Image Quality of Digital Photography Prints—II: Dependence of Print Quality on Pixel Condition of Input Camera

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In digital photography, input photoimages to the electronic camera are sampled by segmental imager and converted into image data. The smallest unit of division is called a pixel and the segmentation fixes the size and number of those pixels. Output picture definition is directly related to the pixel number of the input imager. Moreover the image processing to modify the pixel condition influenced the tonal quality of output image. This article discusses the relationship between the conditions of pixel in the imager of the input digital still cameras (DSC) and the image quality of output prints in a digital photography system. Sample color prints showing the same test pattern images in different definition proportional to the numbers of pixel were produced by a single digital photography system. The correlation between the pixel condition of input device and the structural and tonal image quality of output prints were apparent to the subjective visual examination and the objective physical analyses. The effects of pixel condition appeared in the drastic MTF changes on the image structure and the apparent definition changes on the tone rendition of reproductions on the sample prints. The results suggest that there is a limiting pixel number for digital cameras to produce satisfactory hand-held size digital photography color prints.

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Introduction

In a digital photography system, there are three major factors contributing to the output print quality. These are the resolutions of input capturing device and output printing and displaying equipment, data transforming format from input to output and the quality of printing media.

The resolution expressed by number of pixel is one of the determinative factors to the image quality of output prints. The definition of image information expressed by data level is determined by electronic system and relates to the tone expression ability of the outputs. Its conditions are modified by manipulation of image processing and phase conversion processes of data from the electronic signal to photo-signal on the display equipment or the colorant deposition on the print media, respectively. The tone and color expression abilities of the printing medium is dominant to the quality.

This article discusses the relationship between the number of DSC input pixel and the image quality of serial output sample prints. The primary factor was the pixel count and the secondary factor was contribution of image processing. The image quality characteristics of the print media used in this work were excellent. These did not add any distinctive defects to the image quality. Our experiments evaluate the using both subjective and objective examinations to check the structural, tonal and color image quality.

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Color plates 2 and 3 are printed in color in the color plate section of this issue, pages 81 and 82.

The sample prints used in these examinations were pictures of a human model and various evaluation charts. These prints were produced by sequent processes of shooting, manipulating and printing. The target images were shot by a DSC, its output image data manipulated by personal computer under the serial processing condition and then printed by three digital color printers. Image quality examinations were done by subjective viewing of human model images and objective measurements of the densitometric, micro-densitometric and colorimetric analyses of the chart pattern images on the sample prints.

Preparation of Sample Prints

Between the DSC's imager that detects photoimages and the output digital value for a pixel reside a complex sequence of electronics. These electronics vary from camera to camera. We developed a zooming, cropping and interpolating strategy so as to use only one set of electronics to make fine different images as shown in Plate 2 (p. 81).

The evaluation images were pictures of a model, and of various evaluation charts. They were printed on three kinds of digital print media. These sample images were produced by the following procedures; (1) objects were shot and recorded by a DSC under optimum illumination to overcome the narrow dynamic range of the camera imager, (2) image data from the camera was manipulated by personal computer using a graphic software, and (3) modulated signals expressed by data were supplied to the printers to produce sample color prints. Thus, the samples were modified images and had the same image patterns in the different image structures.

The process to make sample prints can be compared to enlarge and to print the same size positive photo-

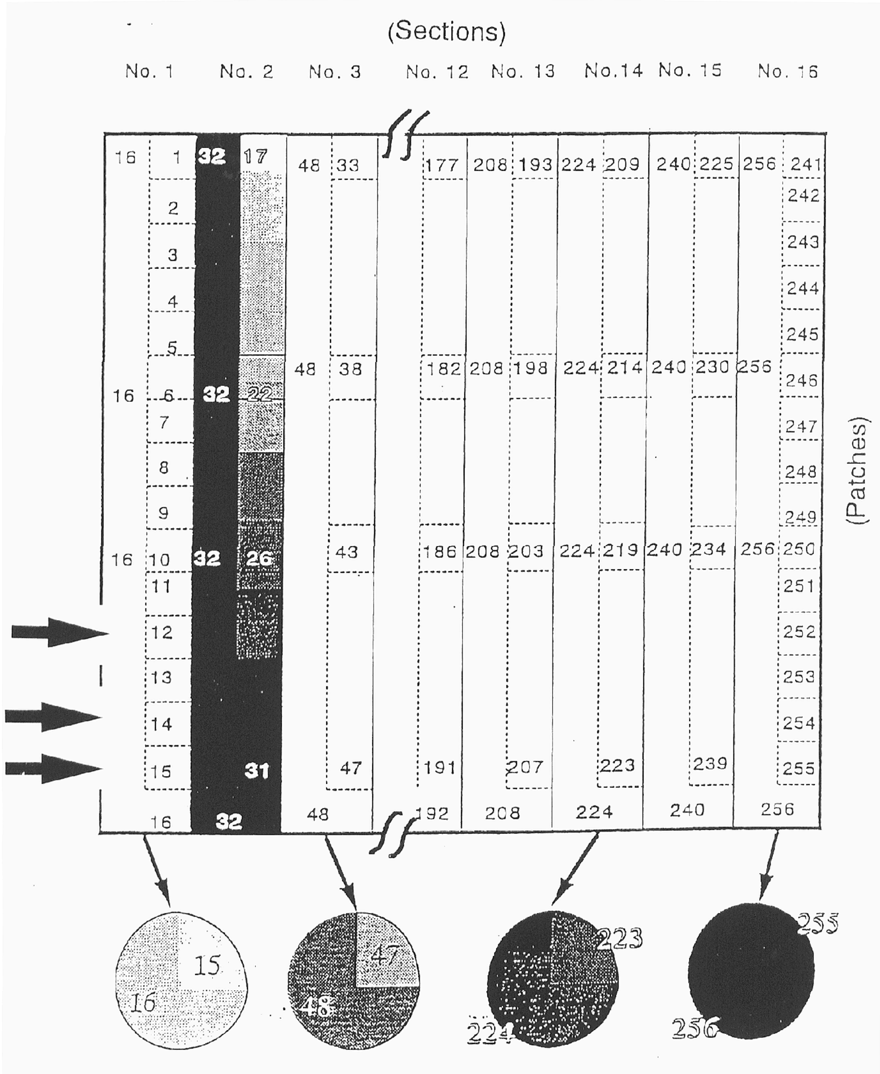

Figure 1. Printing pattern of 256 levels of imaging data.

graphic prints using the different size negative films having the same objects in the fixed frame.

Pixel Conditions. In digital photography, the pixel is the geometric unit for image handling. There are two types of pixels: a capturing pixel and a printing pixel. In this work, the authors have named them as P_1 and P_2, respectively.

A capturing pixel, P_1, is the geometric unit of the imager in the DSC and generates a unit image signal called the image data. Its size and number are decided by the sampling of the imager. Each P_1 generates an individual image data according to the input photo-image to the imager.

The printing pixel, P_2, consists of colorant dot(s) deposited on the unit area of a printing medium. The numbers of P_2 depend on those of P_1 and its size is determined by density elements. In this article, the individual P_2 on the outputs picture of three printers were consisted of a single dot of deposited colorant. The amount of deposited colorant on the P_2 is directly proportional both to the input image data from P_1 and their color density on the substrate. This color density expression on the pixel is named as the direct density method. According to this linear relation between amount of deposited colorant on the print substrate and its density expression, the look up table (LUT) of printer was simple and the continuous tone reproduction on the printed image was realized easily. On the output, the print size is defined as the relation of input P_2 number and the resolution of printing head of the printer.

The number of P_1 is equal to that of P_2 in the original condition. On the original prints without image processing, the image data generated by all P_1 are supplied to all P_2 and converted to the appropriate amount of colorant on the medium. However, on the modified prints to resize images, the numbers of P_1 and P_2 are quite different. On the modified prints, the image data generated by one P_1 was interpolated to be input to the plural P_2s. Thus P_1 was converted to form a bundled P_2. Such modified P_1 was so-called an effective or equivalent form and the total number of P_2 in all outputs was constant and thus produced the same size prints.

One more big issue for the pixel is the quantization related to the data capacity of it. In the digital photography, the definition of tonal level on the pixel is discussed by the data level of image. The data level corresponds to the digit signal intensity. In this work, the P_1 on the DSC provides 8 bits, 256 levels. That condition was succeeded to the output P_2. Moreover the tone and color expression abilities of the final thermal dye transfer medium was retained to be near 256 level.[1] The data level of P_2 on the output was supposed to be modified by the manipulation and printing. It will be described in the **Colorimetry** section.

Shooting. The DSC used in this work was a Sony studio camera, DKC-ST5, which has three, 2/3 inch class 1.4 million pixel charge coupled device (CCD) imagers arranged by the spatial offset method.[2] In the case of this DSC, the visual subjective camera output resolution evaluated by a chart pattern reproduced on a print was 1500 lines per picture height (LPH).

The camera lens was a zoom-type, adjustable focal length from 12.5 mm to 63 mm. These focal lengths were equivalent to 50 mm to 250 mm for a 35 mm film camera. The shooting conditions of the model was the bast shot, the full frame from the top the head to bottom of chart. In the cases of chart shootings, the first standard shooting condition was the full framing of the height of chart. This camera had a buffer memory device to save the data of nine shots, so that short interval shooting was available. The shooting took only a few seconds to make four or five shots of the model in the same pose, with different focal lengths. Shooting was done using an electronic flash (strobe light).

Objects. The objects were, first, a model holding a Kodak gray scale chart (D = 0.10 step) or the Macbeth Color Checker Board, and second, two targets of a combination of the ISO resolution chart for DSC[3] and Electronic Industry Association of Japan (EIAJ) "sin density" modulation transfer function (MTF) chart for video cameras and third, a home made special magenta staircase tone chart.

The first two charts were standardized by International and Japanese domestic standard societies. The last, a home made magenta tone chart consisted of 256 level magenta density patches were formed by a thermal dye transfer print using a magenta colorant alone. The reflective density difference on the chart was approximately linear with the 256 data level. This relation is based on the realization of Beer's law. It is currently a big issue to approve the establishment of direct density method for the perfect continuous tone expression on the medium. Figure 1 shows the configuration of this tone chart and its organization, which was as follows:

1. We divide a print into 16 sections and to assign 16 groups of serial printing data levels individually. These sections numbered from 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. In every section, the left half 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(X-1) + 1]th to [16(X-1) + 16])th level data. X was integral number of 1 to 16. As the result in the each section, the angle shape consolidated patches printed by constant [16X]th level data surrounded 15 patches printed by stepwise [16(X-1)+1]th to [16(X-1) + 15]th level data.
3. Print sample size was 165×135 mm square and the area of each of the patches was 4×8 mm^2.

The details of its procedure and characteristics were discussed in the previous paper[1] and the same chart was used.

Image Processing. The image processing was done on a Macintosh personal computer, Power Mac. G3 using Adobe's Photoshop Ver. 3.0 J graphic software. The procedure of the manipulation was summarized in Plate 2 (p. 81).

The procedures included cropping the specific patterns from the original images and resizing by interpolation of P_1 pixels to bundle up the pixel size for printing.

On shooting with the longest focal length setting, the first image for print A described a previously captured a scene that was bounded by the top of the models head and the bottom of the Color Checker or the gray scale chart. With the shortest focal length, the last image for print E captured the model with the chart in the center, and the middle of the frame represented the desired image. The cropping was to extract the fixed patterns from the serial images taken at different focal lengths.

As the result, four or five differently sized pictures, showing the same pattern consisting of various numbers of P_1, were extracted. The sizes and numbers of pixel for the cropped images showed a distinct relation. The non-cropped biggest image had the largest number of pixel P_1 and the cropped images had a variety of smaller numbers. The interpolation was accomplished by adjusting the pixel P_2 numbers to a fixed 5.24 million for printing.

In this work, the recovery of P_1 pixel number by manipulation was done by the simple interpolation method. The principle of it is to insert new pixels which have the same data level as the neighboring original ones. In the case of the interpolation ratio of four, the individual original pixel was bundled with three extra pixels having the same level data. As a result, the P_1 pixel size appeared to be elongated. This method is called the "nearest neighbor" interpolation in the Adobe Photoshop software.

In the experiment, the first step of computer manipulation was to crop out the unwanted surround from the pictures shot at shorter focal lengths. The cropping, the extraction of a specific part of the original picture, was normalized by height of image of the resolution chart. The chart image size of the original pictures were decreased by shortening of focal length on the camera's zoom lens. The cropping of the chart images was normalized by their picture height. On the original picture, taken at a focal length of 63 mm, the full frame of the picture filled with the chart pattern was formed and consisted of 2048 P_1 pixels for the vertical direction. As the shooting by continued at shorter focal lengths, the size of the chart images became smaller and the vertical P_1 pixel number decreased. The vertical P_1 numbers in the cropped pictures decreased from 2048 to 1310, 942, 594 and 435 for the focal lengths of 40, 30, 20 and 12.3 mm, respectively. Their area cropping ratios were 0.40, 0.23, 0.10 and 0.04, respectively. We extracted four or five pictures of the same pose of the model with different numbers of pixels.

The next stage was the resizing by interpolation. The vertical pixel numbers in the cropped pictures were increased to 2048 for all images. The individual pixel, P_1, in the cropped picture was multiplied and bundled up. As a result, larger size P_1 pixels showing the same data level, were formed. The bundle ratio was inversely proportional to the cropping ratio. Thus after the processing, the image data of the original pictures supplied to the printer consisted of the same pixel P_2 numbers (2048×2560), however output prints from the printers contained different information density. The non-cropped sample print, contained the entire original information as supplied by over five million P_1 pixels. While that of the extracted print E, with an area cropping ratio of 0.04, could only supply the information from about 0.2 million P_1 pixels from the original image data.

Printing. The reproduction of manipulated images was done using three digital printers under different printing conditions. All three printers employed the direct density expression method for the tonal expression as described previously. The individual printing pixel, P_2 expresses the continuous density change proportional to the quantitative colorant deposition. The three types of printer have the individual LUTs to adjust the preferable tonal characteristics for the outputs. Thus the different image characteristics as shown appear in the three sample prints. Therefore the discussion of the comparison of image quality was restricted to the series of four or five sample prints produced by same printer.

Plate 3 (p. 82) shows Sample A of the model pictures in the three format prints. The first prints were made by a thermal dye transfer printer, a Sony UPD 8800 with printing resolution of 300 dot per inch (dpi). The size of the reproductions composed of 2048×2560 P_2 pixels were 173 mm × 214 mm. The second prints were made using a therm-developable silver halide color printer, Fuji Film's Pictrography 2000, having a printing resolution of 400 DPI and the finished picture size was 130 mm × 161 mm. The last prints were printed by negative/positive type, experimental laser printer made by Fuji Photo Film Co. Here the printing resolution was 500 DPI and the print size of the output was 103 mm × 128 mm on color photographic paper. Thus the tone renditions of the outputs from those printers appeared by continuous density change to be like regular photographic prints. The three format prints were named "large", "medium" and "small", respectively. As a result on the three format prints, the sizes of equivalent P_1 pixel changed from 84 μm^2 to 423 μm^2, 63 μm^2 to 300 μm^2 and 50 μm^2 to 239 μm^2 for the "large", "medium" and "small", respectively.

Examinations

Subjective Evaluations. The subjective evaluation by visual examinations were done of the image quality of the model image in Plate 2. The evaluation of the sample prints took place on an office table under the illumination of 1200 lx fluorescent lamps. The series of sample prints, printed from image data of 2048, 1310, 942, 594 and 435 P_1 pixels in the vertical direction were mounted one on top of another and were numbered A, B, C, D and E, respectively. The viewers looked at the A to E samples in the three size prints, which were in a row. Viewing distance was about 300 mm equivalent to hand-held viewing distance. The viewers were two groups of 38 students from photography course in an art school and 17 engineers from the DSC manufacturer. Their average ages were 20 and 35, respectively. The experiments were limited to the same group prints.

In the first part, observers voted 3 points for "excellent", 2 points for "fair", 1 point for "poor" and 0 point for "unacceptable". In second part, they indicated the color fidelity of model's face and accuracy of the Macbeth Color Checker images on the sample prints. These results described viewer's feeling; the colors of targets were different from each other, or they were changed darker or lighter.

Objective Evaluations. The objective examinations were the densitometric and the colorimetric analyses of chart images. Densitometric analyses were used to measure the macro- and micro-density changes of staircase density chart images and the spatial response of the MTF chart image. The colorimetric analyses were the measurement of the L*, a* and b* (CIE 1976) color space values of patches on the Macbeth Color Checker and the magenta tonal chart, and the calculation of color difference, dE, using the measured color space values between the specific color patches on the both charts.

The reflective density changes on the images of gray scale chart held by the model and the magenta tonal charts were measured by Macbeth 914 reflective densitometer using status A and green filters and Konica PDM 2405 microdensitometer using the status A filter. The image sizes of individual density step on the gray scale chart printed on the large format sample was 5.5 mm (width) × 10 mm (height), 4 mm (width) × 8 mm (height) and 14 mm square for the gray scale chart, the tonal chart and patches on the Color Checker images, respectively. The reflection density was measured at equipment apertures of 2 mm for the densitometer, and variable apertures for the microdensitometer, respectively.

The spatial response was measured by sine density MTF charts images on the prints with the above microdenstometer in the reflection mode. The slit apertures were 50 μm (width) × 100 μm (height).

The L*, a* and b* (CIE 1976) color space values of chromatic patches on the Macbeth Color Checker and the magenta tonal chart image on the prints were measured by Gretag SPM 100 spectrometers. The CIE measuring angle was 2° and the color temperature of the illumination was 5500 K. The measurements were three spots per individual patch and the color space values were the average values of these three points.

The color difference, dE between the adjacent patches were calculated by Eq. 1 as follows;

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

In Eq. 1, ΔL^*, Δa^* and Δb^*, are the difference of L*, a* and b* values between two patches. The specific adjacent patches printed on the magenta chart shown in Fig. 1 were the uniform 16(x)th in the left hand side of each section and [16(x)-1]th, [16(x)-2]th, and [16(x)-4] th patches in the right hand side of the section, respectively.

In sections two and three, these were adjacent patches of 16th and 15th, 16th and 14th, 16th and 12th and 32nd and 31st, 32nd and 30th, 32nd and 28th, respectively. These measuring points were indicated by arrows in Fig. 1. According to the measurements and calculations the color differences between 1, 2 and 4 patches were obtained.

Results of Evaluations

Table I shows the cropping conditions, visual resolutions and the pixel sizes for the manipulated sample prints. The vertical pixel numbers of cropped images expanded from 2048 to 406 for A to E samples, respectively and these numbers spread from that corresponding to twice the scanning lines of a high definition TV (HDTV) picture to those of the current "video graphic array" (VGA) level pictures.

The visual resolutions checked by ISO chart pattern on the five samples spread from over 1500 lines to 333 lines per picture height for A to E, respectively. Generally for electronic cameras, the limiting resolution is experimentally supposed to be 70% of the numbers of vertical pixels or scanning lines.[4] In this study however, the individual visual resolutions were determined to be 57 to 72% of the equivalent vertical pixel numbers. It would be reasonable therefore to suppose that the five

TABLE I. Original and Sample Print Evaluation Parameters

	Original pictures Shooting and processing			Sample print (Large) Effective pixel (P_1)				
Print Number	Focal length (mm)	Pixel number (million)	Cropping ratio* (%)	Interpolation ratio* (%)	Pixel number (million)	Printing pixel size (μm²)	Pixel (P_2) number (million)	Visual limiting resolution (LPH)**
A	63		100	—	5.24	84		1500
B	40		40	250	2.10	132		800
C	30	5.24	23	435	1.20	176	5.24	550
D	20		10.1	990	0.53	264		350
E	12.5		3.9	2564	0.20	423		250

* area

** LPH: lines per picture height

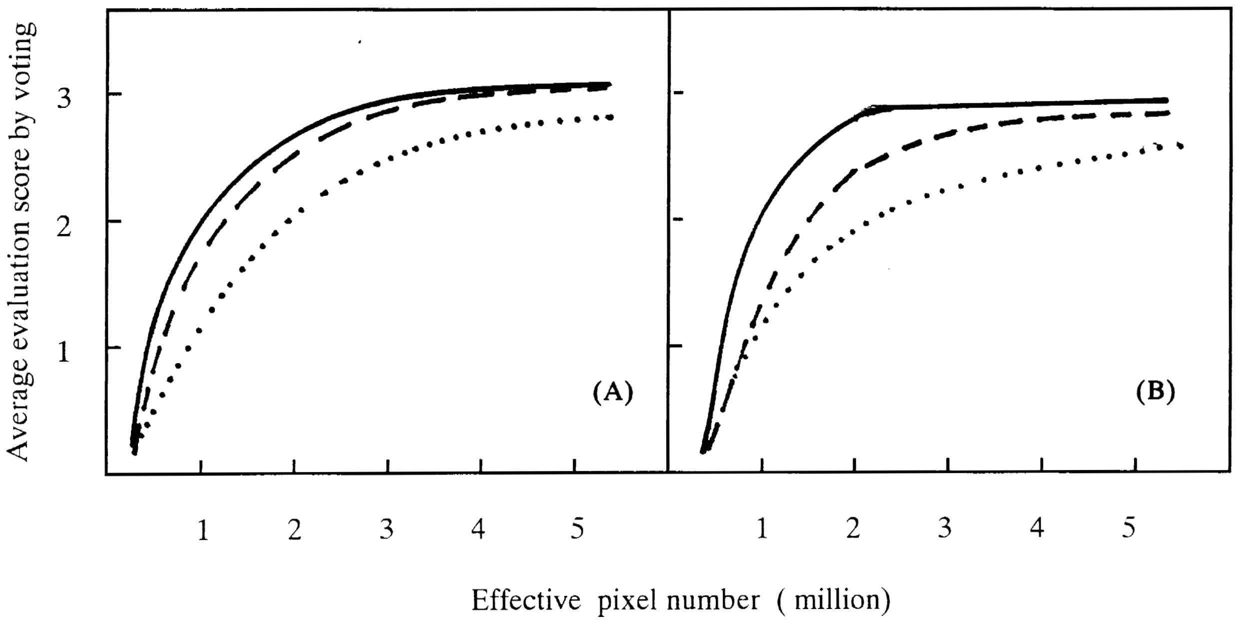

Figure 2. Relationship between effective pixel numbers of each sample prints and evaluation scores. (A) Students. (B) Engineers. Rating system: 3 = excellent, 2 = fair, 1 = poor, 9 = unacceptable; (———) Large sample, (— — —) Medium sample, (• • • •) Small sample.

sample prints (A to E) are equivalent to pictures shot by digital cameras having imagers of vertical pixel numbers from the 360 to 2000.

Subjective Evaluations. In the following discussion, the term P_1 means "pixel". Plate 4 (p. 82) shows the reproductions of sample prints and the magnifications of four target parts in the Samples A, D or E.

Visual evaluation of the model prints was conducted by two groups of observers. This examination was a psychological evaluation striving to identify if the sample print image quality was equal to photographic standards. This examination was the so-called a category evaluation.[5] The basis of this method is to compare quality level of Sample A through E with cabinet size traditional color photographic prints made by printing 35 mm color negative film images on positive color paper.

In this category evaluation, the question was to determine subjectively if the general image quality of the sample prints matched the level of color photographic prints. Color photographic prints standards were defined as: smooth and continuous tone rendition; plentiful color reproduction; fine and smooth expressions of original scenes; and a comfortable feeling with print itself, i.e., its durability and permanence. In this evaluation, the terms were limited to the fine and smooth expression of the scene. This judgment was applied to sample prints A through E.

Figure 2 shows the relationship between equivalent pixel numbers of the sample prints and the subjective evaluation scores of the observers. The evaluation scores on the vertical axes are the average of the voting points. In general, the evaluation values rose smoothly with the increase in pixel numbers. For the medium and small format prints, the values were appeared to saturate pixel numbers over 2 million.

When students from a photography school evaluated the sample prints having over five million pixels, the average marks were close to 3.0. Generally the average scores increased evenly. In the cases of sample prints C, D and E, less than two million pixels, the results are nearly the same. For the large format prints, the average scores are markedly lower. However, the evaluation score given by engineers show little differentiation. The steepest increase of evaluation values are near the pixel number of two million.

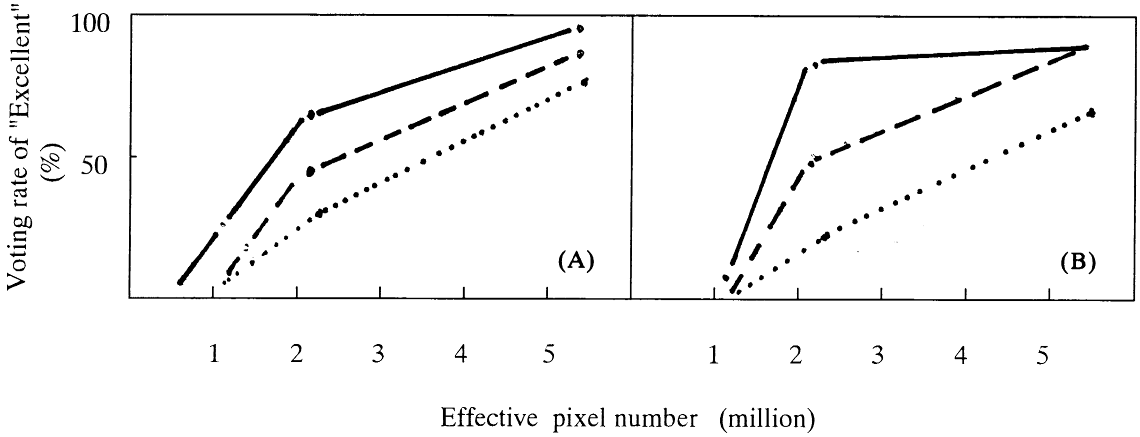

Figure 3. Relationship between effective pixel number and voting rate of "Excellent". (A) Students. (B) Engineers. (————) Large sample, (— — —) Medium sample, (• • • •) Small sample

Figure 3 shows the relationship between the voting ratio of "excellent" and the equivalent pixel numbers of sample prints as evaluated by both groups. A voting ratio of 100% means that all 38 students or 17 engineers evaluated the sample as "excellent". The highest scores were only given to sample print A. There were no "excellent" votes for prints having less than one and a half million pixels, i.e., Samples C, D and E. Print B data shows a distinct difference which appeared between the students and engineers. The voting ratio by the engineers was the nearly same as for Print A with five million pixels.

Most observers did not report color changes among the five sample prints, although some observers indicated that the face color of model images on the Sample D and E on the large format print looked to be "faded". The observer's concerns with the color was very low.

Objective Evaluations. The objective examination was intended to monitor the physical conditions of sample prints and to check the critical variation of image characteristics. On the objective examinations, the authors chose mainly the large format sample prints produced by thermal dye transfer printing. The reasons were convenience in preparing the various type sample prints and to introduce the results of a previous study.[1]

The first physical examination was the densitometric analysis of the images of gray scale charts held by the model and the magenta tonal chart as shown in Plate 4 (p. 82) and the second was the microdensitometric analyses, which measured sine density patterns for the MTF chart image on the sample prints. The third examination was the colorimetric analyses of the images of Color Checker and magenta tonal chart. Most of those examinations were done using the "large" sample printed by thermal dye transfer prints.

Densitometry. The densitometric curve suggested the tone characteristics of this digital photography system. Figure 4 shows the neutral density curves for the original gray scale chart and its reproductions held by the model on the sample prints produced by triple tranfers of yellow, magenta and cyan dyes. The density curves for the stairase images on the all sample prints show sigmoidal shapes. It suggests that the tone characteristics on the sample prints were compressed both on the light low density and dark high density regions. There were indistinct differences between the neutral density

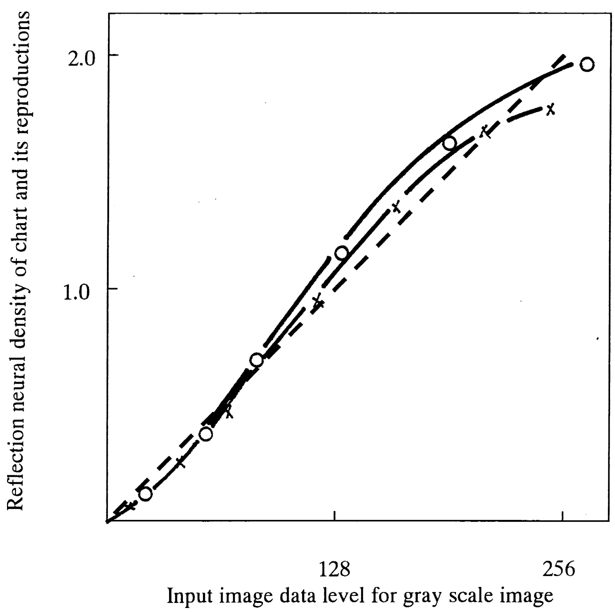

Figure 4. Density curves of gray scale chart image held by the model: (———) density change of original gray scale chart; O – sample print A; X – sample print E.

curves of image on Sample A and those of the rest of the images on Samples B and E . The maximum density on the curve for Sample A was nearly equal to that of the original staircase chart, however those for Samples B and E are little lower.

In the case of staircase images of the magenta tonal chart printed by magenta dye alone, there were apparent differences between green density curves for the image on the Sample A and those on the rest of sample prints. Figure 5 shows the relation of green density of patches and the input data level to the printer for the reproductions of the magenta tonal chart. The dotted curve expresses the density level of the original chart. It was a modified chart that established Beer's law as described previously. That curve exhibits a little bending because of its reflection status.

In Fig. 5, the sigmoidal density curves of sample prints are more strongly emphasized. The differences between those of Sample A and the rest samples are more distinct than those of neutral density curves

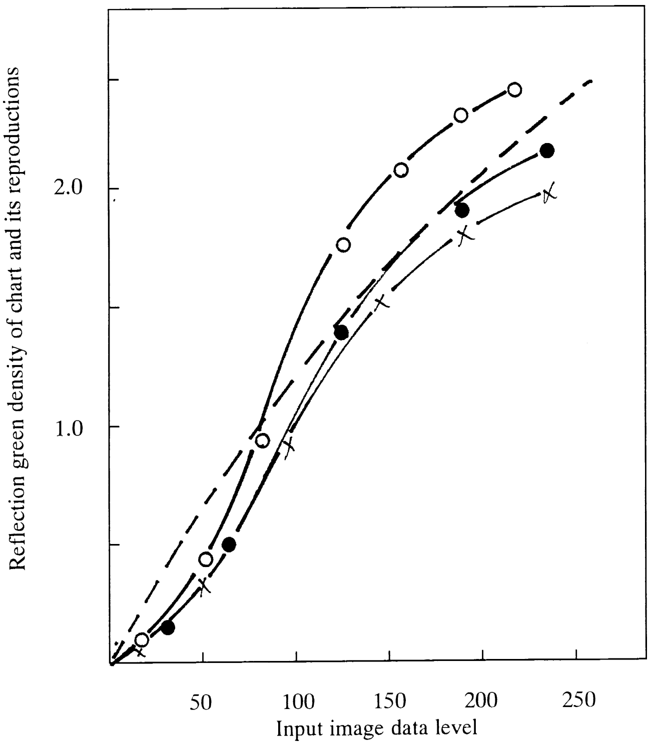

Figure 5. Density curves of magenta staircase chart and its reproductions: (— — —) density change of original magenta staircase chart; ❍ Sample print A; ● – B; X – E.

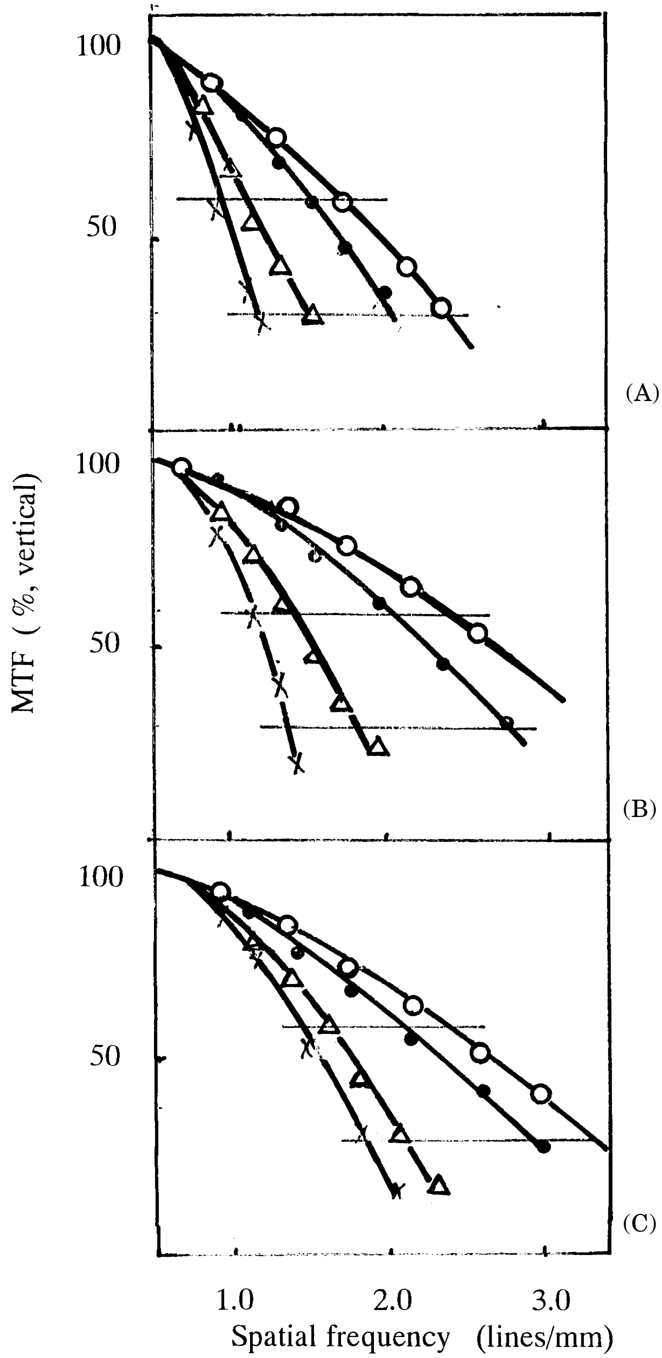

Figure 6. MTF characteristics of sample prints: (A) : Large print; (B) : Medium print; (C) : Small print; ❍ Sample print A; ● – B; Δ – D; X – E.

shown in Fig. 4. The effect of manipulation is so distinct that curves for Samples B and E are different from that of Sample A. The maximum density for Sample A is nearly equal to that of the standard chart and those of Sample B and E are lower than it. In Sample A, the input 256 level data expressed in the range of $D_g = 2.40$, however those for Samples B and E expressed on the density ranges of $D_g = 2.10$ and 1.95 respectively. In the case of the curve for the original chart itself, the unit density, dD for the one level image datum printed on the print was approximately $D_g = 0.01$. However, the sigmoidal density curves for the sample prints suggest that the average dD for the one level data printed on the those prints is not constant.

As a result, the alteration of tone characteristics caused by image processing was apparent on the magenta tonal chart images of the various samples.

MTF Measurement. Figure 6 shows the MTF characteristics of three format sample prints measured by images of the EIAJ's sin MTF chart on the sample prints. On the measurements, the aperture width of the microdensitometer was 50 μm square. It was equivalent to the printing pixel, P_1 in the "small" format sample prints.

On the direct viewing of hardcopy prints, the comparative resolution of human eye having normal sight is supposed to be[6] 80 μm and that of 50 μm is the value including the prolixity of above resolution.[7] In Fig. 6, the spatial frequency values are converted to the style of photography (lines/mm) to simplify discussion when directly viewing hardcopy prints.

The MTF curves of three format sample prints show different trends because they were produced by different printers. Thus detailed discussion is limited to the same format prints prepared by serial processing. In every sample print, the MTF curves are modified by manipulation. Especially, the MTF curves for Sample print A had a gentle slope and tailed to the high spatial frequency regions. Print E curves were very steep and fell in the low frequency region. Those of print B showed a very similar trend to print A, and print D curves were close to print E. Notice that there were big differences between the MTF curves for the B and D prints.

Typical MTF characteristics were apparent in MTF values of 30 and 60%. Table II shows the spatial fre-

TABLE II. Spatial Frequencies of MTF at 30 and 60% on Sample Prints

	Spatial frequency (lines/mm on vertical direction)							
	MTF value at 30%				MTF value at 60%			
Sample print	A	B	D	E	A	B	D	E
Print size								
Small*	5.75	4.80	3.25	2.95	3.70	3.00	2.20	1.90
Medium†	5.90	4.70	2.90	1.80	3.80	3.10	1.70	1.40
Large‡	3.95	3.40	2.10	1.50	2.40	2.10	1.25	0.90

* Small: 103 × 128 mm; † Medium: 130 × 161 mm; ‡ Large: 173 × 214 mm

quencies of the MTF values at 30 and 60% for four sample prints in three formats. In general, the frequency changes were more distinct in the smaller format sample prints than in the large format ones. At both MTF values, frequencies changes between Samples A and B, and D and E were significant, although those of B and D were greater. These trends were more apparent at 60% MTF.

Colorimetry. The colorimetric analyses were done measuring the L*, a* and b* (CIE 1976) color space values of the Macbeth Color Checker board and the magenta tonal chart images shown on Plate 4 (p. 82). This examination was to check the effects of image processing on the color reproduction and tone reproduction of the sample prints. The color reproduction was evaluated by the simple comparison of the chart images on the reproductions, and the tone reproduction was evaluated by color difference, dE on the magenta tonal chart reproduction images. On the colorimetry of reproduction of the single color tonal chart, the color difference measurement is a neat and well-defined method to examine the printing of individual input image data. Moreover, the discussion of dE for the single colored image chart image showing stepwise density change was compatible with that of tone reproduction.[1]

The color space values of 18 chromatic patches in the Macbeth color checker board image in the four large format serial sample prints were measured. The discussion was done using the color difference (dE) values between the same patches on the Sample A and Samples B, D and E. Table III shows the dE values of color patches of the sample prints. The average dE values of total 18 patches Samples A to B, A to D and A to E were 1.85, 3.04 and 2.69, respectively.

In Table III, the dE values for the patches of dark and light skin, foliage, orange, purple–blue, moderate red, yellow–green, green, and yellow showed larger than average values. Critical changes in values appeared between A and B and between A and D; these actual differences are around 2.0.

Figure 7 shows the relation of color difference, dE, between the one, two and four patches on the reproductions of the magenta tonal chart and the input image data level. With respect to the colorimetric discussion, dE = about 1.0 is thought to be the threshold at which people recognize two different colors.[8,9] In Fig. 7, the horizontal axis expresses the input data level by patch number shown in Fig. 1. The dE value of every sample decreases toward the higher density region and reach the critical point of dE = 1.0. The input data level value represents the section of printed staircase image of tonal chart shown in the Fig. 1.

In the case of dE for one patch, the dotted curve for the original chart was plotted from data measured in

TABLE III. Color Difference Values CIE L*A*B* (dE) Values Between Sample Print: A, B, D and E for Chromatic Patches of Macbeth Color Checker Reproductions (Large Format Prints)

dE between	Dark skin	Light skin	Blue sky	Foliage	Blue flower	Bluish green
A & B	2.17	2.19	1.10	1.97	1.57	1.84
A & D	3.70	3.74	2.54	4.14	1.98	2.21
A & E	3.08	3.62	1.40	3.32	1.60	1.51
	Orange	Purple blue	Moderate red	Purple	Yellow green	Orange yellow
A & B	2.75	2.23	2.29	1.32	1.57	1.34
A & D	4.65	3.86	3.19	2.81	2.90	2.08
A & E	4.32	2.63	3.29	1.97	3.15	2.07
	Blue	Green	Red	Yellow	Magenta	Cyan
A & B	2.22	2.02	1.75	2.25	1.74	1.03
A & D	3.00	3.35	2.81	3.17	2.90	1.71
A & E	2.17	3.85	2.62	3.67	2.31	1.96

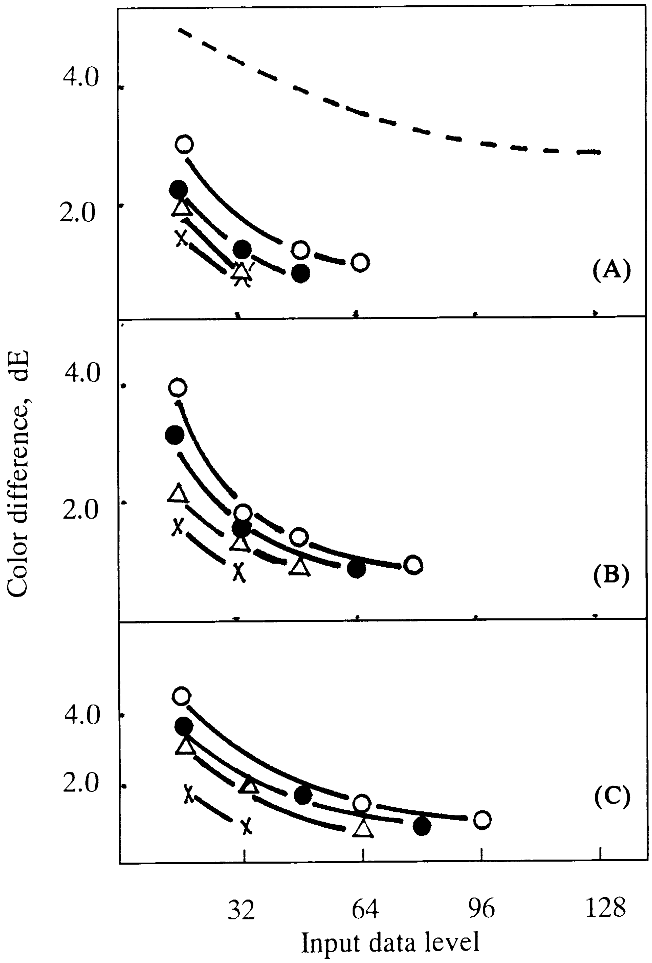

Figure 7. Color difference, dE between one, two and four patches on the images of magenta tonal chart: (A): patch one; (B): two; and (C): four; (— — —) dE change on the reproduction printed by original image data, ❍ Sample print A; ● – B; Δ – D; X – E.

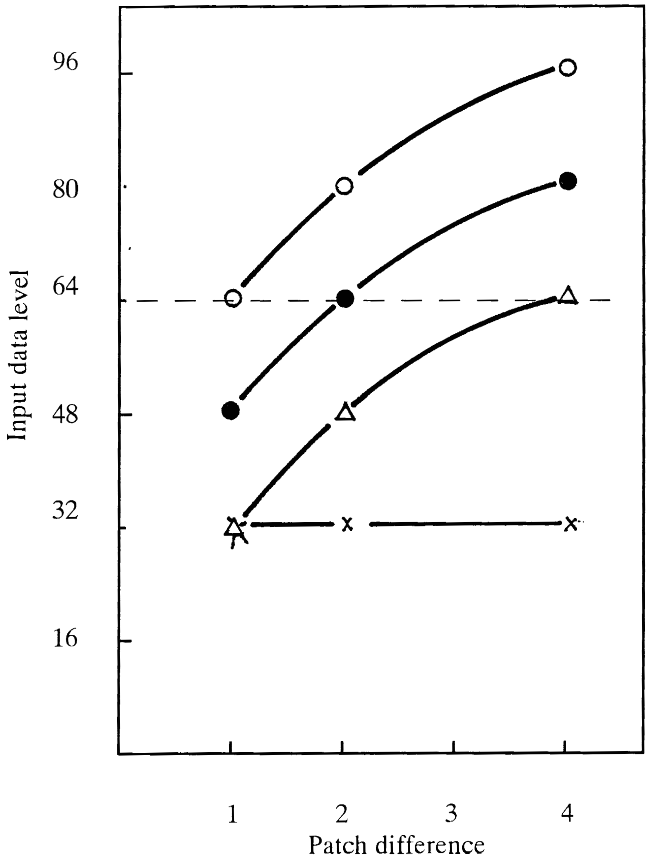

Figure 8. The relation of input data level and the measured patch difference for the critical dE value of 1.0: ❍ Sample print A; ● – B; ∆ – D; X – E.

the previous article.[1] Its curve is located in the higher dE range than those of the sample prints. The dE value between the highest 256th and 255th level data plotted was over 2.5, and the dD value for the individual level datum is estimated to be D_g about 0.01 as described previously. In the every case in Fig. 7, the dE values at low input data level were high, however the average dD value for levels 16 and 32 estimated from Fig. 6 were around $D_g = 0.005$. The relationship of color density and color space value is not so simple that the direct comparison can be made. Thus the authors have tentatively decided a reasonable key to identify the discriminative dE for individual patches. The sufficient condition is to obtain critical values of both dE = 1.0 and dD in D_g = 0.01. For the input data level of 64, the average dD values for all samples cleared the restriction of $D_g = 0.01$, demonstrating adequacy of the tone reproduction of the chart image printed with input data level of 64.

Figure 8 shows the relation of input data level and the measured patch difference for the critical dE value of 1.0. According to the increase of patch difference, the appearance of dE critical point moved to higher input data level region. With the input data level of 64, the section four of the tonal chart image shown in Fig. 1, a one patch difference the dE critical point appeared only for Sample A; a two patch difference could be identified for Samples A and B and a four patch difference could be recognized on Samples A, B and D. In the case of Sample E, even a four patch difference could not be identified on the basis of the reproduction printed by that input data level.

The results of Figs. 7 and 8 suggest that the definition of tone expression of the image data was different on the individual samples. The tone reproduction of the output integrates characteristics of shooting, image processing and printing processes. In this study, the shooting and printing processes were common for all sample prints, thus the image processing would be the key issue in modifing the tonal characteristics.

Summary

The criteria of photographic color prints necessary to satisfy viewers are too numerous to mention. In the case of a traditional photograph, the so-called analog prints embody the excellent characteristics of the media itself, its photographic equipment, and the long efforts made by people in the industries and its users.

However, in the case of digital photography prints, there are large structural problems caused by the arrangement of the digital pixels. No one likes to identify the notched image structures made by large printed pixels. We must eliminate that problem and attain the quality of current analog photography. We are studying the limiting conditions for the advancement of digital photography.

This study attempts to discover the limiting image structure needed to produce digital prints as good as the current color photographic prints. The easiest way uses an image pixel structure small enough to be invisible to the human eye. In this work, the correlation between the structural quality and the pixel number of the digital prints was clarified. The discussion of such correlation using digital prints produced by segmented traditional color photographic prints was described.[6] In that study, the preparation of unified size sample prints that have the same image with different pixel conditions was difficult. Thus, the systematic discussion was not complete. In this study the discussion evolved using real digital prints having wide ranging pixel conditions in different print formats.

The most important photographic characteristics are thought to be the resolution and tone reproduction of output picture image. The non-digital visible image structure, the wide density range and the recognition of continuous density change on the print are the key issues. In this study, the results shown in Fig. 4 and in Fig. 5 suggest that the gray scale image on the Sample print A was perceived to be perfect continuous tone, and the definition of 256 level image data was reproduced distinctively. Thus, that digital photography print is thought to be the same as a regular photographic image.

The results of the subjective evaluation, shown in Fig. 2 and Fig. 3, suggested that an "excellent" quality level required more than two million pixels. A "fair" quality level, required more than 1.5 million.

The print sizes ranged from 173mm × 210 mm to 103mm × 128mm. However, the effect of print size was not very clear. The prints were all hand-held size, and the viewing conditions were nearly the same. One important discovery was that the evaluation scores for the large format were lower than the other formats. The sample prints of A and B consisting of five million and nearly two million pixels, respectively were subjectively evaluated to be the same level as the current photographic prints.

The results of objective evaluations showed that the most critical differences between the physical property of images appeared in the MTF characteristics and tone expression. In the microdensitometric and colorimetric analyses, the sample images consisting of the higher interpolation ratio showed somewhat poorer results. There was a critical difference in the MTF. Subjectively acceptable prints showed that the MTF characteristics extended to high frequency range. There was a big difference in the spatial frequencies between the MTF values at 60% in the sample prints of B with two million pixels and D, with a half million pixels. Considering the human visual frequency response, such characteristics are very effective for the comfortable viewing of prints.

In the case of tone expression, the manipulation to resize the simulation images affected the definition of the printed image. Edge artifacts and the visible digital tone expression are not comfortable to our vision. Data handling in the system was carried out on an 8 bit scale, although in the printed images, the definition was altered according to the printing procedure.

According to the results of Figs. 7 and 8, evaluated by color difference, dE, the printed 256 level image data will be recognizable as individual steps up to input data levels of 64 and 48 for Samples A and B, respectively. However in Samples D and E, the data were recognizable until only 32nd level. It was doubtful to accept high dE values for the low input data level because of too low dD values. Thus discussion of the tone reproduction is confined to the images printed by typical input image data, specifically the staircase image of 64th level data and the dE differences of one, two, and four, which were those between 64th and 63rd, 64th and 62nd and 64th and 60th levels, respectively. In Fig. 8, the difference between one, two and four patches corresponded to one step of 8, 7 and 6 bit data. Thus in the magenta tonal chart image on the Samples A, B and D, the 64th level of 8 bit input image data appeared as the 8, 7 and 6 bit level printed data respectively. The definition of printed data was apparently affected by manipulation.

The result of MTF characterization showed the critical point for the spatial response to be located between Samples B and C. However tone reproduction response had not suggested such distinct change. Thus the first critical issue in the objective image quality comparison is the structural image quality, and the second issue will be the tonal problem.

The issues of evaluations by subjective viewing examination and the objective analyses of the tonal expression, and the frequency response of the microstructure of sample prints showed the same trends. The order of image quality of sample prints lined up from the best, A, to the worst, E. The critical changes on the examinations of viewing and MTF measurement appeared between the serial sample prints B and C, formed by image data of 2 and 1.2 million P_1 pixels, respectively.

The results of this study, using a portrait image, concluded that a 2 million pixel imager in the DSC can generate sufficient image data to produce hand-held size digital prints which will satisfy the customer demand for tone and structural image quality.

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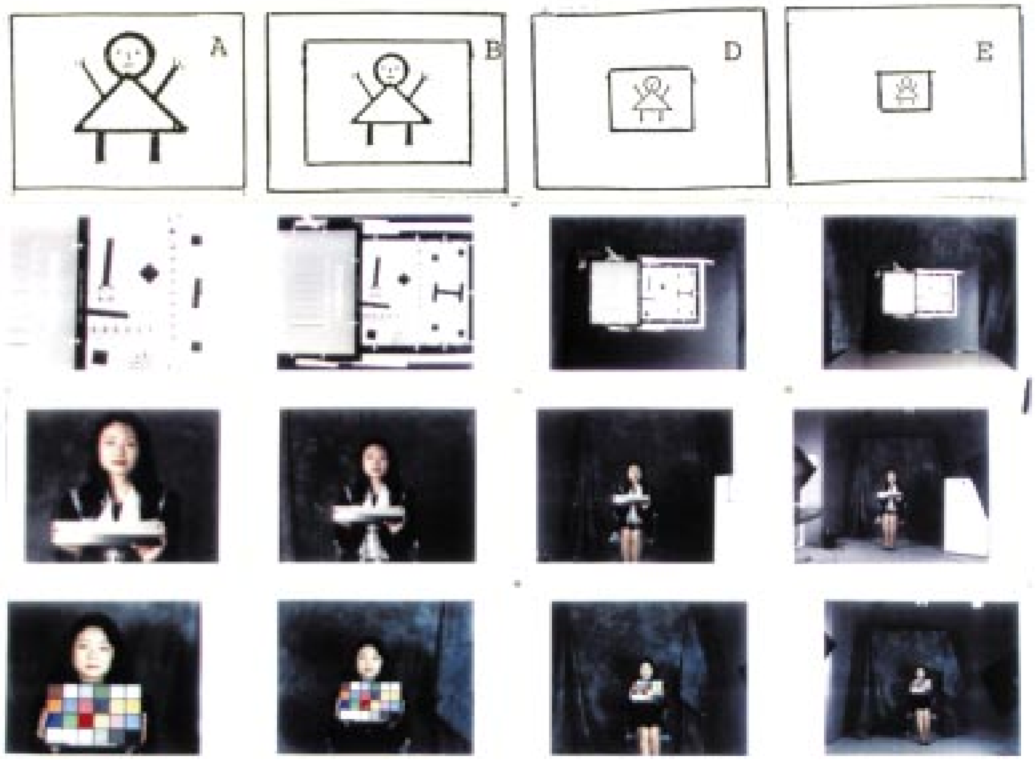
Original Pictures

(Cropping)



Sample Simulation Pictures

(Resizing by interpolation)

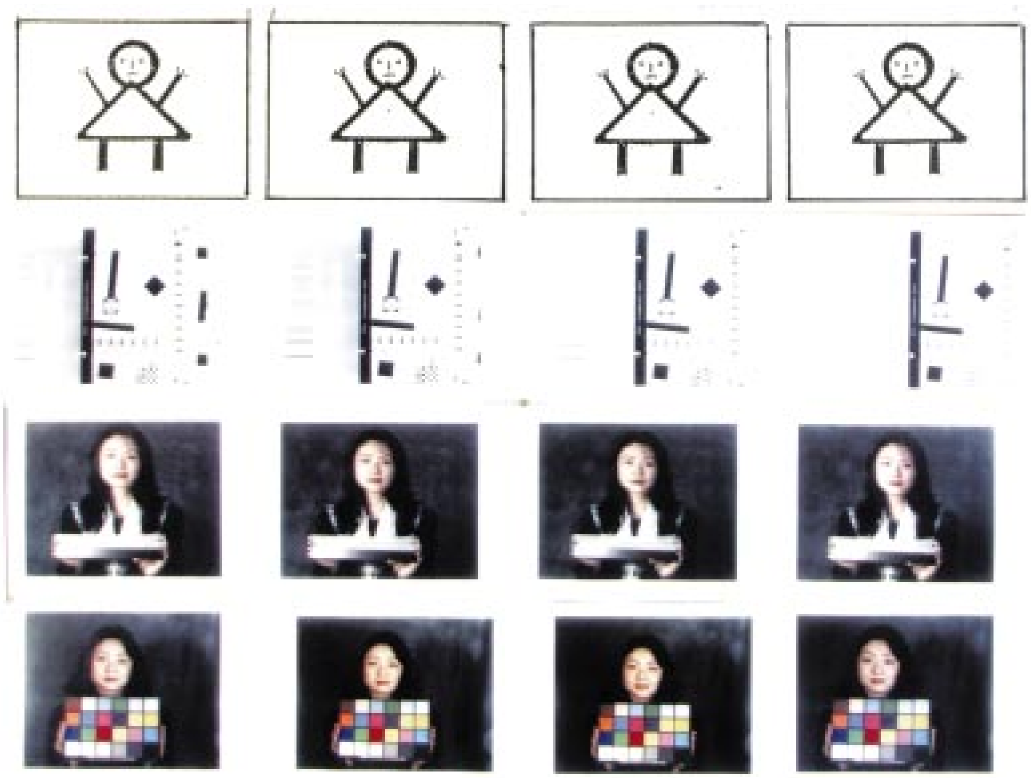


Plate 2. Original pictures and simulation sample prints for evaluations (Ohno, *et al.*, pp. 51–60).

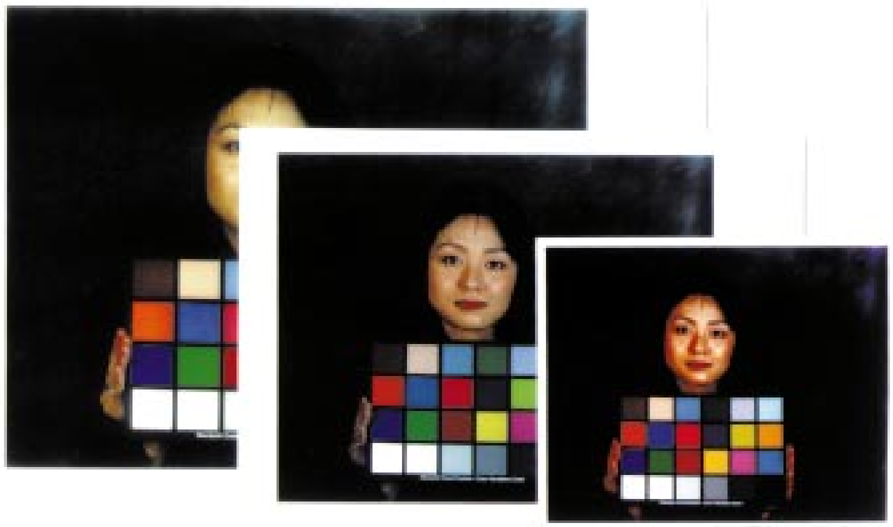


Plate 3. Sample print A on the three format specimens (Ohno, *et al.*, pp. 51–60).

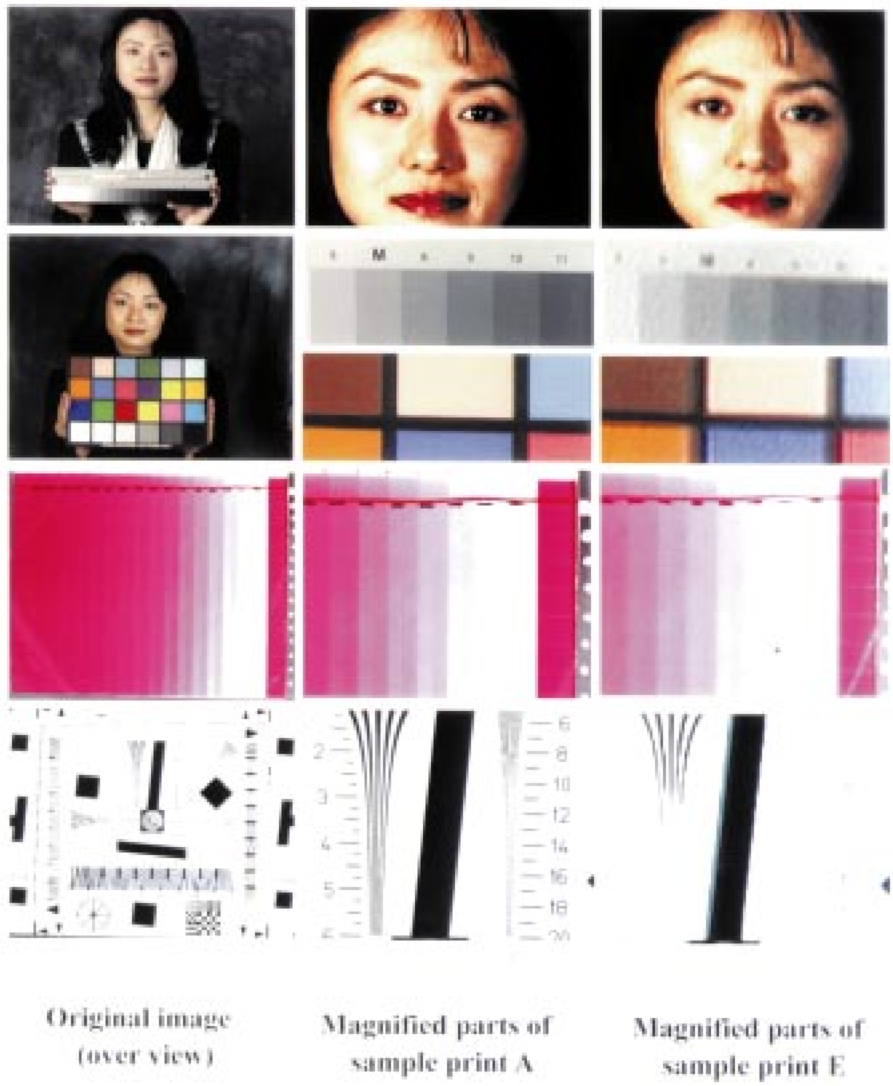


Plate 4. Print samples—Magnified target parts of prints for evaluations. The first column shows the complete views of Sample print A. The second and third column show the magnifications of selected parts of Sample print A and E, respectively (Ohno, *et al.*, pp. 51–60).