An Investigation of the Relationship between Gray Balance and Printed Dot Area

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Abstract

This study reports the findings of a series of press tests designed to gain more precise knowledge about the nature of gray balance. Given the importance of gray balance for good quality printing and its seemingly unpredictable nature, the authors sought to determine if useful gray balance specifications could be established for sheetfed lithography. During the 1999 GATF Sheetfed Lithographic Print Attribute Study (Stanton and Hutton, 1999) it was found that traditional "gray balance curves" were well modeled by a second-order polynomial relationship between the cyan and the magenta/yellow printed dot areas. Effectively, we found that gray balance was predictable across screen rulings if total printed dot areas of cyan, magenta, and yellow were considered. The current study has used more precision to examine the interrelationship of gray balance and printed dot areas. For any neutral area with a given cyan dot area, the magenta dot area can be calculated by the second-order polynomial:

$$Mag_{DotArea} = 0.0028(Cyan_{DotArea})^2 + 0.69(Cyan_{DotArea})$$

The yellow dot area can then be calculated by the linear relationship:

$$Yel_{DotArea} = 0.95(Mag_{DotArea}) \cdot$$

These relationships were relatively stable across the full range of solid ink density settings and with several paper/ink combinations. When these relationships were applied to the average sheetfed lithographic printing conditions determined from the 1999 study, the 25%, 50%, and 75% C/M/Y combinations that yield neutral grays on gloss coated paper at 150 lpi are 25/18/17, 50/41/39, and 75/66/62, respectively.

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Historical Background

References to gray balance as an important parameter and a sensitive process control measure can be found from the literature of the mid 1950s. Archer (1954) advocated that a printing system first be adjusted to produce a neutral gray scale without black, and then black ink be used to provide the neutrals wherever practical. Archer explained that the spectrophotometric curve of a three-color gray contains three distinct peaks, making gray susceptible to changing light sources. Archer referenced the color photography book by Evans, Hanson, and Brewer (1953) as providing a useful appreciation of gray balance.

Evans, et.al., described gray balance as one of the prime requirements for a color reproduction process. They pointed out that a lack of proper gray balance will cause the picture as a whole to have a color cast. Their work dealt with reproducing neutral gray scales with CMY photographic dyes, but the case is similar to printing neutral scales with CMY inks.

In 1966, Pobboravsky wrote that "Gray balance is not only important for the accurate reproduction of neutrals in a picture but is also important for the overall hue balance of the picture" (1966, p.11). Pobboravsky compared two methods for calculating the ink requirements for gray balance. The first was to use the Neugebauer and Murray-Davies equations, and the second utilized an empirically derived equation.

In 1972, Elyjiw and Archer reported a case where all the patches in a gray balance matrix had a greenish cast due to abnormal ink trapping conditions on the press. The relationship between ink trapping and gray balance was more pronounced in the shadow areas where heavier ink coverages occurred. In later research, Elyjiw concluded that "A scale of neutral grays can be considered the backbone of any color reproduction system" (1989, p. 376). He cautioned that deviations from gray balance affect all the colors in the reproduction, which would have an overall color cast, even if there were no neutrals in the picture.

In the 1980s, work on gray component replacement (GCR) systems forced developers to accurately define parameters for gray balance. Schwartz, Holub, and Gilbert (1985) found that images with more GCR were less prone to metameric effects. This observation was attributed to the more continuous spectrophotometric curve of the black ink vs. that of the equivalent three-color gray. Their findings support the theory that the perception of CMY gray is sensitive to color shifts.

Johnson (1988) recommended gray balance as the most critical parameter to define before meaningful GCR standards could be written. He saw gray balance as a direct function of platemaking, ink hue, ink film thickness, opacity, printing sequence, dot gain, and paper properties.

In 1987, System Brunner (Brunner, 1987) used a process control strategy that categorized pictures by color contrast and image complexity. Picture contrast profiles (PCPs) were developed to sort pictures into groups that had different tolerance limits for obtaining similar quality levels. Images with large uniform patches of near neutral hue had the most stringent tolerances. Brunner reported that a gray patch with CMY values of 50/41/41 was especially well suited as a measuring point. This system recognizes both the importance and the difficulty of maintaining uniform gray balance.

The following year, DuPont based its product Print Expert on the System Brunner approach (Muirhead, 1988). Print Expert used a series of concentric color balance hexagons in which each ring represented different levels of color balance variation. Muirhead reported that color balance variation of 1% was very noticeable in pictures with the least amount of image complexity.

Evaluating neutral in measurements of gray balance has long been a subjective task, but spectrophotometric measurement has been found to be a reliable alternative to visual appraisals. Malikhao (1993) reported that machine evaluation of gray charts was very successful and much faster than human evaluations. However, he cautioned that gray balance could be disturbed by fluctuations of dot gain in any of the process inks.

An appreciation for the critical nature of gray balance is still being seen in current research. Lo and Chiang (1998) found that gray balance was a very important parameter in developing characterizations of multicolor printing processes, even though their work was on a seven-color reproduction system.

The books of Southworth and Southworth (1989) and of Field (1999) cover the important concepts on the subject of gray balance. Gray balance is a primary requirement of any color reproduction system. The reproduction system of the lithographic press suffers from high variation in gray balance due to the influences of many important components in the system, like paper, ink, fountain solution, plates, and blankets. Even slight variations in the reproduction of any of the primary tones will result in noticeable color shifts. When a color scanner is being calibrated to a printing system, one of the early steps is to calculate the CMY requirements to print a neutral scale. The appropriate gray balance values are input into the system while the scanner optics are trained on a neutral gray sample, typically, a carbon dye continuous tone scale. The gray balance adjustment is needed because the hue errors in printing inks make it impossible to reproduce a neutral scale when the inks are printed in even amounts. Gray balance is not the process of correcting for a color cast in an original photograph, which is actually performed as part of the color correction process after the gray balance settings have been made. In practice, after the gray balance values have been input using the continuous carbon dye scale, the scanner optics are trained on a neutral value within the picture and color casts in the photograph are evaluated and corrected if necessary.

In general, solid ink densities should be adjusted to produce saturated overprints; good gray balance should be built into the files. Visual evaluation of gray yields good results if standard viewing is used and side-by-side comparisons are possible. Field recommends using a printed black ink scale as a reference in making the visual evaluations to avoid problems of different chromatic adaptations.

Gray balance is specified in the Specifications for Web Offset Publications (SWOP) for heatset magazine printing at 133-lpi. It is similarly specified in the Specifications for Non-heatset Advertising Printing (SNAP) where it is designed for 85-lpi printing on newsprint with non-drying inks. The General Requirements for Applications in Commercial Offset Lithography (GRACoL) publication does not include gray balance in its Printing Guidelines Chart (pp. 4-5). In fact, the GRACoL document offers only a perfunctory explanation of gray balance in its Technical Supplement section.

Introduction to the Study

This study was conducted to investigate the relationship between gray balance and printed dot area and to identify variables that affect that relationship. The underlying purpose is to develop meaningful gray balance print specifications for the sheetfed lithographic printing process.

During late 1998 and early 1999, GATF conducted a study of the sheetfed lithographic print attributes of quality-conscious printers. Several measurable print attributes were analyzed from samples representing 70 different printing conditions from over 35 printing companies. These print attributes included ink dryback, dot gain, solid ink density, print contrast, ink trapping, total area coverage, gray balance, and the colorimetric properties of inks. Preliminary results were presented at the 1999 TAGA Conference (Stanton, Hutton, 1999). Final results were published as a *GATF Research & Technology Report*, entitled "The Sheetfed Lithographic Print Attribute Study." Some of the findings show relationships that can be used for benchmarking or for establishing industry specifications. However, the analysis of gray balance gave ambiguous results. Initial analysis of the most-gray patches (those with the lowest Chroma values) revealed that none were the recommended SWOP CMY gray combinations. A strong correlation was found between the cyan printed dot area and the magenta/yellow printed dot areas. This correlation was used to specify optimum CMY combinations for each screen ruling after adjusting for dot gains. Results for the 150-lpi screens were close to the SWOP values. This conflicted with our earlier finding, but it was predictable because many commercial sheetfed lithographers running 150-lpi screens use the SWOP gray balance specifications as their default values.

The current study was designed to investigate the relationship of gray balance with printed dot area and screen ruling. The goal was to develop equations for gray balance based on 50% dot gain. The equations could be used to specify gray balance for a wide range of printing conditions, or to calculate gray balances in real time for a closed-loop press control system.

Review of Previous Findings

The gray balance chart in Figure 1 was included on the 1999 Print Attribute Test Form. The chart consisted of four matrices of squares with various combinations of cyan, magenta, and yellow coverage. Each matrix represents a different tone level. The 25%, 50%, and 75% CMY gray balance recommendations from SWOP are in the center of those three matrices. There are no industry-wide guidelines for gray balance for sheetfed lithography, so the SWOP recommendations for heatset web lithography were used as a basis for comparison in the 1999 study. The SWOP CMY combinations are 25/16/16, 50/39/39, and 75/62/62 to produce 25%, 50%, and 75% grays, respectively.

This gray balance chart was used in measuring the CIELAB values of various CMY combinations. The best CMY gray balance combinations were identified as the patches where the (a*, b*) coordinates were closest to the origin (i.e., low Chroma values). Most of the selected patches were less than 1.0 Chroma unit from the origin. Where larger Chroma differences were found, it was assumed that the true most-neutral CMY combinations were outside the range contained on the gray balance chart.

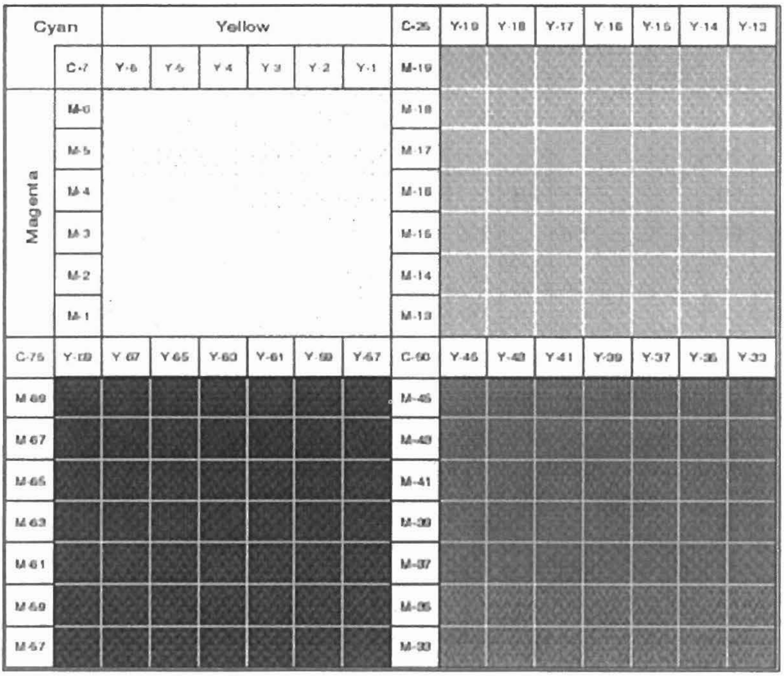

Figure 1. Gray balance chart.

Table 1 gives the most neutral gray patches from the printed results on gloss coated paper at 150 and 175 lpi. From this data it was noticed that the SWOP gray balance values did not coincide with the most neutral patches for any of the members of this subgroup. However, when the measured most neutral patches were evaluated in terms of printed dot values instead of film dot values, the results were better aligned with the SWOP gray balance recommendations.

Cyan		Yellow						C-25	Y-19	Y-18	Y-17	Y-16	Y-15	Y-14	Y-13
	C-7	Y-6	Y-5	Y-4	Y-3	Y-2	Y-1	M-19	**3/1**						
Magenta	M-6							M-18	**3/1**				**0/1**		
	M-5							M-17	**1/1**						
	M-4							M-16	**1/1**					**1/0**	
	M-3							M-15	**0/1**			**1/0**			**0/1**
	M-2							M-14		**1/0**			**1/0**		
	M-1							M-13	**1/0**						
C-75	Y-69	Y-67	Y-65	Y-63	Y-61	Y-59	Y-57	C-50	Y-45	Y-43	Y-41	Y-39	Y-37	Y-35	Y-33
M-69			**0/1**		**1/0**	**1/0**	**0/1**	M-45	**1/0**						
M-67	**1/0**				**1/1**		**1/0**	M-43		**2/0**					
M-65		**1/0**						M-41	**1/0**	**1/1**	**1/0**		**0/1**		**1/0**
M-63		**0/1**				**0/1**		M-39		**1/2**	**1/0**			**0/1**	**1/1**
M-61	**1/1**	**0/1**			**1/0**		**1/0**	M-37			**1/1**				
M-59			**1/0**				**1/0**	M-35	**1/0**						
M-57	**1/0**						**1/0**	M-33							**1/0**

Table 1. The most neutral three-color gray patches (150 lpi/175 lpi).

Figure 2 shows the CMY combinations of all of the most neutral patches with a*, b* coordinates less than one Chroma unit from the origin. It was found that the most neutral CMY combinations followed a very strong polynomial equation of the form $y = 0.0034x^2 + 0.6119x$, where y represents both the yellow and magenta dot areas and x represents the cyan dot area. This equation was used to estimate the best CMY gray combinations for sheetfed lithography on gloss coated paper, after factoring in the average cyan, magenta, and yellow dot gains. This resulted in CMY gray balance values for 150-lpi screen ruling of 25/15/15, 50/38/38, and 75/61/61. For 175-lpi screen ruling the best gray values were determined to be: 25/17/17, 50/41/41, and 75/64/64.

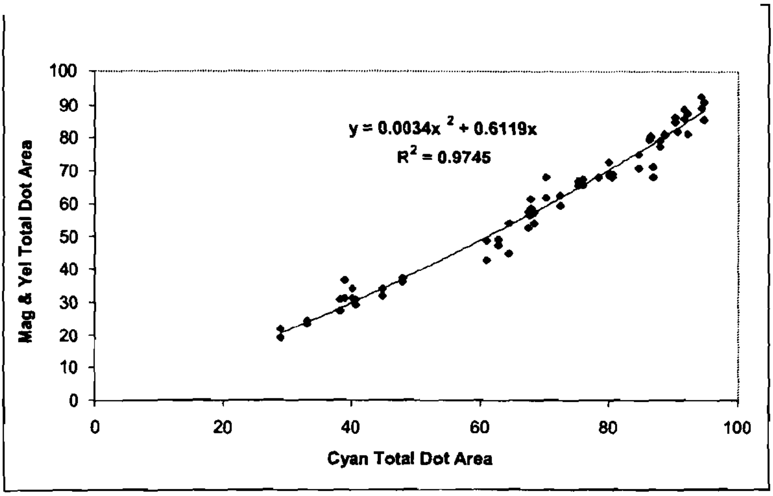

Figure 2. Most Neutral CMY Combinations for ΔE (a*, b*) < 1.

Additional study of gray balance was required because the test form used for the 1999 print analysis study did not have sufficient precision to test the relationship between printed dot area and gray balance.

Methodology

A new test form (Figure 3) was designed for this study that presented gray balance and dot gain information for eight tone levels: 10, 20, 30, 40, 50, 60, 70, and 80%. Each gray matrix is printed in line with tone scales having the same increments (2%) and the same range. Each set of tone scales and gray balance matrices are in line to reduce variations in densities and dot gains due to ink key settings.

Other elements on the test form include:

- A color control bar to help the press operators balance out the ink key settings on the press.
- Two sets of GATF ladder targets to determine if there are any adverse directional printing conditions (like slur or doubling) affecting the outcome.
- Register marks to aid in achieving accurate register during the pressrun.

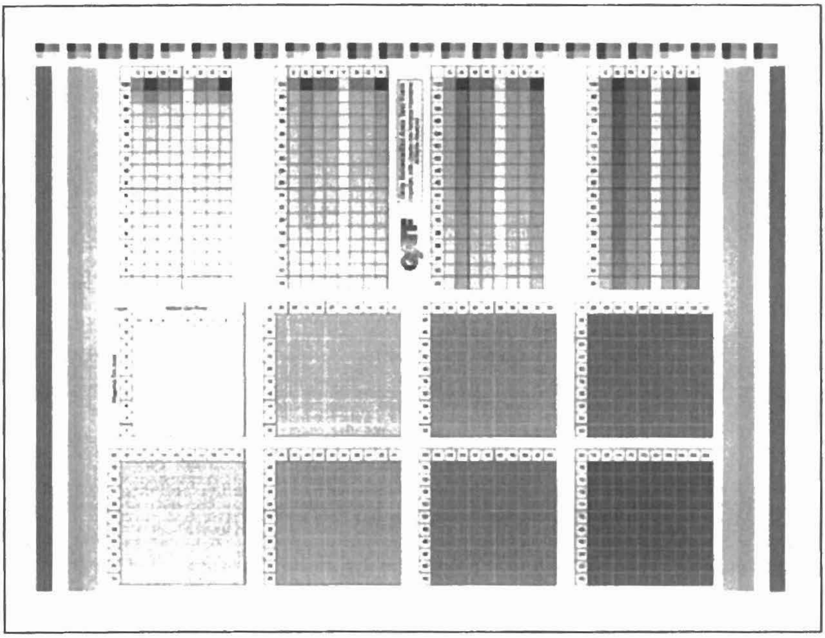

Figure 3. Gray Balance Test Form.

The Gray Balance Test Form was imaged on proofing equipment in addition to an offset press. In total, it was imaged under 14 different ink/paper/density/screen ruling conditions. Table 2 shows the conditions that were analyzed in this study. A more complete description of the materials is listed immediately after the table.

No.	Sample	lpi	Colors	Density*	Substrate
1	Dig. Proof	150	GRACoL P	High	Gloss P
2	Conv. Proof	200	SWOP P	Mid	Gloss I
3	Conv. Proof	175	SWOP P	Mid	Gloss I
4	Conv. Proof	150	SWOP P	Mid	Gloss I
5	Print	200	SWOP ink	Low	Cons. Prod.
6	Print	200	SWOP ink	Mid	Cons. Prod.
7	Print	200	SWOP ink	High	Cons. Prod.
8	Print	175	SWOP ink	Mid	Cons. Prod.
9	Print	175	SWOP ink	High	Cons. Prod.
10	Print	150	SWOP ink	Mid	Cons. Prod.
11	Print	150	Flint ink	Mid	Cons. Prod.
12	Print	150	K+E ink	Mid	Cons. Prod.
13	Print	150	K+E ink	Mid	Westvaco
14	Print	150	K+E ink	Mid	Mead C_1S

Table 2. Printing Conditions.

List of Abbreviations for Table 2

Sample
Dig. Proof: PolaProof digital halftone proof
Conv. Proof: Imation Matchprint photomechanical proof
Print: Press sheets printed on a sheetfed press

Colors
GRACoL P: PolaProof GRACoL Transfer Sheets
SWOP P: Imation SWOP Classic Color Transfer Sheets
SWOP ink: Sun Chemical Corp. OS SWOP Process Inks
Flint ink: Flint Ink Agritek Process Inks
K+E ink: K+E Printing Inks Skinnex Process Inks

Density*
High: C > 1.50, M > 1.50, Y > 1.10 (except PolaProof, Y=1.00)
Low: C < 1.25, M < 1.30, Y = 0.86
Mid: All others

*The overall sheet densities are determined as the average solid ink densities across the form.

Substrate
Gloss P: Polaroid Premium Gloss Base Paper
Gloss I: Imation Commercial Base Paper
Cons. Prod.: 100# Consolidated Productolith Gloss Paper
Westvaco: 80# Westvaco Citation Gloss Paper
Mead C_1S: 80# Mead Coated One Side Paper

The press sheets were printed over a two-day period on a Komori Lithrone press. One sample from each printing condition was selected for analysis. Density measurements of the tone scales were made with a Tobias SXY-40 Status-T scanning densitometer. Colorimetric measurements were made with a Gretag SpectroScan scanning spectrodensitometer using D50 illumination and a 2-degree observer. The film dot area was checked with an X-Rite 361T transmission densitometer. For the film dot area only one sheet per 4-color set was measured. There were three sets of film made at screen rulings of 150, 175, and 200 lpi.

Results

After all the density and colorimetric measurements were made, the CMY patches with the minimum Chroma values from the origin were identified. The CMY coordinates from the patches were referenced to the tone scales above each gray balance chart. From these tone scales we determined the CMY dot area combination that produced the most neutral gray in each gray balance chart.

Table 3 shows the results for the first five printing/proofing conditions. (Appendix A lists results for all 14 printing conditions.)

Printing Cond.	Min dE	Gray Tint	Cyan Area	Mag Area	Yel Area	Cyan Gain	Mag Gain	Yel Gain
1	0.48	10	21	15	14	11	8	5
	0.11	20	36	27	24	16	13	8
	0.31	30	49	39	37	19	17	13
	0.45	40	59	50	45	19	20	15
	0.49	50	70	59	55	20	19	17
	0.42	60	79	71	66	19	19	18
	0.50	70	87	81	76	17	19	14
	0.50	80	93	89	86	13	17	12
2	0.68	10	26	20	13	16	12	6
	0.17	20	45	38	32	25	24	18
	0.63	30	59	49	44	29	27	22
	0.49	40	69	63	56	29	31	26
	0.36	50	79	72	68	29	30	26
	1.00	60	85	78	73	25	30	25
	0.44	70	90	85	80	20	27	24
	0.78	80	94	90	87	14	20	19
3	0.13	10	26	21	16	16	13	9
	0.33	20	43	35	31	23	20	16
	0.80	30	57	49	42	27	25	20
	0.53	40	67	60	55	27	28	23
	0.53	50	77	69	66	27	27	24
	0.83	60	84	79	73	24	27	23
	0.67	70	89	84	80	19	24	22
	0.65	80	94	89	87	14	19	17
4	0.43	10	26	21	16	16	14	10
	0.32	20	43	34	31	23	19	17
	0.36	30	58	49	43	28	25	21
	0.31	40	69	60	54	29	28	24
	0.33	50	77	70	65	27	28	25
	0.74	60	83	78	73	23	26	23
	0.52	70	89	84	81	19	22	21
	0.49	80	93	89	87	13	17	17
5	0.60	10	28	22	24	18	14	15
	0.21	20	43	36	35	23	21	20
	0.29	30	56	50	48	26	26	24
	0.24	40	66	60	58	26	26	26
	0.60	50	78	73	69	28	27	27
	0.49	60	84	82	75	24	24	23
	3.65	70	89	82	85	19	24	17
	4.57	80	94	82	90	14	22	14

Table 3. CMY combinations that gave the minimum Chroma values.

Notice the last two rows in Table 3 are shaded. The minimum Chroma values in these gray balance charts were much greater than 1.00. As in the 1999 print attribute study, when minimum Chroma differences were larger than 1.00 it was assumed that the true most-neutral CMY combinations were outside the range contained on the gray balance matrix. These values were discarded. There were a total of 25 instances where Chroma values greater than 1.00 were rejected. This left 87 CMY gray combinations from 13 printing/proofing conditions for the final analysis.

When the cyan dot gains for the most neutral gray patches were compared to the magenta and yellow dot gains, weak relationships between them were found, as seen in Figure 4a for all the conditions of Appendix A. The R^2 values for the best-fit polynomials were below 0.60 for both the yellow and magenta relationships to cyan. When the yellow dot gains were compared to the magenta dot gains, as in Figure 4b, a stronger relationship of 0.75 for the R^2 value was found.

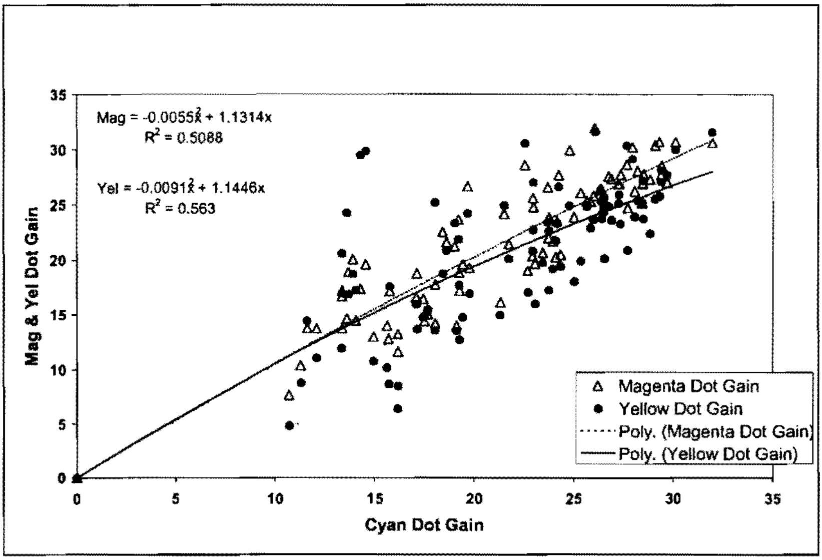

Figure 4a. Magenta and yellow dot gain compared to cyan dot gain.

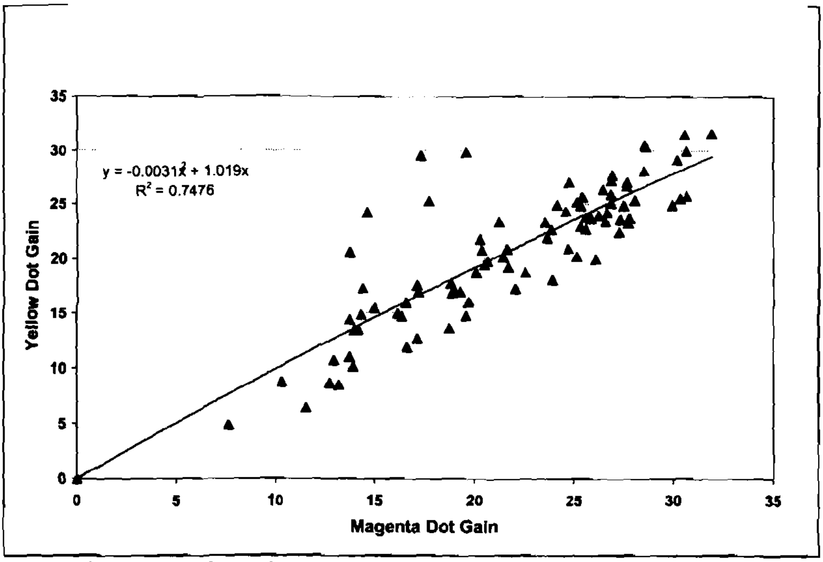

Figure 4b. Yellow dot gain compared to magenta dot gain.

However, when the same most neutral gray data was used to examine the relationships between the printed cyan dot areas and the magenta and yellow dot areas, the correlations were stronger, as seen in Figure 5a. For all three relationships, the best-fit polynomials yield R^2 values close to 1.00. The high precision of the tone scales used in this study reveals a small yet significant difference between the magenta and the yellow relationships to cyan. The two best-fit lines in Figure 5a show this relationship. Figure 5b shows the relationship between the yellow dot areas and the magenta dot areas. In this instance, the best-fit polynomial can be simplified to a linear relationship with an R^2 value of 0.98.

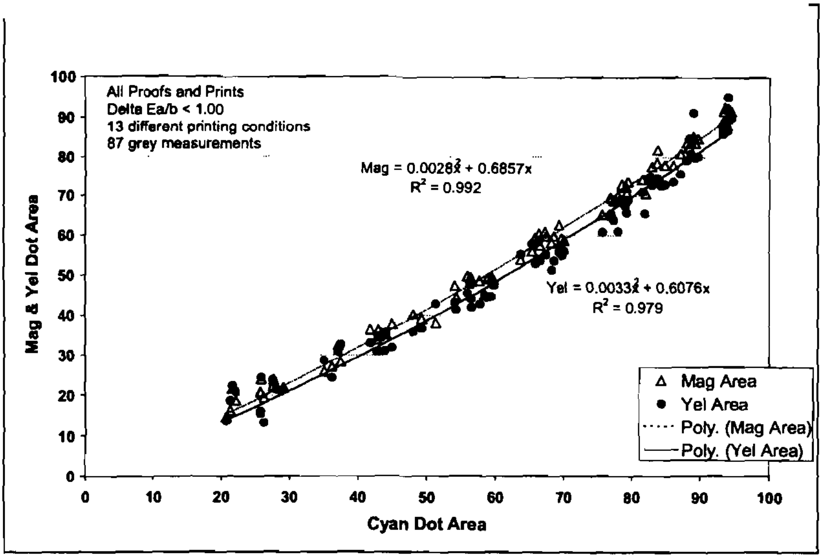

Figure 5a. Magenta and yellow dot areas compared to cyan dot areas.

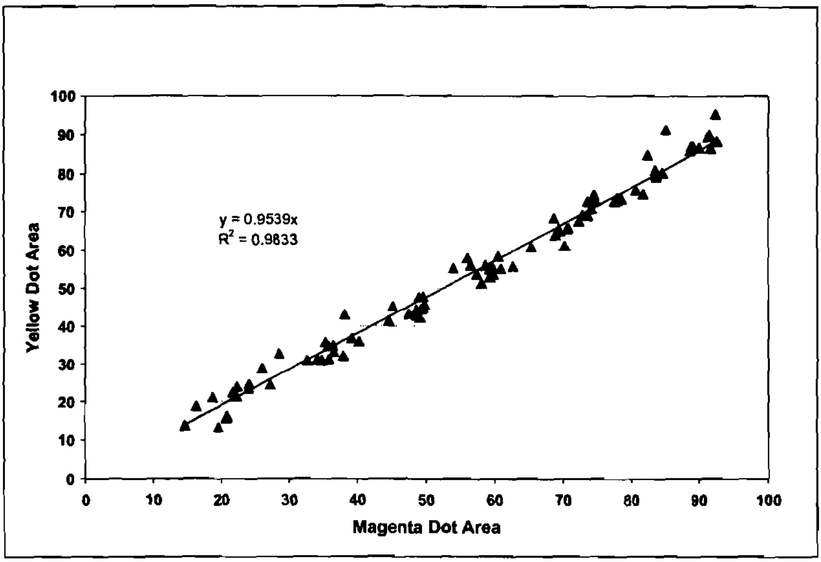

Figure 5b. Yellow dot areas compared to magenta dot areas.

These relationships enable us to calculate the best CMY gray combinations for sheetfed printing throughout the tonal range. A five-step procedure can be used to find the best CMY combination for any printing condition:

1. Choose the desired tone level of the CMY gray.
2. Determine the cyan dot gain at that tone level.
3. Substitute the corresponding cyan printed dot area into the polynomial
   $$Mag_{DotArea} = 0.0028(Cyan_{DotArea})^2 + 0.69(Cyan_{DotArea})$$
   to determine the optimal magenta dot area.
4. Substitute the magenta dot area into the equation
   $$Yel_{DotArea} = 0.95(Mag_{DotArea})$$
   to determine the optimal yellow dot area.
5. Determine what corresponding CMY film dot areas were needed to achieve the calculated printed magenta and yellow dot areas.

Because gray balance numbers are dependent on the specific dot gain levels, it is valuable to have a precise set of tone scales for the required measurements.

Screen Ruling Dependence

One of the goals of this study was to identify the printing parameters that affect the most neutral gray formula. The test form was printed/proofed under 14 different conditions in an attempt to isolate several variables and observe their influence on the most neutral gray formula.

One of the variables under scrutiny was screen ruling. The test form was both proofed and printed at three different screen rulings with all other parameters held constant. These results can be found in Table 3/Appendix A under Print/Proof conditions #2, #3, #4 for the proofs and #6, #8, #10 for the prints. Proofs were used for this comparison because the variables in proofing can be more precisely controlled than the corresponding printing variables. Figures 6a and 6b show the CMY relationships for the most neutral gray patches on identical proofs produced at three different screen rulings.

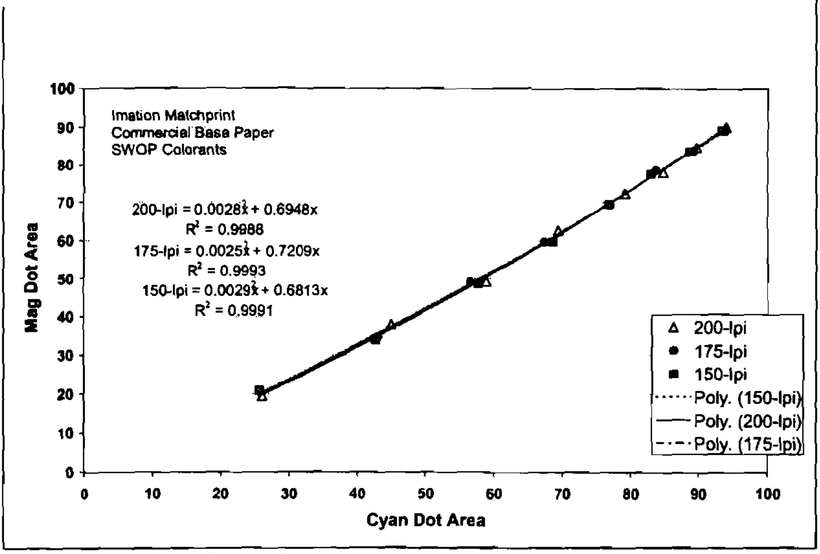

Figure 6a. Comparing different screen rulings on Imation Matchprints.

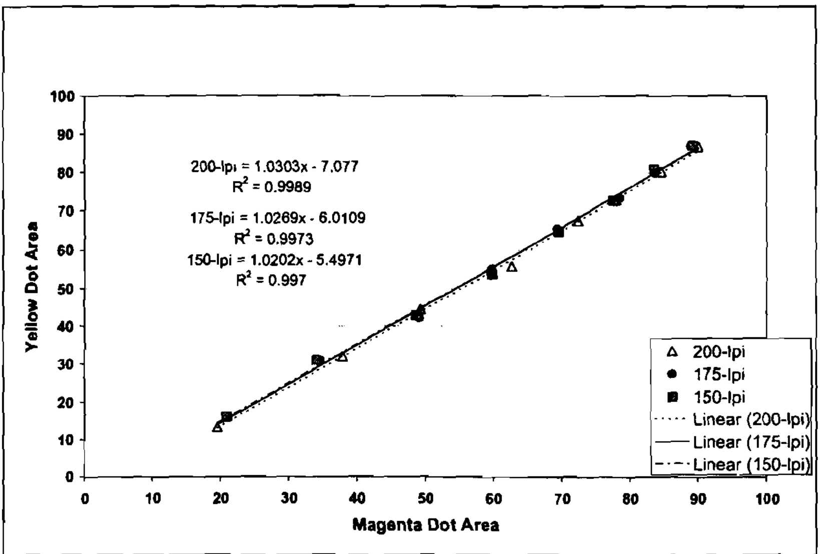

Figure 6b. Comparing different screen rulings on Imation Matchprints.

The best-fit polynomial in Figure 6a shows the same relationship between cyan and magenta as was observed in Figure 5a. In Figure 6b, however, the relationship between yellow and magenta indicates a highly linear, yet non-zero intercept fit. This is different from the yellow-magenta fit for press sheets, which show a very linear, zero intercept fit. The negative y-intercept in Figure 6b may be an indication of a higher amount of yellow in the hue of the magenta donor sheets for Imation proofs than in typical magenta sheetfed inks.

Due to the more precise control of proofing parameters, the variation of the data points about the best fit lines are insignificant. This would indicate that the CMY relationship for the most neutral gray point on proofs is independent of screen ruling. However, on press, dot gain is known to increase as screen ruling increases and dot gain does not occur uniformly throughout the tone scale. Two press sheets, printed at different screen rulings, have different amounts of dot gain and thus produce different printed dot areas for a given film dot area. This means that gray balance requirements are dependent on screen ruling for printed sheets. The variation can all be attributed to the differences in printed dot areas. The required changes in gray balance can be calculated because if the 50% dot gain is known, the printed dot areas of the entire scale can be accurately calculated. In other words, step 5 from the procedure for determining most neutral gray combinations would change for different screen rulings, but the CMY dot area relationships would remain the same.

The screen ruling dependence on press sheets was measured to verify this conclusion. Figures 7a and 7b show the CMY relationships for press sheets printed at three different screen rulings with all other parameters held constant. The best-fit polynomials in Figure 7a have zero intercepts and are nearly identical to those found in Figure 6a. These relationships are independent of screen ruling.

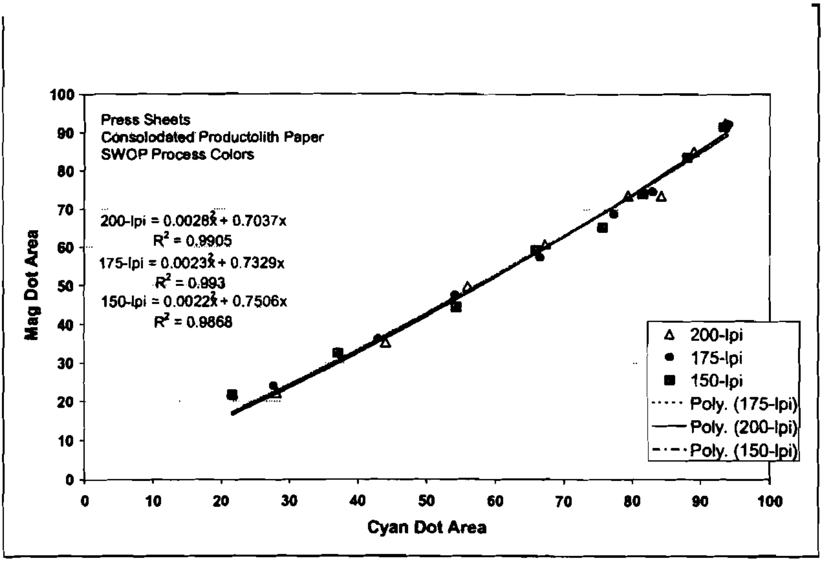

Figure 7a. Comparing different screen rulings on press sheets.

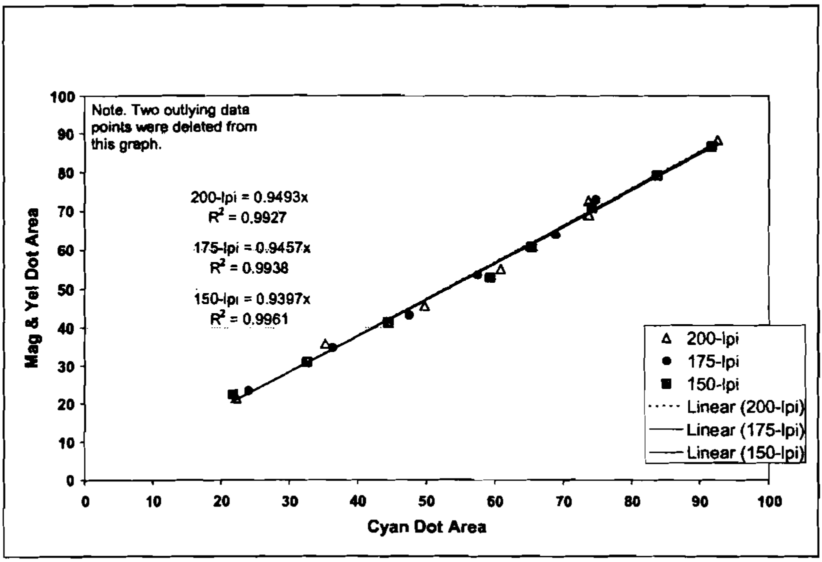

Figure 7b. Comparing different screen rulings on press sheets.

The difference in the yellow-magenta relationships between the Imation Matchprint proofs and the press sheets indicates that grays would not accurately match between the proofs and the press. This would be most pronounced in the lighter tone values. If the CMY gray combination were chosen to produce optimum gray on the proof, then the same gray patch on the press sheet would be deficient in yellow. Likewise, if the CMY combination were chosen to produce optimum gray on the press, then the proof might have a yellow cast in the gray tones.

Solid Ink Density Dependence

The dependence of the CMY gray balance relationships on solid ink density was analyzed. For the proofs, printing/proofing conditions #1 and #4 were used, and for the press sheets conditions #5, #6, #7 were used. Three solid ink density ranges were defined so that the mid-range solid ink density encompassed approximately 66% of the printers in the industry.

Figures 8a and 8b show the relationships between the CMY dot areas for press sheets; while Figures 9a and 9b show the relationships for the proofs. For both the press sheets and the proofs, the best-fit polynomial curves for the cyan-magenta relationship diverges at high dot areas. This implies a second-order dependence on solid ink density. In both instances, as the solid ink density (SID) increased, the magenta dot area decreased for a given cyan dot area. The numerical difference in the magenta dot area at a given cyan dot area between the best fit curves for the low SID region and the high SID region is approximately 5 percentage points. This gives a maximum error of approximately plus or minus 2.5% from the optimally calculated dot area, assuming the solid ink densities are within the extremes of this study. This error should be much less at lower gray tone values, but still it would be a visually noticeable difference.

The yellow dot area dependence on the magenta dot area exhibited no significant difference between different solid ink density ranges. The difference between the Imation curve and the PolaProof curve in Figure 9b is probably due to the hues of the donor sheets since the densities are approximately equal in yellow.

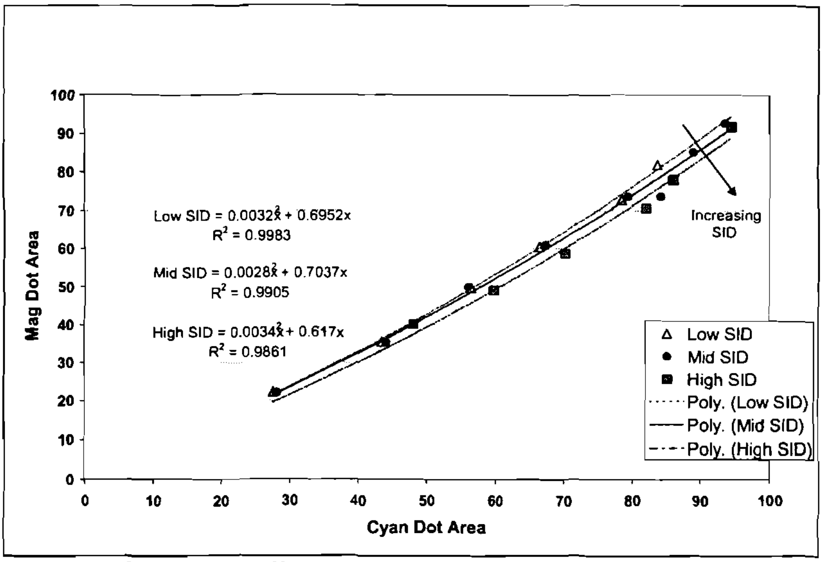

Figure 8a. Comparing different solid ink densities on press sheets.

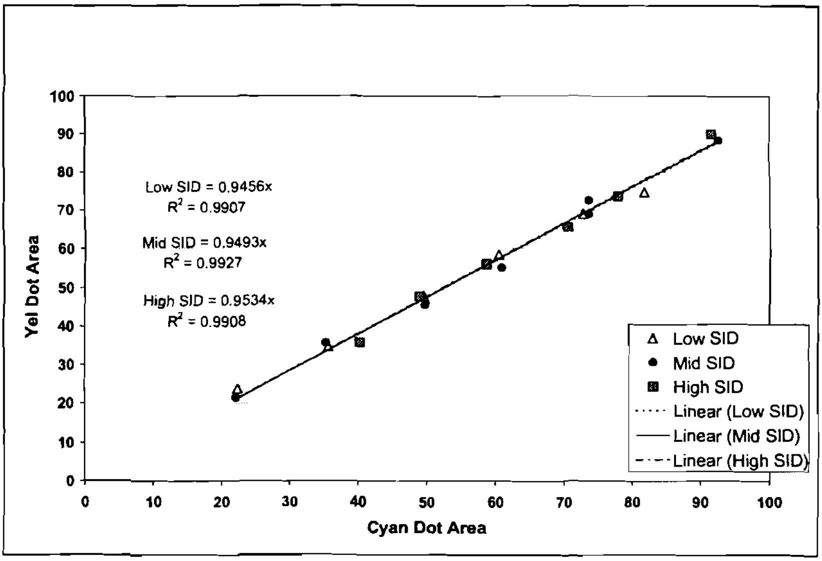

Figure 8b. Comparing different solid ink densities on press sheets.

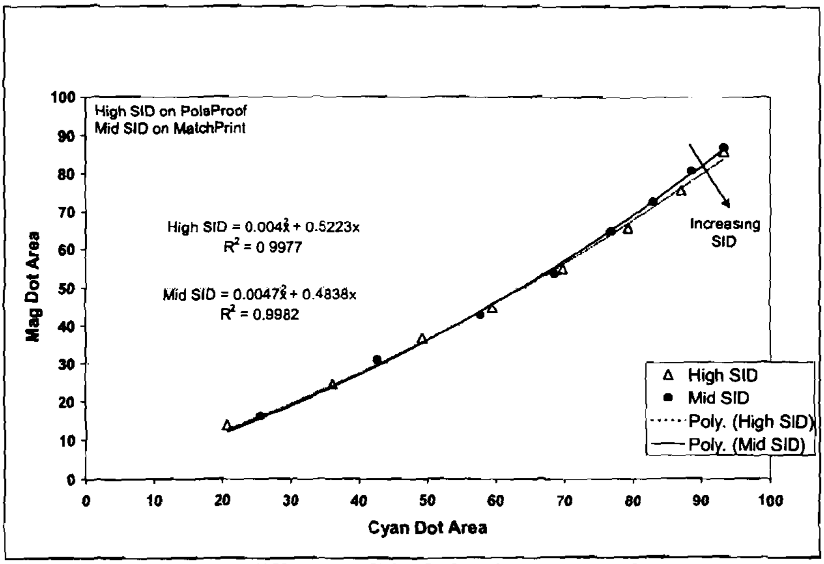

Figure 9a. Comparing different solid ink densities on proofs.

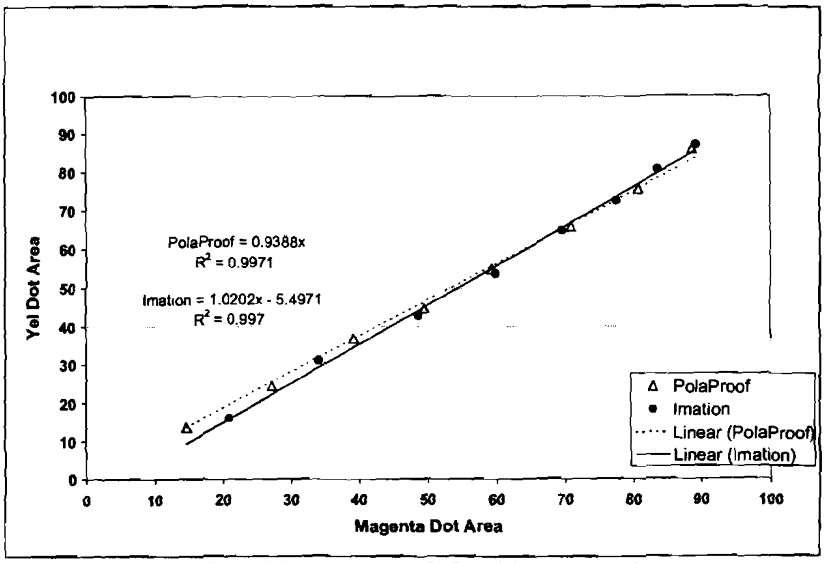

Figure 9b. Comparing different solid ink densities on proofs.

Solid ink density has little effect on gray balance within a mid-density range (i.e., within one standard deviation of the mean of high-quality lithographers). At density extremes, a change of 2.5% might occur. As with the findings regarding screen ruling, density level has a clear relationship with dot gain, which in turn influences gray balance requirements.

Paper and Ink Dependence

It seems obvious that different papers and inks will affect gray balance requirements. In the previous section it was found that an error of up to ± 2.5 could be expected between the cyan-magenta dot areas (also cyan-yellow dot areas) when calculating the CMY dot area combinations from the empirical best fit curves, depending on the ink film thickness. To estimate the amount of error attributable to different ink/paper combinations, Figures 10a and 10b show the CMY relationship for four ink and paper combinations, printed at the mid-density region. The printing/proofing conditions included in these figures are #10, #11, #12, and #13. Of course, this is a very small sample of the possible ink and paper combinations in the industry, and the conclusions should be taken as anecdotal.

Figure 10a shows the best-fit polynomial curves to each of the conditions. Bear in mind that some of these conditions only had three or four data points, the minimum number required to draw a second-order best-fit polynomial, and this results in high error in the equation. Throughout the tonal range the difference in magenta dot area between all four curves never exceeded 5 points. This supports the previous conclusion that an error of ± 2.5 points from the optimally calculated dot area for magenta is a good general rule-of-thumb.

Figure 10b shows the relationship between the yellow dot areas and the magenta dot areas. The three different inks produced three significantly different slopes. However, the two different types of coated paper printed with the same ink produced identical slopes. This meant that, in our small sample, the CMY dot area relationships for most neutral gray were influenced more by the ink hue differences than by the paper differences. As with the screen ruling differences, different papers produce different dot gains for given inks. Although the dot area relationships may be the same, the dot gain differences must be taken into account when calculating required CMY film dot areas for neutral gray.

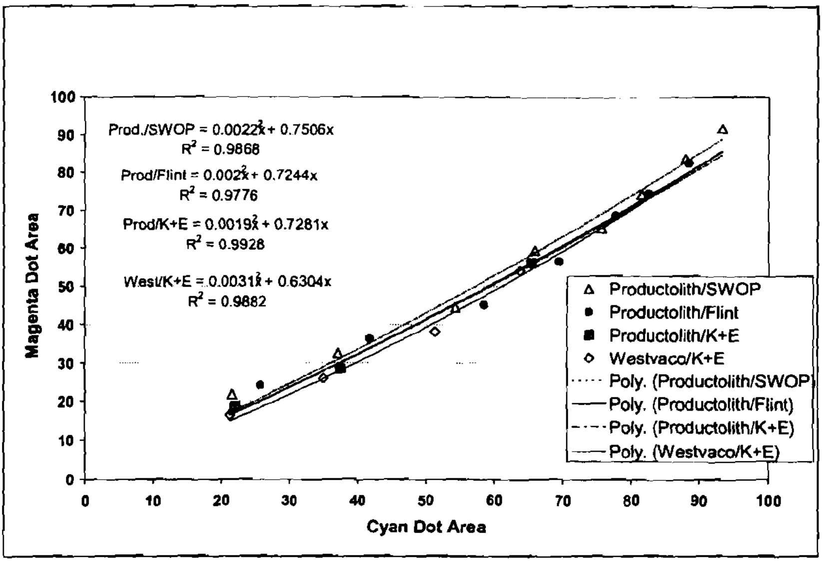

Figure 10a. Comparing different ink/paper combinations.

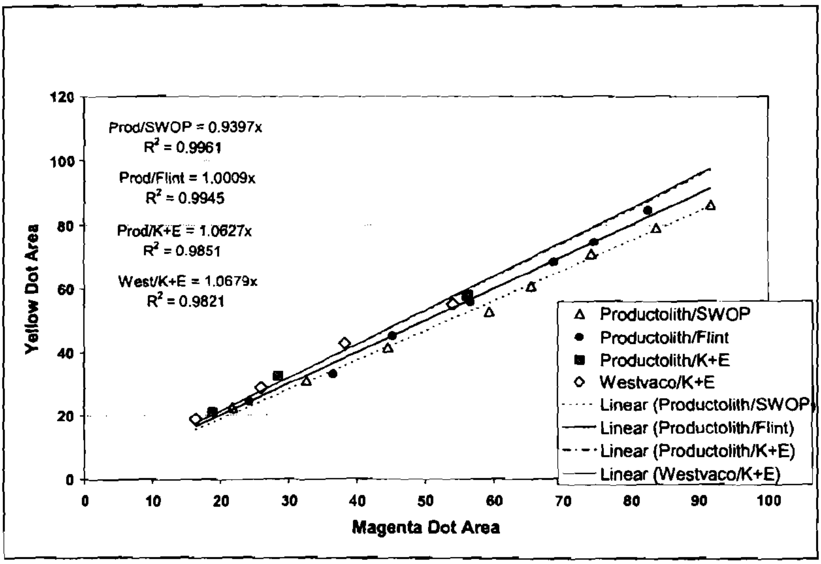

Figure 10b. Comparing different ink/paper combinations.

The yellow-magenta relationships for both the proofs in Figure 6b and the press sheets in Figure 10b show that the magenta colorants had the greatest fluctuation in hue in this study.

Dot Gain Ratios

In the 1999 print attribute study, it was found that the ratios of the 50% to 75% dot gains were fairly consistent for all colors across different printing conditions. This means that, given a 50% dot gain, the 75% dot gain could be calculated by dividing by the ratio. In most cases the calculated 75% dot gain was within 1.5% of the measured 75% dot gain. For this study, the ratios were calculated for the full range of tint values from 10% to 80%. Table 4 shows the average ratios of the 50% dot gain over the tint dot gain for the 10 printing conditions in this study (proofs were not included).

Film Tint	Ratio	Film Tint	Ratio
10	1.71	46	0.98
12	1.52	48	1.00
14	1.43	50	1.00
16	1.35	52	1.03
18	1.30	54	1.05
20	1.26	56	1.09
22	1.26	58	1.12
24	1.20	60	1.15
26	1.17	62	1.23
28	1.15	64	1.27
30	1.09	66	1.33
32	1.05	68	1.38
34	1.02	70	1.43
36	1.02	72	1.50
38	1.00	74	1.57
40	1.00	76	1.67
42	0.99	78	1.78
44	0.96	80	1.92

Table 4. Ratios of 50% dot gain over original dot area.

The values in Table 4 are based on an imagesetter workflow and gloss coated paper. The ratios in Table 4 enable us to calculate dot gain at any step of the tone scale from the measured 50% dot gain by applying the equation:

$$A_{Total} = A_{film} + \frac{G_{50\%}}{R},$$

where A_{Total} is the printed dot area, A_{film} is the film dot area $G_{50\%}$ is the 50% dot gain, and R is the ratio. These values, together with the 50% dot gain, can be used to calculate gray balance combinations.

Table 5 shows the GRACoL and SWOP substrates, screen rulings, and dot gains for the 50% tone value.

	Substrate	lpi	50% Dot Gain			
			K	C	M	Y
GRACoL	Premium gloss/dull coated	175	22	20	20	18
SWOP	Grades 3 & 5 coated	133	26	22	22	20

Table 5. GRACoL and SWOP guidelines for gloss coated papers.

By applying the 5-step procedure for determining the optimum gray balance and using the ratio table, gray balance combinations can be calculated for the GRACoL printing conditions. The 50% cyan dot gain in GRACoL is 20%, yielding a printed dot area of 70%. Substituting 70% into the second-order polynomial in step 3 gives a magenta dot area of 61%. Substituting 61% into step 4 gives a yellow dot area of 58%. For the whole tone scale (10–80%), the estimated three-color gray combinations for GRACoL printing conditions on gloss coated paper are shown in Table 6.

Film Dot Area	Cyan Printed Area	Mag Printed Area	Yel Printed Area	Film Dot Area	Cyan Printed Area	Mag Printed Area	Yel Printed Area
10	22	22	21	**46**	67	67	64
12	25	25	24	**48**	68	68	66
14	28	28	27	**50**	70	70	68
16	31	31	29	**52**	71	71	70
18	33	33	32	**54**	73	73	71
20	36	36	34	**56**	74	74	73
22	38	38	36	**58**	76	76	74
24	41	41	39	**60**	77	77	76
26	43	43	41	**62**	78	78	77
28	45	45	44	**64**	80	80	78
30	48	48	47	**66**	81	81	80
32	51	51	49	**68**	83	83	81
34	54	54	52	**70**	84	84	83
36	56	56	54	**72**	85	85	84
38	58	58	56	**74**	87	87	85
40	60	60	58	**76**	88	88	87
42	62	62	60	**78**	89	89	88
44	65	65	63	**80**	90	90	89

Table 6. Estimated dot areas for original dot by using the ratios in Table 4.

Table 6 can be used as a lookup table to determine the optimum film dot areas that give the most neutral 3-color gray. For the above example the CMY combination that produces the most neutral three-color gray at the 50% gray tint should be 50/41/40. To increase the precision of the CMY gray combination for a specific printing condition, tone scales can be printed and a lookup table can be made from measurements of press sheets. Otherwise, the method just described provides general guidelines on calculating the most neutral CMY gray formula.

Using the methods and procedures described in this report, the calculated most neutral three-color grays for GRACoL and SWOP printing conditions are presented in Table 7.

	Neutral Gray (C/M/Y)		
	25%	50%	75%
GRACoL	25/18/18	50/41/40	75/66/62
SWOP	25/18/18	50/41/40	75/65/62

Table 7. Calculated neutral gray combinations.

As part of the 1999 print attribute study, recommendations for GATF Sheetfed Offset Print Specifications (ShOPS) were made based on the results of the study. Using the methods and procedures described in this report, the calculated most neutral three-color grays are presented in Table 8 for ShOPS recommendations.

lpi	50% Dot Gain				Neutral Gray (C/M/Y)		
	K	C	M	Y	25%	50%	75%
150	22	20	20	19	25/18/17	50/41/39	75/66/62
175	25	23	23	22	25/18/17	50/42/39	75/66/60
200	27	25	25	24	25/18/17	50/42/39	75/64/59

Table 8. Recommended sheetfed screen rulings, dot gains, and gray combinatons.

As a cursory check on the tables above, the measured 50% gray CMY combinations from this study were averaged for eleven printing/proofing conditions (only conditions where the most neutral patch had a Chroma value <1.00). These average values were 50/42/39, which reaffirms the calculated CMY combination.

Conclusion

This study examined the relationships between the CMY dot areas for the most neutral three-color grays from 10% to 80% gray tone range. It was found that when the dot areas were examined instead of the dot gains a very consistent relationship between the cyan, magenta, and yellow dot areas emerged. For a given cyan dot area the optimal magenta dot area can be found simply by employing the polynomial:

$$Mag_{DotArea} = 0.0028(Cyan_{DotArea})^2 + 0.69(Cyan_{DotArea}) .$$

The optimal yellow dot area can then be calculated with the equation:

$Yel_{DotArea} = 0.95(Mag_{DotArea})$.

This knowledge enables us to calculate gray balance requirements for different screen rulings and different tone values if we know the 50 % dot gain.

In this study it was found that the assumption of equal magenta and yellow dot areas with respect to cyan area was inaccurate. A small but significant difference between the magenta and yellow dot areas affects the calculation of the most neutral CMY gray combination.

This study found that gray balance was influenced by difference in screen ruling, but the differences could be wholly accounted for as changes in printed dot area. The solid ink density also influenced the most neutral CMY combination, but this influence was minimal under typical density ranges. It was concluded that the difference in the actual magenta dot area would be within ± 2.5 percent from the optimal calculation.

Further study remains to test the equations developed in this study, and to measure the gray balance characteristics of a larger sample of printing companies. If the approach advocated in this paper proves to be generally valid across different sheetfed printing systems, it would greatly simplify the task of specifying gray balance values for different screen rulings and levels of dot gain.

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Appendix A

Printing Cond.	Min dE	Gray Tint	Cyan Area	Mag Area	Yel Area	Cyan Dot Gain	Magenta Dot Gain	Yellow Dot Gain
1	0.48	10	21	15	14	11	8	5
	0.11	20	36	27	24	16	13	8
	0.31	30	49	39	37	19	17	13
	0.45	40	59	50	45	19	20	15
	0.49	50	70	59	55	20	19	17
	0.42	60	79	71	66	19	19	18
	0.50	70	87	81	76	17	19	14
	0.50	80	93	89	86	13	17	12
2	0.68	10	26	20	13	16	12	6
	0.17	20	45	38	32	25	24	18
	0.63	30	59	49	44	29	27	22
	0.49	40	69	63	56	29	31	26
	0.36	50	79	72	68	29	30	26
	1.00	60	85	78	73	25	30	25
	0.44	70	90	85	80	20	27	24
	0.78	80	94	90	87	14	20	19
3	0.13	10	26	21	16	16	13	9
	0.33	20	43	35	31	23	20	16
	0.80	30	57	49	42	27	25	20
	0.53	40	67	60	55	27	28	23
	0.53	50	77	69	66	27	27	24
	0.83	60	84	79	73	24	27	23
	0.67	70	89	84	80	19	24	22
	0.65	80	94	89	87	14	19	17
4	0.43	10	26	21	16	16	14	10
	0.32	20	43	34	31	23	19	17
	0.36	30	58	49	43	28	25	21
	0.31	40	69	60	54	29	28	24
	0.33	50	77	70	65	27	28	25
	0.74	60	83	78	73	23	26	23
	0.52	70	89	84	81	19	22	21
	0.49	80	93	89	87	13	17	17
5	0.60	10	28	22	24	18	14	15
	0.21	20	43	36	35	23	21	20
	0.29	30	56	50	48	26	26	24
	0.24	40	66	60	58	26	26	26
	0.60	50	78	73	69	28	27	27
	0.49	60	84	82	75	24	24	23
	3.65	70	89	82	85	19	24	17
	4.57	80	94	82	90	14	22	14
6	0.80	10	28	22	21	18	14	13
	0.15	20	44	35	36	24	20	22
	0.62	30	56	50	46	26	26	24
	0.67	40	67	61	55	27	27	25
	0.83	50	79	74	69	29	28	27
	0.48	60	84	74	73	24	28	27
	0.68	70	89	85	91	19	21	23
	0.56	80	94	93	88	14	15	24
7	1.06	10	32	25	25	22	17	17
	0.13	20	48	40	36	28	26	24
	0.58	30	60	49	48	30	27	28
	0.16	40	70	59	56	30	31	30
	0.23	50	82	71	66	32	31	32
	0.23	60	86	78	74	26	32	32
	1.04	70	91	86	84	21	28	34
	0.43	80	95	92	90	15	20	30

Appendix A

Printing Cond.	Min dE	Gray Tint	Cyan Area	Mag Area	Yel Area	Cyan Dot Gain	Magenta Dot Gain	Yellow Dot Gain
8	0.38	10	28	24	23	18	15	15
	0.20	20	43	36	35	23	20	21
	0.36	30	54	48	43	24	24	23
	0.30	40	67	57	54	27	25	26
	0.48	50	77	69	64	27	27	26
	0.16	60	83	75	73	23	25	27
	1.68	70	89	86	81	19	18	27
	0.74	80	94	92	95	14	14	17
9	0.19	10	29	22	21	19	14	13
	0.24	20	44	36	31	24	22	19
	0.83	30	56	49	44	26	25	24
	0.58	40	68	58	51	28	28	25
	0.79	50	78	70	61	28	30	29
	1.69	60	84	79	72	24	29	30
	1.18	70	90	84	81	20	24	31
	0.70	80	94	91	89	14	17	29
10	0.57	10	22	22	22	12	14	14
	0.34	20	37	33	31	17	17	16
	0.51	30	54	45	41	24	21	19
	0.65	40	66	59	53	26	25	23
	0.72	50	76	65	61	26	25	25
	0.99	60	82	74	71	22	24	25
	0.41	70	88	84	79	18	18	25
	0.52	80	93	92	87	13	14	21
11	0.38	10	26	24	25	16	17	18
	0.25	20	42	36	33	22	21	20
	0.60	30	58	45	45	28	25	25
	0.66	40	69	57	56	29	29	28
	0.52	50	78	69	68	28	29	30
	0.16	60	83	75	75	23	29	31
	0.28	70	88	83	85	18	23	19
	1.40	80	93	88	91	13	18	15
12	0.54	10	22	19	21	12	14	11
	0.38	20	37	28	33	17	16	15
	1.19	30	54	40	45	24	20	17
	0.44	40	65	56	58	25	26	20
	2.44	50	75	60	66	25	26	20
	2.51	60	81	67	75	21	27	19
	3.24	70	88	79	83	18	21	16
	3.52	80	93	87	89	13	17	13
13	0.29	10	21	16	19	11	10	9
	0.17	20	35	26	29	15	13	11
	0.89	30	51	38	43	21	16	15
	0.97	40	64	54	55	24	22	17
	2.21	50	73	60	64	23	22	18
	2.08	60	80	66	73	20	24	17
	2.42	70	86	78	82	16	18	14
	4.22	80	92	85	88	12	15	12
14	1.37	10	22	8	20	12	3	10
	1.24	20	22	26	20	2	12	1
	2.93	30	55	26	20	25	4	-8
	3.39	40	55	57	50	15	27	12
	6.21	50	55	57	50	5	21	4
	7.31	60	55	57	50	-5	17	-8
	7.67	70	76	57	72	6	-1	4
	9.31	80	76	75	72	-4	3	-4