An Evaluation Method of Gradation Reproduction Based on Micro Colorimetry

Jun Abe, Toshihiko Inagaki
R & D Center, Document Products Company, Fuji Xerox Co., Ltd.
Ashigarakami-gun, Kanagawa, Japan

Abstract

As the image quality of color and monochrome electrophotographic printers has improved, they are beginning to be used for graphic users. Printer output images that contain gradations have been increasing, and smooth reproduction of gradation is one of the important subjects of image quality. This paper describes an evaluation method of gradation by using decomposition into Lightness and Chroma based on micro colorimetry with a flatbed scanner. In order to evaluate the reproducibility of gradation, difference value from a desirable gradation is computed, and a perceptual threshold value is determined that can be used as a basis for judgment of detecting difference value. The desirable gradation is derived from compensating for measured gradation by the transfer function of human visual perception. A high correlation between the total of difference value that is greater than a perceptual threshold value and psychological score of smoothness of gradation, is achieved.

Introduction

Sharpness, graininess, tone and color reproducibility, etc., are key factors that determine image quality. Especially in the case of the color printer, there are many opportunities to output pictorial images, and users are asking for continuous tone reproduction like silver halide. The gradations, in which tone and color and density change gradually, are widely used not only in graphic designs but also in office documents, and smooth reproduction of gradation has become an important factor in image quality. However, if the tone reproduction characteristic of the printer deteriorates, a tone jump, i.e., a sudden color change with gradation, will occur. A superior tone reproduction characteristic indicates the flexibility of neutral color expressions and with few tone jumps, like silver halide.

The human vision system is characterized by a Visual Transfer Function (VTF),[1] and an observational object size is appropriate, approximately 200 levels of gradations can be discriminated.[2] Furthermore, since discrimination capabilities decrease with increasing spatial frequency, it can be said that levels of gradation above the visual performance limits are sufficient continuous gradation reproduction. Theoretically, a printer typically reproduces 256 levels of gradations, but high-light washout, shadow saturation, and contours exist, which are recognized as tone jumps.

In the printer side approach regarding tone reproduction, the ink jet printers, so-called photographic-quality printers, improve the graininess by using light ink, but even if ink is increased, the levels of gray that can be expressed by one ink droplet are only white (paper background) and the ink color. Therefore, for increasing the levels of gradations, attempts have been made through piling up ink, raising resolution to increase the ink placement patterns per unit area, and expressing more dots with smaller ink droplets. On the other hand, in electrophotographic printers, it is not easy to increase the number of color materials and to overprint as in the case of ink-jet printers, and improvements are limited to the range of area levels of gray within the compass of CMYK four colors. Therefore attempts to improve the gradation have been restricted to raising resolution and optimizing digital halftoning.

With regard to quantitative evaluation of image quality, many reports of graininess and sharpness have been seen, but few reports concerning characteristics of gradation have been seen.

Generally, the characteristics of gradation images are evaluated visually by printing appropriate images and grading the levels of tone jumps. This leads to various problems, such as ambiguity in the criteria of tone jumps, and variation between evaluators.

This report suggests an evaluation of gradation characteristics taking VTF into consideration by using micro colorimetry, for which measurements are carried out through decomposition into the Lightness (L*), the Chroma (C*) and hue angle (hue) components with a commercially available high-resolution color scanner. Furthermore, these image quality evaluation items are applied to outputs of electrophotographic printers for validation of agreement with subjective evaluation.

Threshold Value and Weight Coefficient of L*

It can be considered that our criteria for judging whether a gradation is good or bad include perceived magnitude of tone jumps in gradation images, and the extent of such jumps. Thus, in order to understand the influence of tone jumps on vision in reference to the standard color space, subjective evaluations of threshold values and weighting coefficients were made by using samples on which 10mm-square patches are placed. Figure 1 shows an example of comparative images.

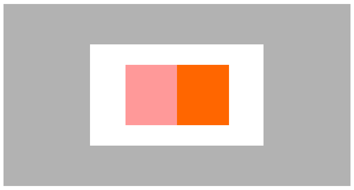

Figure 1. An example of images used for evaluation of threshold values

Evaluation samples were created by two systems: the electrophotographic printer originally targeted for evaluation, and a silver halide printer with low noise.

The subjective evaluation method we used for this report is category evaluation in which sample pairs are classified into categories according to the perceived color difference of the color steps.

Table1 Terms and score used for evaluations

score	Evaluation Term
1	Difference is imperceptible.
2	Difference is barely perceptible. (Detection limit)
3	Not objectionable although difference is visible. (Permissible limit)
4	Not obstructive although difference is annoying. (Patience limit)
5	Difference becomes a little obstructive.
6	Difference becomes quite obstructive.
7	Difference becomes very obstructive.

According to the evaluation terms used in the category method, score 2 refers to a detection limit, score 3 refers to a permissible limit. Results summarized by a detection limit and permissible limit are shown in Figure 2 and 3. When attention is given to threshold values (detection limits) to recognize the gradation characteristics, the threshold values vary to some extent between colors, but it can be said that there is not a great difference in threshold values between colors with variations in subjective evaluation taken into consideration. Also, regarding the difference in threshold values by output method, it can be said that steps by electrophotographic method are harder to recognize than those by the silver halide process. The cause of this is considered to be the existence of defects in xerography, resulting in larger threshold values. For this reason, the threshold values of tone jumps with the L* component by the silver halide process with less other-than-L* disturbance, and detection limits are used in terms of recognition of the gradation characteristics.

Next, when tone jumps exceeding detection limits exist, compensation with the weight coefficient of L* is necessary for conversion of the amounts of tone jumps into subjective evaluated values as subjective evaluated values are not the same in the L* space where tone jumps occur, but dependent on the developed L*. Then, in order to obtain this relationship, Figure 4 shows the relationship between subjective evaluated values and data with deltaL* from 1 to 1.5 by silver halide in the L* space. From the figure, the relationship between subjective evaluated values (Q) and tone jumps (TJ) is given by the expression (1).

$$\mathrm{Log}(Q)=\mathrm{Log}(TJ^{0.375}) \qquad (1)$$

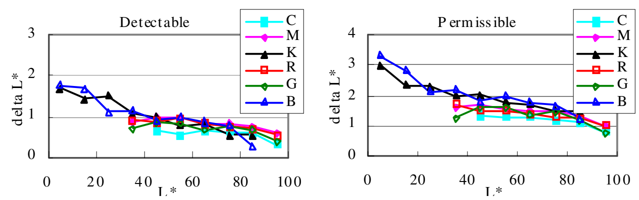

Figure 2. Detection and permissible limit in silver halide

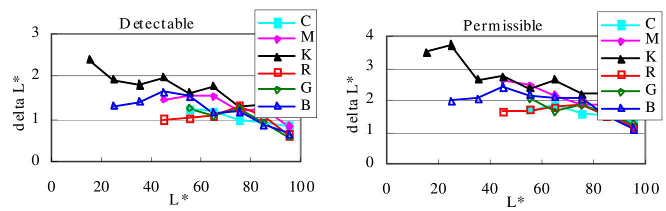

Figure 3. Detection and permissible limit in electrophotography

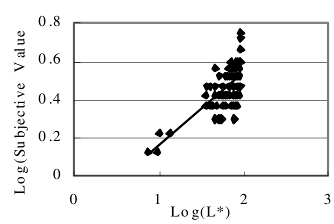

Figure 4. Weight coefficient of L to the subjective gradation*

Subjective Evaluation

For evaluation of the gradation characteristics of subjectivity by using actual samples having gradation, seven kinds of samples in primary colors were prepared, and output under seven types of conditions wherein printing methods, screens, etc., were altered. An example of sample images used for evaluation is shown in Figure 5. The evaluation method we used is category evaluation, which was used for subjective evaluation of threshold values.

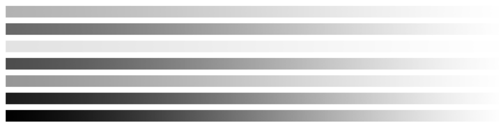

Figure 5. An example of images subjective evaluation

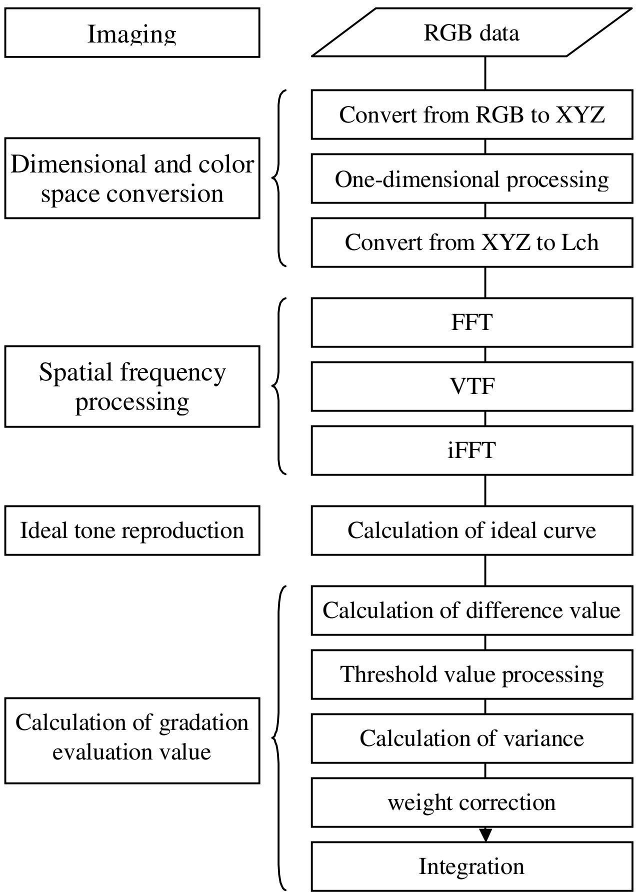

Figure 6. Flowchart of evaluation of gradation

Objective Evaluation

Analyses were made using TH and weight coefficient in consideration of human visual characteristics, so as to obtain physically evaluated values in high correlation with subjective evaluated values. Analyzing procedures are shown below. (1) By using a commercially available flatbed scanner as a sample image input device, two-dimensional images are captured and the RGB color signals output by the scanner are converted to CIEXYZ color space. For conversion, it is used due to the relationship between colorimetric data and RGB output signals of the scanner. (2) Two-dimensional XYZ data are averaged in a perpendicular direction to the gradation to obtain one-dimensional XYZ values. (3) One-dimensional XYZ values are converted into L*, C*, and hue. (4) To add weight coefficient in consideration of visual characteristics for improvement of correlation with subjective values, conversion is made into the spatial frequency domain, and reconversion is made into the real-space domain after multiplication by the VTF.

Therefore, the value of L*, C* and hue can be obtained by quantization of images when gray-scale images are observed at a standard observation distance. Here, it is preferable that the ideal gradation curve to be output from the printer should originally have a positive correlation between the input image density and output image, but due to the halftoning processing in consideration of electrophotography characteristics in design of image quality, an ideal gradation curve cannot unequivocally be determined from the input image density. In other words, it is considered that an ideal gradation curve exists according to each output system of images targeted for evaluation. This report, regarding tone jumps as noise in gradation images, adopts an ideal gradation curve locally operated in the system.

Tone jumps are observed by changes in L*, C* or hue existing in gradation images. To be more specific, since they are perceived by deviation from the ideal gradation curve predicted from each gradation image, (5) after VTF processing, the difference from the ideal gradation curve is obtained.

Next, (6) the threshold value (detection value) is subtracted from the difference in calculating variance. In addition, weight coefficient compensation is made with the L* or C* axis, and integration is made in the gradation direction. The flowchart of these gradation characteristics evaluated value calculations is shown in Figure 6. Since yellow cannot be evaluated by L*, it is evaluated by using C* in like manner.

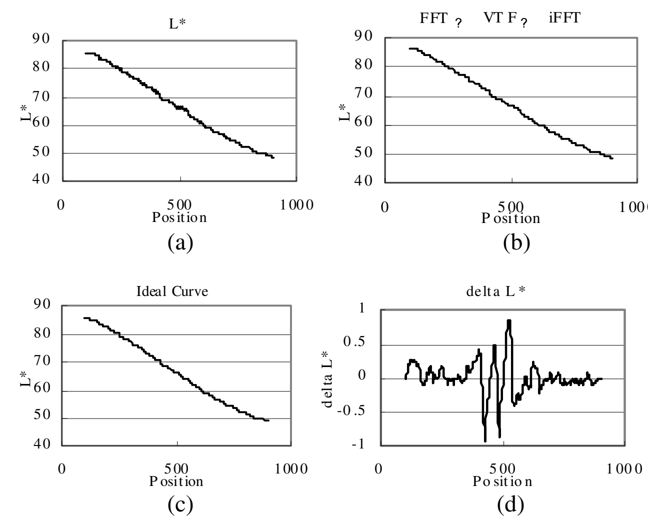

Figure 7. Explanation of analysis data

Figure 7 shows the data of the results of analysis in progress. (a) shows the RGB signals of the two-dimensional image obtained by image acquisition, which are converted into CIEXYZ, one-dimensionally processed, and converted into L*. (b) shows raw L* data compensated with VTF in the spatial frequency domain, and reconverted into real-space. (c) shows the ideal gradation curve of the target image obtained by calculating a local average from the results of (b). (d) is a difference between (b) and (c), and is the L* amount of the tone jump existing in the gradation image that is actually perceived by the visual system.

Validation of Correspondence

The relationship between objective gradation characteristic evaluated values and subjective gradation characteristic evaluated values is shown in Figure 8. As a result of logarithmic approximation with the data in this report, the gradation characteristic evaluated values of yellow alone were linearly approximated as it was characteristically evaluated by chromaticness and its tendency was different from other colors. From the figure, the correlation coefficient (R^2) between cyan, magenta, yellow and black is equal to or more than 0.8. Figure 9 shows the results of data organized in five colors (Cyan, Magenta, Red, Green, Blue), where there is a strong correlation (R^2=0.89) between objective gradation characteristic evaluated values and subjective evaluated values, so that the gradation characteristics can be evaluated. Black is shifted compared with the above five colors, and also, black is slightly low in correlation even though it is in isolation. This is caused by large variations between subjective evaluators because the outlines of tone jumps in black are easy to recognize.

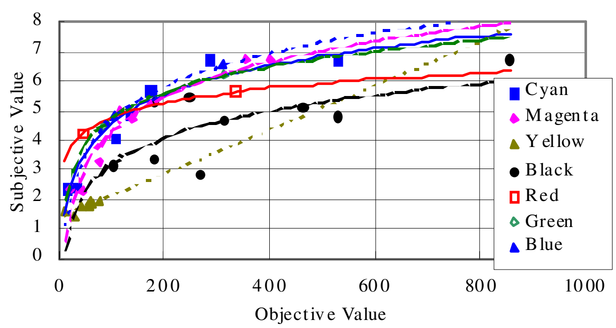

Figure 8. Relationship between objective evaluated values and subjective evaluated values by color

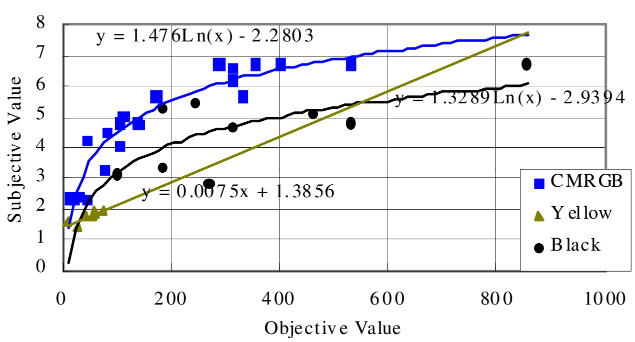

Figure 9. Relationship between objective evaluated values and subjective evaluated values

From the above, objective gradation characteristic evaluated values of gradation images in high correlation with subjective evaluation can be obtained, so that the gradation characteristics can be evaluated. Further conversion from physical evaluated values to perceptual evaluated values allows comparison of gradation characteristics between gradation images different in color with the common scale of human visual perception.

Conclusion

As a result of the study of evaluation methods of gradation characteristics, important for the color printer with an eye on high quality was considered. It is possible to evaluate the subjective gradation quantitatively by using decomposition into Lightness and Chroma based on micro colorimetry with a flatbed scanner. In order to evaluate the reproducibility of gradation, a difference value from a desirable gradation is computed, and perceptual threshold value is determined that can be used as a basis for judging detection of difference value. Furthermore, perceived gradation is derived from compensating for measured gradation by the transfer function of human visual perception. A high correlation is achieved between the total of difference value that is greater than a perceptual threshold value and a psychological score of smoothness of gradation.

References

1. R. P. Dooly and R. Show, *J. Appi. Photogr. Eng*., **5**, 190-196, (1979).
2. Paul G. Roetling, Visual Performance and Image Coding, *SPIE/OSA* Vol. **74**, (1976)

Biography

Jun Abe received a B.S. degree in Mechanical Engineering from Waseda University in 1985. Since 1985, he has worked at Fuji Xerox Co., Ltd., and now works in the Document Products Company Research and Development Center of Fuji Xerox. His work is primarily focused on image quality.

Toshihiko Inagaki is image quality research group manager of Research & Development Center of Document Product Company in Fuji Xerox Co. Ltd. He has been developing image quality evaluation methods and systems for 25 years in Fuji Xerox. He has been in charge of extraction of psychological attributes in image quality evaluation, development of objective measurement method of psychological attributes, development of image quality prediction model, development of image quality meter, and so on. He is project editor of ISO 13660 addendum on system compliance test and ISO 13660-2 measurement of image quality attributes for hardcopy output – large area color images. And he is chief examiner of Working Group 1 of technology committee in the Imaging Society of Japan since 1990.