dE and the data level. In identifying color difference, dE = about 1 is thought to be the critical point at which to recognize two colors independently.[6,7]

In Figure 12, dE values decreased toward the higher data level region, although, the three color specimens all show the different trends. In the M and C specimens, all the dE values were located over the dE = 2.0 region. However, dE values for the Y specimen decrease to the critical point of dE = 1 at the No. 8 section. The results of the examination using the color difference of dE show that all 256 levels of M and C specimens were physically recognizable. But only 144 levels were recognizable in the Y specimens.

Conclusion

The number of discriminative colors on a full-color print is estimated to be a product of the C, M, and Y appearance levels that are equivalent to the amount of the colorant level.

Thus, in thermal dye-transfer prints, the number of visually recognizable colors is estimated to be 6,048,000 (240 × 225 × 112). As the result of physical examination using the color difference of dE, a product of recognizable numbers of the three colors is estimated to be 9,937,184 (256 × 256 × 144).

The color expression ability when judging thermal dye-transfer prints was shown to be at different levels when viewed objectively and subjectively. Particularly a distinct difference was noticed in the recognition of the Y specimen. The sections that were discriminative when viewed under 5500 K illumination were lower than that of the physical examination.

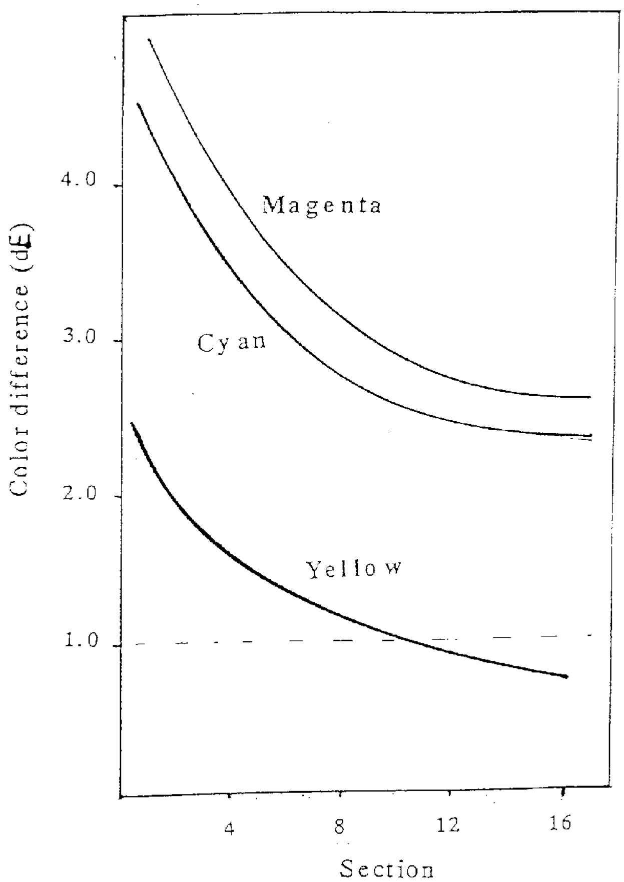

Figure 12. Color difference (dE) of patches between definite boundaries in every section.

From the results of the objective evaluation, the number of recognizable colors responding to the input of 2^8 step R, G, and B digital data were considered to be 6 million, which is equal to 36% of the possible 16,777,216 (2^{24}). But the results of the dE Lab color metrics showed that the color differences were 9,937,184, equivalent to 59% of the possible differences.

These numbers showed slight increases when using other specimens with uniform density change on their patches. The results of Fig. 8 demonstrate that in the specimen patches shown, density change were suppressed in the dark sections.

The results of this work suggest two major advantages when using thermal dye-transfer prints to reproduce continuous-tone pictorial color hardcopy. The first advantage is that the reproduction range of density and color expression matches the range of quantiztion of input image data levels. At present, the most useful and familiar quantized image data level is accepted to be 8 bit. On thermal dye-transfer prints, the characterized tone rendition will be expressed in an achromatic image. It was the integration of the renditions made by three colors. In the black and white sample print, 240 out of 256 levels of input image data responded to recognizable print densities. This was estimated by sensitive subjective evaluation to check the boundary of adjacent patches showing minimum density difference.

In the cases of the R, G, and B color image data levels of 7 bit (2^7 steps), the maximum possible number of color expressions was determined to be 2,097,152. Thus, this medium has to respond to the data level between 7 and 8 bit. An input image data range of 10^8 is generally sufficient for thermal dye-transfer printing.

The second advantage is the significant adaptability of thermal dye-transfer printing for fine imaging. It can show macroscopically perfect continuous tone and full-color reproduction, while microscopically showing a faithful response to the input data levels of more than 7 bit. Moreover, the print appears uniform and shows a discrimination of only 1 digital level between adjoining parts. This is evidence of low noise and high printing uniformity which are key functions for continuous-tone reproduction on pictorial images.

In summary, the thermal dye-transfer printing method is an outstanding media to reproduce continuous-tone reproduction on digital photography prints. The above results were obtained my model specimens showing nonlinear gamma characteristics in a reflective density. However as an actual color hardcopy has a much thinner overcoat protecting layer than this work, we can expect better discrimination.

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References

1. K. Miyata, *Disp. Imaging* **4**(2), 261 (1996)
2. S. Ohno, *J. SPSTJ*, **59** (1), 155 (1996).
3. S. Ohno, *J. Imag. Sci. Tech.* **39**(5) (1996).
4. R. M. Evans, *Principles of color photography,* Wiley and Sons, 1964 p. 338.
5. N. Ota, *Photogr. Sci. Eng.* **15**(6), 487 (1971).
6. M. Kawakami, *Color Science Handbook,* 1989, Univ. of Tokyo Publishing, Japan, p. 257.
7. H. Komatsubara, *Evaluation and Improvement of Color Image*, Japan Engineering and Technology Center, 1992, p. 21.