A Study of the Printing Ability and Feasibility of the Color Ink Jet Printer in Color Proofing

M. James Shyu*

Keywords: Colorimetric, Ink Jet, Printing Ability, Proofing, Test Method

Abstract

The development of computerized technology not only increases the productivity but also transforms the workflow in the graphic arts industry. For the computer-to-plate or to-press machinery, an accessible and affordable digital color proofing device is needed in accomplishing such workflow evolution. Accordingly, a desktop SWOP simulated ink jet printer system is studied in this research to explore the possibility of its functioning as a digital color proofer. A 4-color test chart is designed to test the printer in the aspects of basic print property and accuracy. The test criteria are developed with specific consideration for desktop ink jet technology. The test results can be a benchmark reference when searching for digital color proofing options in the CTP era. The test procedure can serve as an aid to confirm printing standards.

Introduction

The graphic arts industry has gone through a workflow evolution with the aid of computerization for the past two decades (Romano, 1996). The number of steps in the printing process has been reduced and turn-around time has been shortened. The computerization trend has even

*Department of Graphic Communications, Chinese Culture University, Taipei, Taiwan, ROC.

pushed the industry into a more integrated process flow in which graphic designers will control some of the printing setting as part of the design work, like the trapping ratio in the pagination software. In the mean time, printers may get a preflighted electronic file and send it directly to a computer-to-plate machine or to a digital press in a filmless environment. Given the process-stage shrinkage, a color proof which shows how the design should be is still needed to communicate between content creator and print producer. A fast turn-around and affordable digital color proofing device is therefore an essential element in this computer-to-environment.

A color proof is at its best generated with the same colorants and substrate as it is actually printed on a machine. Various kinds of proofing devices are developed as a press simulator for better cost efficiency and time efficiency. Toner-based and film-based analog proofers have been used quite successfully with the benefit of half tone screen on the actual substrate; however, they start to loose their advantage with their relatively higher cost of labor and consumables (Baron, 1993). The Digital proofer gains popularity for its direct operation from the computer file. Dye-sub type digital proofer is capable of producing A3-size digital proofs on special paper with relatively more expensive consumables and machine costs (Cost, 1997). Another type of digital proofer with promising potential is the ink jet printer (Baron, 1993; Ingraham, 1993b).

An ink jet mechanism in which droplets of liquid are jetted from a small aperture to a medium was first described by Lord Rayleigh in 1878 (Rayleigh, 1878; Le, 1998). High-end continuous ink jet printers are being widely used in high quality graphic arts production houses, and studies indicate that their color consistency is comparable to analog Matchprint proofs (Ingraham, 1993a, 1993b). Recent enhancements and mass production make ink jet technology very affordable and suitable for on-demand printing application. It is very common to find a desktop ink jet printer in a personal computing environment, which prompts this research to explore its possibility to function as a digital color proofer and to reveal how far behind it is compared with the analog proofer and the high end ink jet proofer.

Ink jet printers have improved greatly not only in regard to image quality and imagable size but also in operation cost and machine price. Based on the thermal (Vaught, 1984) or the piezoelectric principle of the drop-on-demand method, an ink jet printer can generate ink droplets as fine as 10 pL. In a high precision manufacturing process, like the laser ablation method, an ink nozzle in a multi-nozzle printhead can be as small as around 20 *u*m. Some ink jet printer can even achieve an image resolution higher than 1000 dpi when used with a properly coated water-receiving layer on the medium to control ink spread and penetration. Large-format ink jet plotters as wide as 60 inches and multi-color inks with 6 or 7 colors are making their way to the market (Mills, 1994). More and more selections of paper stocks for various applications are available. The newer ink jet printer comes either with faster printing speed or at a reduced price.

Ink jet technology has its own merits with certain characteristics such as error diffuse screening, fast-drying ink and special coated substrate, all of which influence the printing ability of the ink jet printer. Error diffuse screening is best for ink jet type drop-on-demand dots. It generates binary images using high spatial frequency (Knox, 1994). However, the tonal response between digital values of the screening and the reflectance factor of the output image is far from linear. Certain tone correction is needed to resolve the non-linearity (Rosenberg, 1992; Lin 1994). Another type of non-linearity results in a reversal of the tonal curve, similar to the reciprocity-failure curve in photography (Hunt, 1987; James, 1977). This is introduced by improper ink-paper interaction on the paper surface that creates the solarization phenomenon. Figure 1 illustrates an example of the non-linearity problem where the lightness of a black ink print-out is reversed in the shadow area. The lower ink viscosity requirement results in a water-based ink with colorants different from the regular press ink and different drop generation properties (Freire, 1994). The ink jet paper also requires special coating to control ink spread and penetration. All these factors influence the printing ability of an ink jet system.

There are certain requirements for a digital proofer in the graphic arts industry. This study explores how close the ink jet printer has come to being suitable for color proofing application given the recent enhancements in the ink jet technology. A test chart and progressive testing procedure have been designed accordingly, to verify the printing ability of the ink jet printer. A desktop ink jet printer system is taken as a test platform to be run through the testing procedure. The test results will provide a reference indicating the printing ability of a desktop ink jet printer system as well as the feasibility for it to serve as a digital color proofer in the graphic arts environment. With this proposed test target and testing method it is possible to test further any newer ink jet printer system for the same purposes.

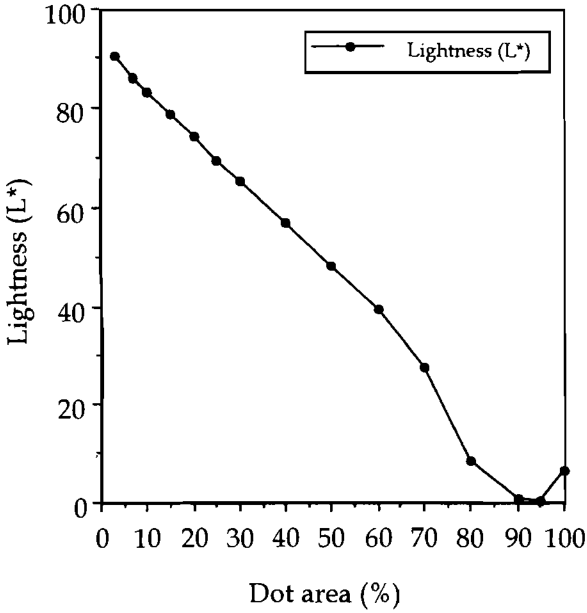

Figure 1. An illustration of the solarization phenomenon on an ink jet printout.

Printing Ability Test of the Ink Jet Printer System

The printing ability tests are divided into two categories, basic printing property and accuracy. The basic printing property relates to the uniformity and precision tests on the printout. The accuracy test compares the print result of a printing system with a known standard.

The basic printing property is associated with the operational conditions of the ink jet printer and its precision in repeating the same values. A common problem is missing dots because of a clogged printhead. An unusual but significant problem is mis-alignment caused by vibration from high-speed moving parts (Lin, 1994). Continuous fine lines in vertical and horizontal directions can be printed to verify both issues. Another issue is the paper and ink interaction which appears as wetting, penetration and spread (Lee, 1994). The presence of these phenomena results in low solid ink density or a more critical phenomenon known as the solarization problem which causes a reversal of tone. This type of non-linearity curve can be detected by plotting lightness values against ink values against the high total ink combination.

Repeatability is the essential printing ability criterion of the ink jet printer for it to be qualified as a color proofer. It is noted that the success of color control is also limited by the statistical deviation an output device undergoes when working under usual conditions (Has and Newman, 1995). If a printer has a repeatability variation greater than the acceptable color tolerance (Schlapfer, 1996), the printer is not suitable for graphic arts application.

Both spatial repeatability and temporal repeatability are relevant to the ink jet printer. Two aspects of the spatial repeatability can be further examined for most drop-on-demand type ink jet printers: in the printhead moving direction and in the paper feeding direction. Temporal repeatability is related to how consistent an ink jet printer can print between different sheets of the same type of substrate. The variation among a number of sampling printouts can give a clear indication of the level of repeatability for certain printing attributes.

It is known that the density range is primarily affected by paper property, and dot gain is primarily affected by ink property in lithographic prints (MacPhee, 1991). For non-impact type printing devices like the ink jet, absorption (wetting), penetration and spread on the paper were found to be the major factors for controlling the dot size (Juntunen and Virtanen, 1991). However, the relation between the dot gain variation from dot size changes and the perceptible visual color difference is still a complicated function of ink density. Furthermore, the colorants in the low-viscosity water-based inks for the ink jet printer are different from regular printing ink. A density comparison between these two kinds of ink is susceptible to the problem of observer metamerism between machine vision and human vision. Therefore, the repeatability test is based on the CIELAB colorimetric difference, ΔE^*ab, to determine the color difference among the samples (CIE, 1986; ASTM, 1994; NPES, 1995b).

To ensure a subjective judgment, a statistical method is needed in sampling the test data (Southworth, 1989). For the repeatability test, a blocking method (Barker, 1985) can be applied in measuring the test samples to reduce the number of test outputs. For example, the repeatability variation for one ink can be calculated from certain samplings on the same printout of the test sheet in both x and y directions and also on the same color patch position on each sheet of the printout for the number of samples. The CIELAB color difference can be calculated between each measurement and the mean LAB values among the measurements of the same test. Finally, a number being referred to as MCDMs is calculated to summarize the test (Billmeyer and Allessi, 1981). The color differences are averaged, and these averages are reported as "means of color differences from the mean of a set of measurements" or MCDMs. Standard deviation can be calculated as well. For ***n*** samples of CIELAB values in one test group, the MCDM ΔE is calculated as follows:

$$L^*_{mean} = (\sum_{i=1}^{i=n} L^*_i) / n$$

$$a^*_{mean} = (\sum_{i=1}^{i=n} a^*_i) / n$$

$$b^*_{mean} = (\sum_{i=1}^{i=n} b^*_i) / n$$

$$\Delta E_i = \sqrt{(L^*_i - L^*_{mean})^2 + (a^*_i - a^*_{mean})^2 + (b^*_i - b^*_{mean})^2}$$

$$MCDM\Delta E = (\sum_{i=1}^{i=n} \Delta E_i) / n$$

There is a certain level of measurement variation within the same spectrophotometer (NPIRI, 1993). A basic "dark current" type repeatability test on plain substrate is very crucial in establishing the base variation figure introduced by the non-uniformity of the substrate and the precision variation of the measuring instrument. Thereafter, a repeatability test for C, M, Y and K solid inks can be established with the inclusion of the base variation.

Accuracy is determined by the difference between a known reference value and a measured value with the inherited repeatability variation (Fairchild and Reniff, 1991). It is significant that the repeatability variation falls closely within the range of accuracy. For the printing press, the color characterization data for type 1 printing (McDowell, 1996; McDowell and Taggi, 1995; ISO, 1995; SWOP, 1993) provide a great source of standard reference values. The 182 color patches of the basic data set on the IT8.7/3 target (ANSI CGATS.6, 1995) have been used as a color difference target for the measure of accuracy (Chung and Komori, 1998; ANSI CGATS TR 001, 1995). The tonal values of the primary inks can also be found in the basic data set (ANSI IT8.7/3, 1993).

A printing ability test chart is derived with a script language under test criteria specifically for the ink jet printer (Sobotka and Handler, 1991; Munger, 1991). The solid color strips of C, M, Y and K inks around the chart in both x and y directions are for the repeatability test. Color steps for C, M, Y, K, R, G and B colors are used to verify the linearity. Some color combinations that are not included in the SWOP basic data set, like 95% dot areas for C, M, Y and K, are part of the test data. Three gray balance patches are included and the values are determined from referencing the target standard. These values are (25, 16, 16), (50, 39, 39) and (75, 63, 63) for (C, M, Y) specified in ANSI CGATS.6-1995. Three-quarter-tone ink values are also included for each ink as optional data to calculate print contrast values. Several high-ink-total colors are included in the test set to increase the sampling resolution for detecting a solarization problem. Lastly, patches of lines with a line width range from 1 pixel to 9 pixels and 15 pixels for the nine major colors are included for both x and y directions to test uniformity and line resolution (currently, 120 dots per cm). Alone with the SWOP 182 basic data set, the test chart consists of a total of 210 patches. A scaled-down test chart is shown in Appendix I.

Experimental Procedures

The experiment was performed in a SWOP simulated system which consists of a DynaLab Light Bridge software RIP and an Epson Stylus 3000 ink jet printer on a Macintosh. The test chart image was stored in an EPS file and processed by the RIP system, then printed out as the SWOP proof under default setting. Epson's A4-size 720 dpi ink jet paper was the substrate.

A Gretag Spectrolino spectrophotometer with automatic measuring tool was used for data acquisition. It was set to D50 illuminant and 2 degree observer as specified in ANSI CGATS.5 - 1993, from which the reference white (96.422, 100.000, 82.521) was defined when calculating the CIELAB color difference values. Other colorimetric values, like hue and chroma, were calculated accordingly (Wyszecki and Stiles, 1982; CIE, 1986). The instrument calibration was performed automatically by the tool referencing the ceramic white calibration plate on the measurement table before each batch of measurements. Density measurements were done with a Gretag SPM100-II under guidelines specified in ANSI CGATS.4-1993. It was assumed that by following the calibration procedures in the instrument, all the measurements would be in line with all other published data, such as ANSI CGATS TR 001-1995.

Theoretically, the sampling size with a double-sided alpha risk of 0.1 and a beta risk of 0.1 is eleven when delta is equal to the standard deviation for the T-test of the mean (Barker, 1985). However, the report of CGATS TR001-1995 stemmed from 12 measurements. The sampling size in the present experiment was then set at 12, so that the comparison with CGATS data will be on statistically equal ground.

Twelve test charts were printed continuously on 720 dpi ink jet quality paper from the same stock for the measurements. The analyses was done as follows:

1. Basic print condition test: The continuous lines, solid ink densities, dot gains and solarization were checked.
2. Plain paper test: Twelve colorimetric measurements on each of the x and the y directions were performed for the "dark-current" type test on a plain ink jet paper to ascertain for the paper and measurement variation. MCDMs and standard deviation were calculated.
3. Repeatability on the same chart: Twelve measurements were performed on each of the C, M, Y and K color strips around the last chart for both x and y directions to ascertain the criteria of uniformity based on the variations for the inks on the same paper. MCDMs and standard deviation were calculated.
4. Repeatability on 12 charts: On each of the 12 charts, all C, M, Y and K solid color patches were measured colorimetrically. The 12 readings of each primary ink are averaged to become the mean values for calculating the MCDMs and the standard deviation.
5. Accuracy test: The mean values of the 12 readings of each of 192 colors were compared with the target reference standard, ANSI CGATS TR 001-1995. Density values of the C, M, Y, K color steps were also gathered (ANSI CGATS.4, 1993).

Test Results and Discussion

Basic print condition test

The vertical and horizontal fine continuous lines leave inkless white gaps of 1 to 9 or 15 pixels for visual inspection. There is no broken or missing line in either horizontal or vertical directions on the printed area for every printed test chart. It is clear that the tested unit is free from the very common problem of a clogged printhead. The 1-line gap is so fine that it is barely visible to the naked eye. After inspection with a magnifier, it is assured that this printer is capable of addressing a 1-pixel-width in a 300 dpi resolution, or 150 lpi in both vertical and horizontal directions. The SID and detail densities of each ink and the dot gains of the last chart are listed in Table 1.

Table 1. Solid ink densities and dot gains.

Ink	*C*	*M*	*Y*	*K*
SID	1.40	1.26	0.87	1.59
Dc	1.40	0.32	0.07	1.62
Dm	0.47	1.26	0.19	1.58
Dy	0.21	0.77	0.87	1.57
% Dot Gain	29	26	13	27

It is important to note that the error diffusion type screening in ink jet technology may introduce a different dot gain characteristic. The dot gain curves for the 4 primary ink-jet inks are shown in Figure 2. The yellow ink has less dot gain than the other inks. There are some bumping curves in low density tints.

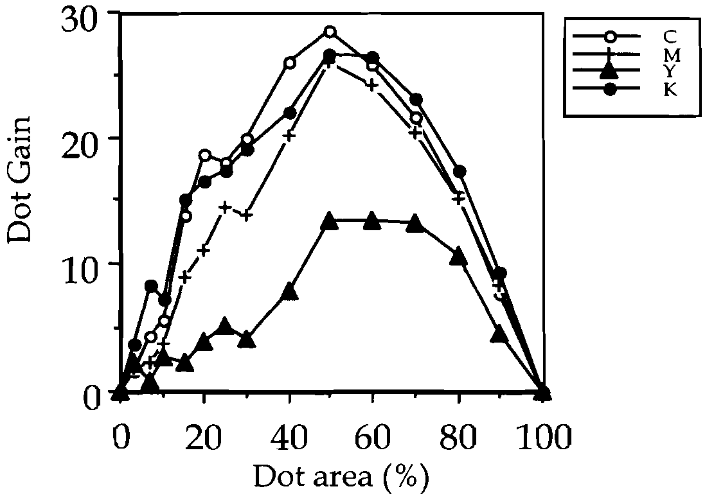

Figure 2. Dot gain curves for the tested ink jet printer system.

The measured chroma values of the 3 gray balance patches are 10.72, 14.71 and 8.93 respectively with a blue cast. The lightness (L*) values of the 10 color patches for the solarization test are a good point of reference for verifying the solarization problem. The measured lightness values are plotted against ink-totals as shown in Figure 3, while the actual values are listed in Table 2. It is noticed that the lightness decreases as the ink amount increases without any reversal curve. Thus it is confirmed that the solarization problem is not found in this test setup. However, the lightness values (L*) rapidly approach a darkest value around 16, which is the highest density this printer can reach. It is possible that even though the Dmax produced by the ink jet printer system can be further increased by increasing the size of the ink drop, the solarization problem may yet occur.

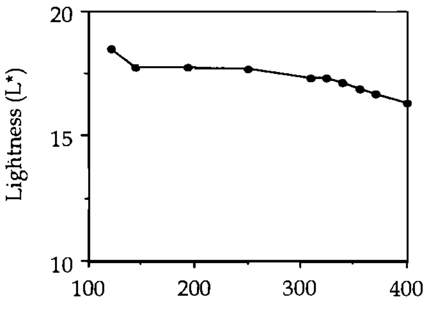

Figure 3. The solarization test results.

Table 2. The lightness values of the solarization test patches.

C	*M*	*Y*	*K*	*Ink total*	*L**
10	6	6	100	122	18.52
20	12	12	100	144	17.77
40	27	27	100	194	17.75
60	45	45	100	250	17.66
80	65	65	100	310	17.34
85	70	70	100	325	17.29
90	75	75	100	340	17.10
95	80	80	100	355	16.86
100	85	85	100	370	16.67
100	100	100	100	400	16.34

Repeatability test on plain paper

Variations among the twelve measures on the plain paper for horizontal (x) and vertical (y) directions respectively reveal the inconsistency contributed by the paper and the measuring instrument. As the A4 paper is fed vertically, the x direction is where the printhead moves. The y direction is the paper-feeding direction where different print lines are formed. MCDM ΔE, standard deviation, maximum and minimum of ΔE for each measurement to their mean CIELAB are listed in Table 3. These indicate that the variations for x and y directions are very similar and the difference is less than 0.5 MCDM ΔE unit. It should be noted that the variation of the instrument is included in these figures also. All the consequence measurements should have variations higher than this.

Table 3. Base variation from measuring the plain paper.

Direction	*X*	*Y*
MCDM ΔE	0.122	0.121
Stdev	0.074	0.088
Max.	0.305	0.350
Min.	0.022	0.028

Repeatability test on solid inks from the same chart

Twelve measurements on each of the C, M, Y and K color strips around the test chart for both x and y directions reveal the variation of the printed ink solid on the same print line and on different print lines on the same sheet. The results are listed in Table 4. The average color difference is close to 1 MCDM ΔE unit and the maximum difference can be higher than 2 ΔE units. The color difference of cyan ink shows a larger variation both in x and y directions. The MCDM ΔE of yellow ink is larger in the y direction than in the x direction. The largest MCDM ΔE was also found to be for Yellow ink in the y direction. Magenta and black inks are relatively more stable in either x or y direction. The fairly consistent trend is that different printlines introduce higher color variation. The values in Table 4 indicate the color variation on the same page.

Table 4. Color variations between measurements from the same chart.

Ink/direction	*MCDM ΔE*	*Stdev*	*Max.*	*Min.*
C-x	0.461	0.272	1.079	0.162
M-x	0.292	0.077	0.417	0.194
Y-x	0.397	0.195	0.745	0.075
K-x	0.271	0.153	0.580	0.046
C-y	0.927	0.566	2.299	0.157
M-y	0.443	0.231	0.835	0.020
Y-y	0.959	0.554	2.215	0.060
K-y	0.469	0.281	1.079	0.079

Repeatability test on solid inks from 12 charts

Measurements on each of the primary ink solids on all of the 12 charts are taken to calculate the variation among different charts. The results are listed in Table 5. The color difference of yellow ink shows the largest variation among these four inks, which is consistent with the findings in Table 4. Again, magenta and black inks are relatively more stable. It is noted that the variations among different charts are not always greater than the variations on the same chart. It implies that the differences between charts do not introduce much more variation.

Table 5. Color variations among measurements from 12 charts.

Ink	*MCDM ΔE*	*Stdev*	*Max.*	*Min.*
C	0.757	0.492	1.610	0.138
M	0.417	0.190	0.736	0.082
Y	1.445	0.672	2.558	0.233
K	0.576	0.429	1.724	0.145

Accuracy test

On each of the 12 charts, the mean CIELAB values of the 12 measurements of each of 182 colors are calculated and are compared with the published ANSI CGATS values for color differences. The 182 ΔEs are averaged for the grand average, and their standard deviation, maximum and minimum are listed in Table 6. The distribution and frequency of the color differences are shown in Figure 4.

Table 6. Grand results in the accuracy test.

Ink	*182(12)*
Average ΔE	9.864
Stdev	4.557
Max.	26.283
Min.	1.344

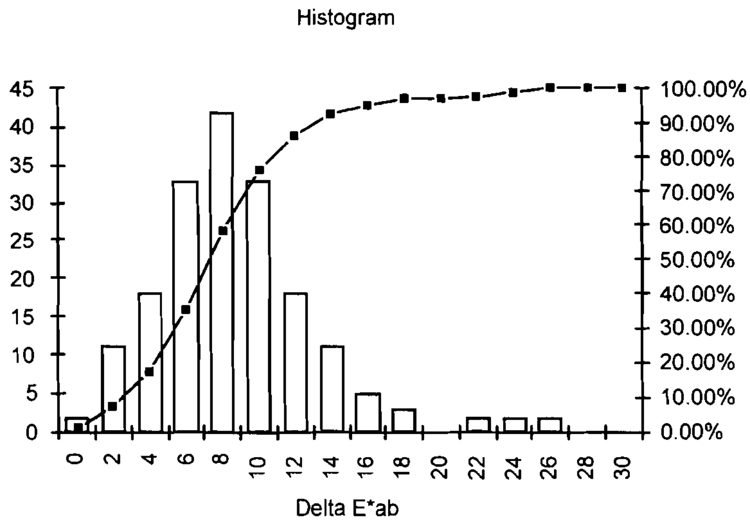

Figure 4. Histogram of the color differences in the accuracy test.

The distribution of the color difference values is very close to a normal distribution with a mean value between 8 and 10 ΔE units. An earlier study reports that the color difference between analog proofs ranged from 0.25 to 5.4 ΔE unit (NPIRI, 1991). Given the result of an average of 9.8, the present tested system is presumably not within the accuracy range of the analog color proofer.

Further analyses are performed to reveal in detail the differences between the ink jet printer system and the SWOP standard. The average a* and b* values of C, M, Y, R, G and B solid patches from the 12 test charts are plotted along with the corresponding SWOP standard data in Figure 5. In addition to those 6 colors, the CIELAB values of the shades of black, of the C, M and Y overprint, and of the C, M, Y and K overprint, as well as of the white paper are listed in Table 7.

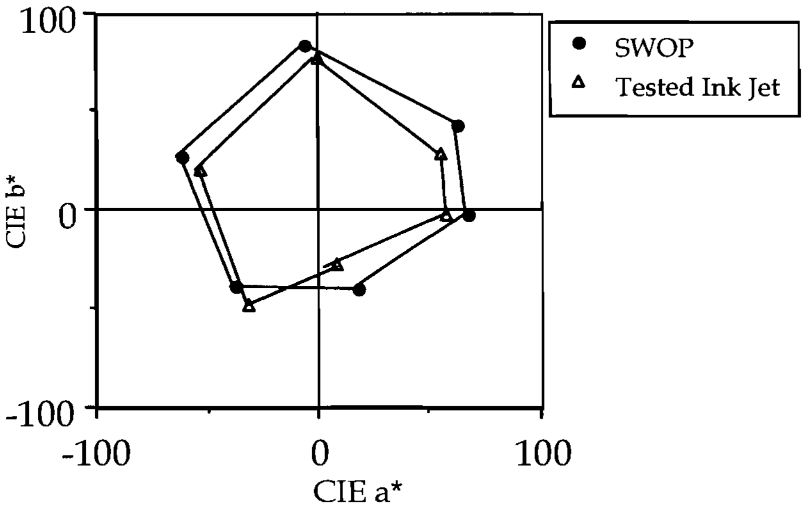

Figure 5. Color gamut comparison.

Table 7. Comparisons of the predominant colors.

	SWOP			Ink Jet			Results
Color	L*	a*	b*	L*	a*	b*	ΔE
C	56.02	-37.58	-40.01	53.29	-31.12	-51.61	13.555
M	47.16	68.06	-3.95	48.60	62.02	-1.90	6.539
Y	84.26	-5.79	84.33	88.18	1.57	80.11	9.346
K	18.62	0.43	1.03	18.11	0.50	-0.94	2.036
G	26.57	17.60	-41.24	28.37	8.47	-30.55	14.173
B	51.46	-61.59	26.08	48.01	-55.57	16.39	11.918
R	46.94	62.21	41.81	49.07	58.69	28.61	13.826
CMY	24.84	-1.30	-0.51	23.02	3.84	-0.66	5.455
CMYK	9.06	-0.10	0.65	16.34	0.99	-1.33	7.623
Paper	88.66	-0.33	3.64	94.05	2.47	-5.97	11.369

It is noted that this desktop ink jet color proofing system has less color gamut than the SWOP standard. Prior literature (Chung, 1998; Williamson, 1998) also reports a similar finding, which indicates the area to be improved for this type of application. Also, the SWOP ink has stronger black in the four-color overprint. However, the ink jet paper base has higher L* values with the same blue cast than the SWOP paper base.

Summary

The evolution of CTP technology has prompted the graphic arts industry to search for a faster turn-around digital color proofer. The advances in ink jet technology have made the desktop ink jet printer system with modest print quality very affordable. This study proposes a test method to benchmark whether a desktop ink jet printer system is suitable to serve as a digital color proofer.

The printing ability test chart designed here has been effective in validating both the repeatability precision and the color accuracy of the tested system. The MCDM analysis model using CIELAB color difference provides a quantitative way in assessing the system's repeatability as summarized in Table 8. The color difference resulted from the non-uniformity of the plain ink jet quality paper, and the measurement variation of the instrument is less than 0.2 MCDM ΔE in average. The repeatability test for the primary inks on the same sheet of paper indicates an average color difference under 1.0 MCDM ΔE, and the maximum color difference is under 2.3 MCDM ΔE. The repeatability test for the primary inks on 12 sheets of the test chart indicates an average color difference under 1.5 MCDM ΔE, and the maximum color difference is under 2.6 MCDM ΔE. These values define the reproduction consistency of the tested printer. The accuracy test indicates an average color difference of 9.8 ΔE for this desktop ink jet printer system simulating the ANSI CGATS TR 001 (SWOP) data.

Table 8. MCDMs ΔE for repeatability test

Factor/Test Object (12)	*Paper*	*C ink*	*M ink*	*Y ink*	*K ink*
Same print line (x)	0.122	0.461	0.292	0.397	0.271
Different print lines (y)	0.121	0.927	0.443	0.959	0.469
Different page		0.757	0.417	1.445	0.576

An earlier study of the color consistency requirements of typical packaging printing suggested a stable print production with a color tolerance of 6 ΔE or less (Stamm, 1981). Recent research reported that an average ΔE between two press runs for all 182 primary patches of the IT8.7/3 target was 3.76 (Chung, 1998). Another investigation of color consistency on analog Matchprint proof and digital IRIS proof concluded that the average colorimetric consistency for both proofing systems was less than 3.0 ΔE (Ingraham, 1993a). The results in Table 5 indicate that the short-term repeatability of the tested ink jet printer system is within those ranges. Another study of accuracy tests between press sheet and color proofs (Match Print III and Rainbow) indicated an average ΔE of 7.34 and 6.41 respectively (Chung, 1998). This is beyond the capacity for accuracy of the system tested here.

To qualify as a graphic arts color proofing device, a proofing system has to be not only consistent within itself but also accurate by the intended target print standard. These test results indicate that it is feasible for this ink jet printer system to function within the consistency requirements; however, the system's accuracy still needs some improvement. Nevertheless, with the advancement of color technology there is great potential for the desktop ink jet printer system to be developed as a digital color proofer in the future. For the time being the test target and test method proposed in this study can serve as an important vehicle in verifying the quality of an ink jet color proofer in the exciting CTP era.

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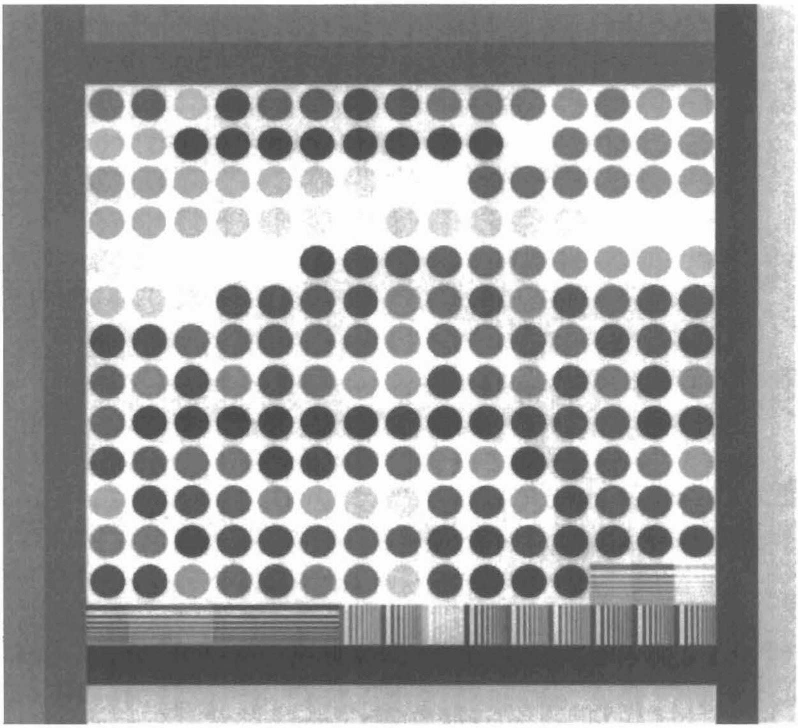
Appendix I - Scaled down test chart



Note: The numbering sequence for the color patches goes from left to right starting at the top.