Color in Digital Photography
Color Quality of Digital Photography Prints

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Abstract

The output color hardcopy in digital photography is printed by digital data supplied to the printer. The number of digital levels of information is decided by conditions of image processing and manipulation using a personal computer. For each color, the typical number of levels for continuous tone renditions of primary color images of red (R), green (G) and blue (B) is 256 levels, equivalent to 8 bits (2^8 steps). There were few studies on the relation of the number of levels of input image data and output image quality of prints[1]).

This paper discusses the relation of number of levels of image data and the color reproduction on thermal dye transfer prints. Further, it discusses the appropriateness of the thermal dye transfer printing for continuous tone pictorial image formation. The evaluations used both subjective human viewing and objective colorimetric measurements to discriminate between different patches printed by step wise 256 level data.

The results show that the maximum 94% of input *256* level image data responds to express different densities in magenta and black samples in visual examination and about 10 million colors were estimated to be physically recognizable on the full color print.

Furthermore the appropriateness of thermal dye transfer printing was discussed. The digital data level of 8 bits for the hardcopying system was almost sufficient and reasonable to match human vision and to express the continuous tone on the reproductions.

1. Introduction

In the current digital imaging systems, the information of the original picture is carried by digital image data and manipulated by digital image processing method using personal computers.

In the usual imaging system, the color information is carried by additive primary color signals of R, G and B from the object images captured by cameras, scanners or images created by computer is carried by R, G and B color signals. Those signals in the digital imaging system are assigned as data. The input color image data of R, G and B supplied to the printer are converted to color hardcopy images on a medium expressed by subtractive primary color materials of cyan (C), magenta (M) and yellow (Y). Thus all color images on the prints are formed by simple and mixed consists of C, M and Y colorants.

The color rendition of hardcopy image is directly related to the tone reproductions of C, M and Y images on the print. On a print expressed its tone reproduction using the direct density method, the color reproduction is realized by quantitative depositions of C, M and Y colorants on a substrate. The thermal dye transfer printing is one of the best color hardcopy systems because the dyes are directly transferred from donor to print proportionally to the input signal intensity. Thus this print is a nice example to examine the response of the input information to the output printed image.

The examinations were done using sample prints (specimen) having a special pattern printed by 256 levels of input image data under the calibrated printing conditions. The samples were made by so called sublimation dye transfer prints and 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 were the recognition of discrimination 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 get the quantitative change of physical values.

2. Experiments

2.1 Specimen and test equipment

The specimens were produced by a model thermal dye transfer media compatible with transparent and reflective outputs. It was basically the same as the transparent medium for OHP (overhead projector), however an additional white cover on the dye receiving layer was available. To watch the printed film from reverse side, the transparency was turned to the reflective medium by white layer in the bottom. In this study, a transparent specimen was remodeled to a reflective specimen that remained the same conditions of transferred dyes. The reflective specimen was equivalent to a hardcopy covered by thick transparent film.

The printing medium was a trial product, named "back light media". The dimensions of the structure of receiving film were as follows, thicknesses of film substrate, dye receiving and white cover layers were 130, 10 and 3 μm respectively. The printer was Sony UPD 8800 A4 printer.

The measuring equipment were a spectrophotometer, a color spectrometer, a densitometer and a micro-densitometer. The absorption spectra and absorbance of transparent specimens were measured by Hitachi 228 spectrophotometer. The color space values of L*,a* and b* for the reflective specimen were measured by Gretag SPM 100 spectrometer. The measuring angle was 2 degree. The transparent and reflective color densities of specimens were measured by Macbeth 924 densitometer. The measuring apertures of the densitometer were 2 mm and 4 mm for transparency and reflectors, respectively. The fine structure of the reflective specimen was checked by Konica PDM 1 0 0 micro-densitometer.

2.2 Test pattern of specimen

The test pattern on a specimen showed in Figure 1.[23]), The consists of the pattern was as follows:

1) To divide a print into 16 sections and to assign 16 groups of serial printing data levels individually. These sections numbered to No. 1 to No .16 and the first section was printed by step wise 1st to 16th level image data and the last No. 16 section was assigned for printing of 241st to 256th level image data.

2) To divide each section into two parts, the left side was printed by constant (16 X)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. X was integral number of 1 to 16. As the result in the each section, step wise 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.

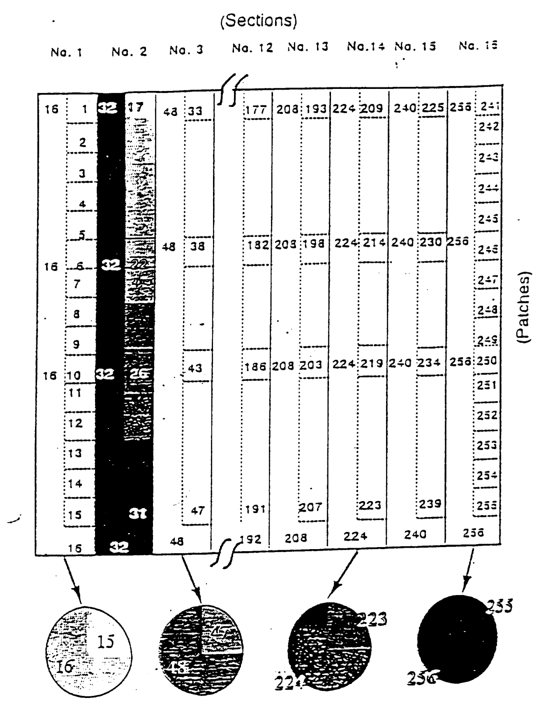

Figure 1 Printing pattern for 256 level image data.

When printing of specimens, the electrical power supplied to the printing heater head was divided in to 256 levels under the special gamma characteristics as described later on. The regulation of 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 date supplied the highest power making the maximum print density. The lowest 1st level was that of 0 electricity showing no density change.

2.3 Calibration of coloration and dye transfer in the specimen

The calibration of quantitative transfer of dye to the specimen was estimated by relation of absorbance and input image level.

Figure 2 shows the absorbance and transparent color density change of the magenta specimen film. The horizontal axis is plotted the 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 realized by special gamma obtained a product of the initial gamma and its inverse function. The approximate linear absorbance changes were realized in the three color specimens. This result approved that the data level was equivalent to the amount of dyes in the patch printed by above gamma characteristics.

In this study, the absorbance values of single colored specimens of Y, M and C measured by spectrophotometer at the peak wavelengths of 452, 540 and 647 nm, respectively were equivalent to the B, G and B color densities measured by transmission densitometer.

Thus on the discussion, the density change was substituted for the absorbance change.

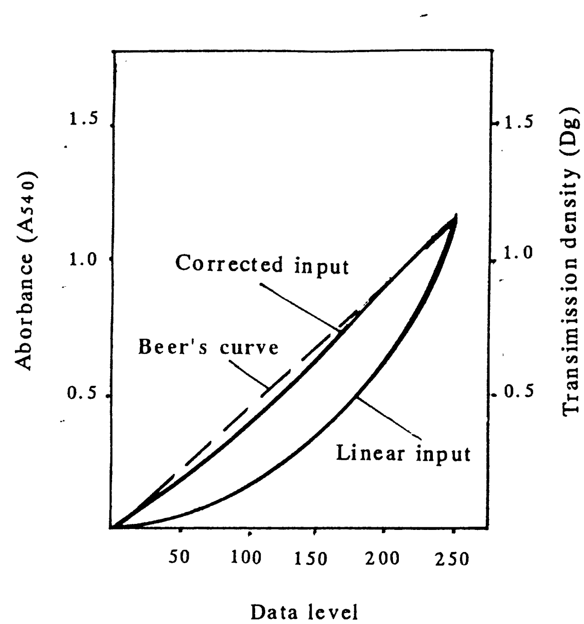

Figure 2 Relation of Absorbance, color density and data level. (Approximate Beer's Law curves)

2.4 Evaluations

The subjective viewing examination was carried out using the following conditions: the sample prints were viewed in a light box (Shinshin Kagaku DCM 460) under the normalized illumination of 5,000 K, 700 lx, the viewing distance was the distinct vision of 300 mm and the viewing angle was about 1 degree.

On the objective examination, the colorimetric measurements were mainly due to check the differences of color density and chromatic physical values between adjacent [16X]th and [16(X-1) + 15]th patches in every 16 sections.

3. Results and Discussion

3.1 Relation of color density and amount of printed dye

The results of calibration curve in Figure 2 showed that the Beer's law was realized in the single colored specimen. The original Beer's law was realized in the liquid phase in diluted dye concentration. The disturbance of this law is thought to be occurred by coagulation of dye molecules in concentrated phase. Those phenomenon is appeared in the wavelength change of the absorption spectrum and the peak wavelength shifts to long wavelength region.

In this study, there were not distinct wavelength changes toward higher absorbance range in three color specimens. The resembled dye concentration maintain in the color photographic film. It was reported that this law was concluded in the solid emulsion layer of color film[4].

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 horizontal axes of Figure 2 regarded as the amount of transferred dye to the specimen as describe previously. The maximum transparent color density of three specimens were Dr = 1.20, Dg= 1.20 and Gb= 1.40 for cyan, magenta and yellow single color specimens, respectively.

As the result, it was realized that the 256 patches in the pattern of printed specimen consisted of different amount of colorants and the amount change was linear by using of special gamma characteristics for printing. Thus the transmission density differences in individual patch were Dr. Dg = 1.20/256 and Db = 1.40/256 for C, M and Y specimen respectively.

3.2 Subjective and objective evaluations

On the evaluations, the specimens were covered by white backing layer and watched and measured from reverse side. Figure 3 shows the density changes in transparent and reflective specimens. The density change of reflective specimen reformed from the transparency shows distinctive difference. The steep of its density curve was around twice of that of the transparence. Moreover the density change was not linear. Thus the reflective density changes of the individual patches in the examined specimen was not constant. Although it was caused by linear change of dye contents and reasonable for this evaluations.

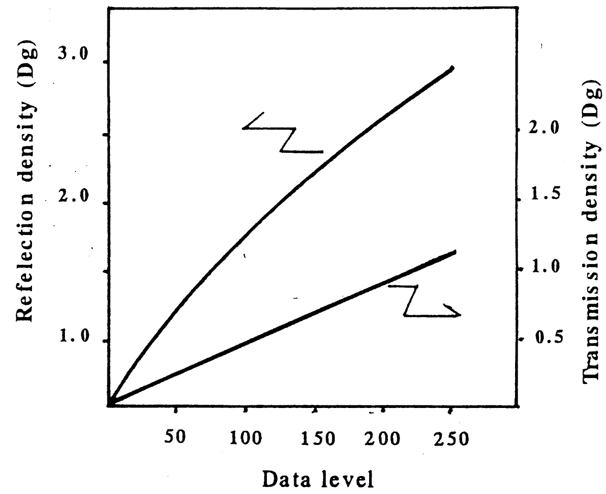

Figure 3 Density changes of specimen in transparent and reflective phases. (Magenta specimen)

a. Subjective visual examinations

The subjective examination were carried out to watch the sample prints setting in the light box. On the viewing of the specimen, the check points to recognize the density change were the boundaries of adjacent patches. The typical boundaries located between the [16(X-1)+15]th and [16X]th levels in every 16 sections as shown in Figure 1. On the examination, if the observer identified boundaries of definite patches in the adjacent sections, then all 16 patches ranging the appointed one were recognized discriminable with each other.

Figure 4 shows the number of visually discriminative patches for each of the 16 sections of three color samples. The results were the average of three observers. In the cases of M specimens, the fifteen boundaries in the first No. 1 to No. 15 section could be identified with each other. In the case of C specimen, fourteen boundaries in No. 1 to No. 14 sections were identified. The black specimen showed the same result as the M specimen.

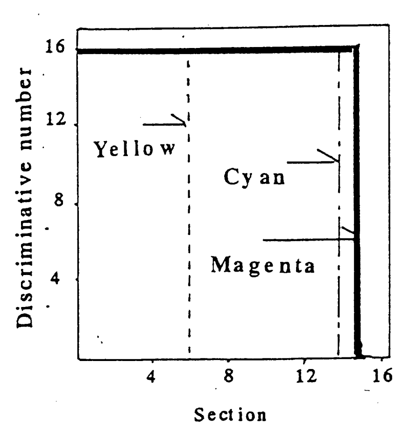

Figure 4 Visual discriminative numbers of patches in colored specimens.

In the above three specimens of C, M and black, observers could not discriminate boundaries in No. 15 or No 14 and 15 sections. Thus the rest of 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 No. 14 and 15 sections were supposed to be due to a kind of black compression.

In the case of Y specimen, the boundaries in the over No.8 sections were not discriminative. Thus the number of discriminative patches was thought to be 112. In the specimens, the individual patches contained different amount of colorant and then above numbers are equivalent to those of discriminative primary color numbers.

3.2 Objective evaluations

There are two categories of objective physical examinations to check the color; one is the color density and another is the 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 the examinations using color space values of L*, a* and b* (CIE 1976) for each adjoined patches between the definite boundaries on the above color specimens measured by spectrometer. At first, the color space values of appointed patches on the four color specimens were measured. The evaluations using individual color space values of L*, a* and b* are pretty good but not perfect to examine the color changes on the color samples because of the appearances of distinctive difference.

The final evaluation was the introduction of the color difference, dE obtained by operation of three color space values of L*, a* and b* on the adjacent patches as the following equation:

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

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

Figure 5 shows the relation of color difference value, dE and the data level. In the identification of color difference, dE = about 1 is thought to be the critical point to recognize two colors independently[4,5]. In Figure 5, dE values decreased toward the higher data level region. Although, the three color specimens shows the different trends. M and C specimens, the all dE values were located over dE = 2.0 region however dE value for Y specimen decreases to the critical point of dE = 1 at No. 8 section . The result of examination using the color difference of dE, all 256 levels of M and C specimens were physically recognizable. In the case of Y specimen, 144 level were recognizable.

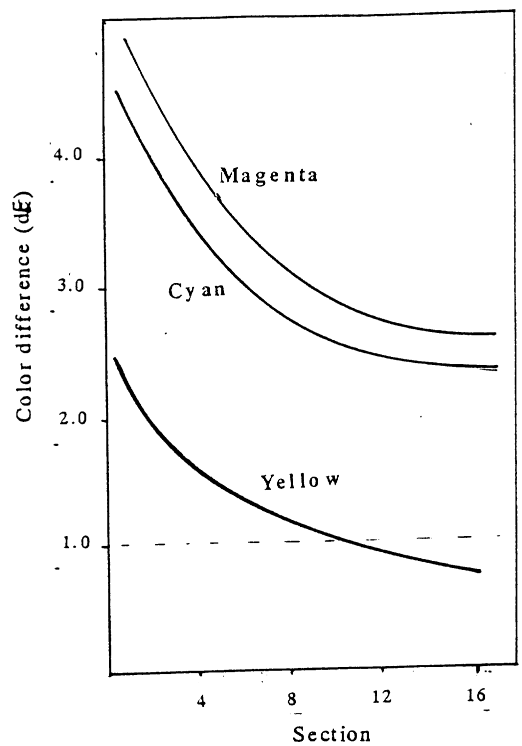

Figure 5 Color differences (de) in boundaries of last patches on every sections.

4. Conclusion

The number of discriminative color appearances on the full color print will be estimated to be a product of C, M and Y appearance levels which are equivalent to the amount levels of colorant.

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

The color expression ability of the thermal dye transfer print was estimated to be difference levels by objective and subjective examinations. The distinctive difference was appeared in the recognition of Y specimen. The result of the viewing examination under 5000 K illumination was lowered than that of the physical examination.

The result of objective evaluation, the number of recognizable color responding to the input of 2^8 step R. G and B digital data was considered to be 6 million and is equal to be 36% of possible number of 16,777,216, equivalent to 2^{24}. On the other hand on the result of dE . Lab color metrics, the color differences indicated the number of 9,937,184 and is equivalent with 59% of the possible number. In the cases of the R. G and B color image data levels of 7 bits (2^7 steps), the maximum possible number of color expression is counted to be 2,097,152. Thus this medium is suppose to respond data level between 7 and 8 bits.

The results of this work suggested two major advantages of thermal dye transfer print to reproduce the continuous tone pictorial color hardcopy. The first advantage is that the reproduction range of density and color expression matches to the range of quantitization of input image data levels . At present, the most useful and familiar quantitized image data level is supposed to be 8 bits. On the thermal dye transfer prints, the characterized tone rendition will be expressed in the achromatic image. It was the integration of the renditions made by three colors. In the black and white sample print, 240 of 256 levels input image data responded to the recognizable print densities. It was estimated by sensitive subjective evaluation to check the boundary of adjacency patches showing minimum density difference. It was shown that the use of image data range of 10^8 is almost sufficient.

The second adantage is the significant adaptability of thermal dye transfer printing for fine imaging. It shows macroscopically continuous tone and plenty color reproduction and respond microscopically to the input data levels of over 7 bits. The ability to print patches that appear uniform and different from patches whose digital level is only 1 digit difference is the evidence of low noise and high uniformity. The noise and uniformity performance is better than the above fine reproducing identification will be specifications for continuous tone reproduction pictorial images.

In summary the thermal dye transfer printing method is an outstanding media to reproduce continuous tone reproduction on the pictorial hardcopy. The above results were obtained by model specimen, however the actual color hardcopy has extremely thinner overcoat protecting layer than this work. We can expect the better results to recognize on Y specimen.

The authors thank Mr. M. Tsugita of Fuji Photo Film Co. and Ms. Toyoko Fujii, Mr. Koichi Oka and Mr. N. Kato of Sony Corp. for their assistance and discussions.

References

1) Kimiyoshi Miyata, “Image Quality and Quantization Levels in Hardcopy” Display and Imaging, 4(2)261 (1996)

2)Shin Ohno, “Consolidated Evaluation of Chained Imaging Equipment in Multimedia Environment”, J.SPSTJ, 59(1) 155(1996).

3) Shin Ohno “Digital Photography and color Printing”, J. IST 39(5) (1996)

4)Ralf M. Evans, “Principals of color photography” p338 (1964) John Wiley and Sons .

5)Motoro Kawakami, “Color Science Handbook” p.257 (1989) Univ. of Tokyo Publishing.

6)Hitoshi Komatsubara, “Evaluation and Improvement of Color Image” p.21 (1992) Japan Engineering and Technology Center.