Interpretation of Dot Fidelity of Ink Jet Dots Based on Image Analysis

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The dot fidelity of ink jet dots has been investigated for several different coated ink jet papers. Serafano and Pekarovicova have defined dot fidelity in terms of dot area and roundness. For ink jet printers, we can also define a nominal dot area and an "ideal" dot area, once the resolution of the printer is known. The nominal dot area is the area of the square pixel defined by the inverse of the resolution of the printer. The "ideal" dot area is defined as the area of the circle in which the square pixel can be inscribed. This is the smallest circular dot that will cover 100% of the area when all dot positions are printed. This pixel area is π/2 times the area of the square pixel. Thus, we can compare the actual printed dot size with both nominal and ideal dot sizes. This analysis provides a direct interpretation of dot gain, which can be compared with values obtained from densitometry. The dot areas observed in our laboratory varied between 1.25 and 13 times the ideal dot area, depending on the resolution of the printer and whether the coating was matte or glossy.

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Introduction

Printed dot fidelity is an important component in image quality.[1] Image quality for a continuous tone gray scale image is determined by effective resolution of the image, the number of shades of gray that can be faithfully represented and the optical density of the darkest tone. The density of the darkest tone minus the density of the substrate determines the contrast of the image.[2] Color images consist of combinations of gray scale images of particular colors (Red, Green and Blue for displayed images and Cyan, Magenta, Yellow and Black for printed images).

For printed images, shades of gray are simulated by patterns of dots.[3–5] The dots may be of varying size on a rectangular grid as in a conventional halftone[3–7] or a random, or stochastic, pattern.[3–5,8] Thus, once the contrast is characterized, the effective resolution is determined by the smallest dot that can be printed. The faithful reproduction of a large number of shades of gray depends on the ability to reproducibly print dots of the desired size and shape. Note that the effective resolution may be different from the stated (addressable) resolution of the device, since printed dots much larger than the spacing between addressed grid points preclude observation of fine detail on the scale of the grid. Reproducibly generating dots of the desired shape is crucial to maintaining image uniformity and sharpness.

Varying shapes of dots are employed in conventional halftones, including square, circular and elliptical.[9] However, for ink jet printers, the theoretical shape of the smallest dot is circular, since the dots are obtained by impact with nucleated drops[10] that are spherical (in the absence of gravity) because of surface tension forces, even in the presence of gravity they must be circular in a cross-section perpendicular to gravity. Thus, the dot fidelity of ink jet dots can be measured by their nearness to circularity, how much their areas vary and how well they are positioned. In addition, we will see that it is insightful to compare the dot area with the nominal and "ideal" (defined in the next section) areas determined by the printer's addressable resolution. Preliminary results have been presented previously.[11]

Theory

The digital representation of a continuous tone image consists of a rectangular array of square pixels. For printing, it is conventional to assign a resolution, in pixels per unit length (*ppl*), to the image. For example, a 4" by 3" image at 600 pixels per inch (ppi) is 2400 by 1800 pixels. The area per pixel is just $1/ppl^2$, where *ppl* is the resolution. We call this the nominal area of a dot. For 600 ppi, the nominal, or pixel, area is 2.778×10^{-6} in^2 or 1792 micron^2 (μ^2).

Consider an image with exactly the nominal resolution of the printing device. If each square pixel in an image is 100% of the ink color, then the full image will be 100% of that color. Printing a circular dot with diameter less than the diagonal of the square pixel at every addressed point will necessarily leave some area uncovered.[3] It is important for a solid area to be fully covered with ink to yield the darkest tone and hence the maximum contrast. The smallest area covering circular dot has a diameter equal to the diagonal of the square pixel (Fig. 1). As seen in the figure, this is just the circle into which the square can be inscribed. The radius of this circle is

$$r = a/\sqrt{2} \tag{1}$$

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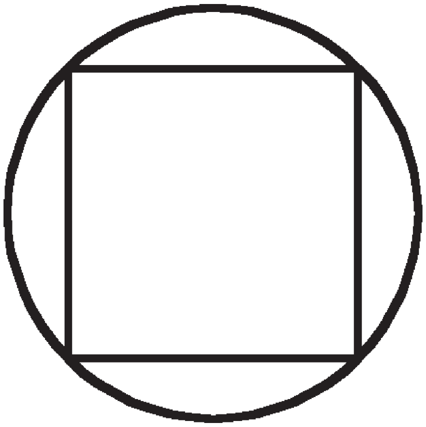

Figure 1. Illustration of ideal dot size showing a square pixel inscribed into a circle.

where $a = 1/ppl$ is the length of the side of the square. The corresponding area of the circular dot is

$$A = \pi r^2 = \pi a^2/2 \tag{2}$$

This result was also noted by Ulichney,[3] who discussed hexagonal dot patterns, in addition to square ones. The radius, r_{hex}, of the smallest circle into which a hexagon can be inscribed is in between a and r, in particular

$$r_{hex} = a/\sqrt{3} \sim 0.57735a \tag{3}$$

where again $a = 1/ppl$. The corresponding area relationship for the circle is

$$A = \pi r_{hex}{}^2 = 2\pi A_{hex}/\sqrt{27} \sim 1.209 A_{hex} \tag{4}$$

where $A_{hex} = 0.5a^2\sqrt{3} = a^2\cos 30°$, where $0.866a^2$ is the area of the hexagon. Similar results have been given by Naing[12] *et. al.* and Briley.[13]

Thus, for the square pixel image, we define an "ideal" circular dot as one whose area is $\pi/2$ times that of the corresponding square pixel. For example, the ideal dot area for 600 dpi is 2815 μ^2.

Results

The size and shape of ink jet dots depends significantly on the nature of the substrate, especially on the type of coating applied. Here, we present results of image analysis of dot fidelity for three different ink jet printers on plain paper and two different matte coated papers. The Matte coated papers were obtained from Mead and Weyerhaeuser Corp. Results for glossy coated ink jet papers are presented elsewhere.[14,15] The printers used for the results reported here were a Hewlett Packard DeskJet™ 932C, an Epson Stylus Color™ 900 and a Canon S450. All are drop on demand[16–18] type printers. The Hewlett Packard and Canon printers are Thermal ink jet printers and the Epson is a piezoelectric[16–18] ink jet printer. These printers are representative of desktop ink jet printers, and samples printed on other printers by these manufacturers have yielded similar results in our studies. All use water soluble dyes for cyan, magenta and yellow.[19,20] The Canon and Epson also use dyes for black, but Hewlett Packard uses black pigments (~100 nm),[19,20] presumably finely ground carbon black.

TABLE I. Dot Fidelity Data for the Canon Printer on Plain Paper

Color	Dot Area (μ^2)	Area Standard Deviation (μ^2)	Roundness	Roundness standard deviation
Black	4395	1245	0.70	0.15
Cyan	9060	2180	0.49	0.13
Magenta	8510	2125	0.53	0.14
Yellow	7780	2590	0.57	0.12
Average	7436	2920	0.57	0.16

TABLE II. Dot Fidelity Data for the Canon Printer on Mead Paper

Color	Dot Area (μ^2)	Area Standard Deviation (μ^2)	Roundness	Roundness standard deviation
Black	2375	319	0.93	0.05
Cyan	9075	1500	0.55	0.12
Magenta	6000	1255	0.57	0.13
Yellow	6075	1625	0.64	0.14
Average	5881	2982	0.67	0.20

TABLE III. Dot Fidelity Data for the Canon Printer on Weyerhaeuser Paper

Color	Dot Area (μ^2)	Area Standard Deviation (μ^2)	Roundness	Roundness standard deviation
Black	3080	667	0.91	0.09
Cyan	9925	1905	0.57	0.12
Magenta	6515	1500	0.59	0.14
Yellow	6675	1385	0.62	0.15
Average	6549	3111	0.67	0.20

Image analysis was aided by ImageXpert 9.1.4 from ImageXpert and Image Pro Plus 4.5 from Media Cybernetics. These systems consisted of microscopes and video cameras interfaced to computers with framegrabber boards. ImageXpert is Macintosh-based and Image Pro Plus is PC-based. We have generally found that the samples measured on either system give results comparable with one another and software from each system can read and analyze images from the other system.

The results are summarized in Tables I through IX. The print pattern consisted of a square array of 36 × 36 dots on a 180 × 180 grid of pixels. With this spacing, dots seldom overlap, even though they may be much greater than the ideal size. The pattern was created with Adobe Photoshop™ in CMYK mode, because that program allows precise pixel-level editing in various color modes. It was printed for each of the four process colors, cyan, magenta, yellow and black. The pattern was printed at 600 dpi for the Hewlett Packard[21] printer and at 720 dpi for the Canon[22] and Epson[23] printers. This is consistent with resolutions of 600 × 600 dpi for the Hewlett Packard printer in normal mode and 720 × 1440 dpi for the Canon and Epson printers. Dot fidelity analysis requires a robust algorithm for dot edge detection. For these analyses, edge detection used an algorithm developed previously.[24,25] This method is designed to find the threshold value as that which is least sensitive to the choice of value.

Care must be taken to choose settings in the printer driver to print single dots of pure color. Printing with pure black is especially problematic, since all of the printers tend to use a "4 color black" when black ink is specified, mixing dots of cyan, magenta, yellow and black

TABLE IV. Dot Fidelity Data for the Epson Printer on Plain Paper

Color	Dot Area (μ^2)	Area Standard Deviation (μ^2)	Roundness	Roundness standard deviation
Black	3160	1156	0.52	0.14
Cyan	5720	1700	0.59	0.13
Magenta	5295	1855	0.53	0.15
Yellow	6640	1860	0.54	0.14
Average	5204	2207	0.54	0.14

TABLE V. Dot Fidelity Data for the Epson Printer on Mead Paper

Color	Dot Area (μ^2)	Area Standard Deviation (μ^2)	Roundness	Roundness standard deviation
Black	5650	2100	0.61	0.12
Cyan	5450	2145	0.55	0.14
Magenta	5955	1775	0.54	0.13
Yellow	8045	1850	0.64	0.14
Average	6275	2304	0.59	0.14

TABLE VI. Dot Fidelity Data for the Epson Printer on Weyerhaeuser Paper

Color	Dot Area (μ^2)	Area Standard Deviation (μ^2)	Roundness	Roundness standard deviation
Black	6005	1676	0.74	0.11
Cyan	6360	2600	0.66	0.14
Magenta	6970	1840	0.56	0.13
Yellow	6935	2020	0.53	0.14
Average	6568	2087	0.63	0.15

TABLE VII. Dot Fidelity Data for the HP Printer on Plain Paper

Color	Dot Area (μ^2)	Area Standard Deviation (μ^2)	Roundness	Roundness standard deviation
Black	4875	862	0.66	0.13
Cyan	4410	1115	0.53	0.13
Magenta	5270	1120	0.56	0.13
Yellow	4530	1090	0.56	0.14
Average	4771	1116	0.57	0.14

TABLE VIII. Dot Fidelity Data for the HP Printer on Mead Paper

Color	Dot Area (μ^2)	Area Standard Deviation (μ^2)	Roundness	Roundness standard deviation
Black	3775	594	0.68	0.12
Cyan	5505	1245	0.61	0.12
Magenta	4330	846	0.60	0.13
Yellow	3975	867	0.57	0.13
Average	4396	1178	0.61	0.13

TABLE IX. Dot Fidelity Data for the HP Printer on Weyerhaeuser Paper

Color	Dot Area (μ^2)	Area Standard Deviation (μ^2)	Roundness	Roundness standard deviation
Black	5255	862	0.71	0.11
Cyan	5580	1170	0.68	0.12
Magenta	4620	804	0.65	0.13
Yellow	4255	825	0.64	0.12
Average	4928	1094	0.67	0.12

when only black is specified. In order to "force" the printers to print with black ink only, the image was specified as a binary black and white image and specified to only use black ink.

The dot roundness reported for the different cases is defined as

$$\text{roundness} = 4\pi A/p^2 \tag{5}$$

where A is the area of the dot and p is the perimeter or the dot. The roundness is equal to unity for a circle and is less than unity for any other closed figure. The closer to unity the roundness, the better the quality of the dot. A rounder dot provides more uniform images, and along with resolution, allows sharp images, with clean boundaries and legible characters.

The coated papers showed significantly better performance for all of the printers. The dots tended to be smaller, rounder and with less variation than with plain paper. The exception is the Epson printer, where the dot areas were smaller for plain paper and the standard deviation did not differ significantly for the different papers. The black dots were smaller than the colored dots for the Canon and Epson printers. The black and colored dots were about the same size for the HP printer.

In all cases, the dots were significantly larger than the ideal dot size of 2815 μ^2 for 600 dpi and 1955 μ^2 for 720 dpi. The average 600 dpi dots on the HP printer were 73% larger than the ideal size for plain paper, 56% larger on the Mead paper and 75% larger on the Weyerhaeuser paper. The 720 dpi dots on the Canon printer were more than a factor of three times the ideal size. The black dots were 2.2 times larger for the plain paper, 21% larger for the Mead paper and 58% larger for the Weyerhaeuser paper. The colored dots for the Canon printer were 4.3 times the ideal size for plain paper, 3.6 times larger for the Mead paper and 3.9 times larger for the Weyerhaeuser paper. The 720 dpi dots on the Epson printer were more than a factor of 3 times the ideal size. The black dots were 62% larger for the plain paper, 2.9 times larger for the Mead paper and 3.4 times larger for the Weyerhaeuser paper. The colored dots for the Epson printer were 3 times the ideal size for plain paper, 3.3 times larger for the Mead paper and 3.5 times larger for the Weyerhaeuser paper. The average dot size of 6622 μ^2 for the Canon printer and 6016 μ^2 for the Epson printer were both larger than 4698 μ^2 for the HP printer, despite the higher apparent resolution. This may be because the stated resolution of the HP printer is 1200 × 2400 dpi in Color Layering High Resolution Mode,[20] while the stated resolution for the Canon[21] and Epson[22] printers is 720 × 1440 dpi.

The larger than ideal dot size reduces the effective resolution. Thus, the effective resolution is only 390 dpi for the Canon prints, 410 dpi for the Epson prints, while the effective resolution is 460 dpi for the HP prints, based the resolution for which the actual dot size is the ideal size. The lower effective resolution reduces sharpness of images, causing loss of fine detail.

Typical images used for the dot area analysis are shown in Figs. 2 through 7. The cleanest dots by far were obtained were from the Canon black on the coated papers. The areas were near to ideal, with smaller standard deviation and nearly circular. This is probably not reflecting the intrinsic quality of the printer since the colored dots for this printer are similar to those for

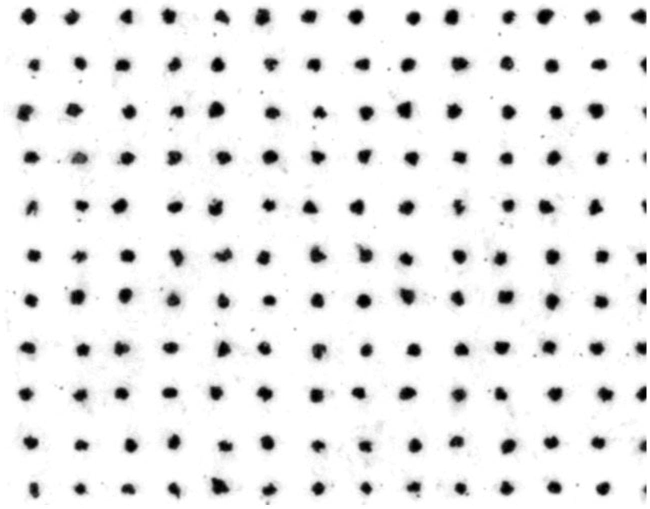

Figure 2. Black dot image for Canon printer on Mead paper.

Figure 3. Black dot image for Epson printer on Weyerhaeuser paper.

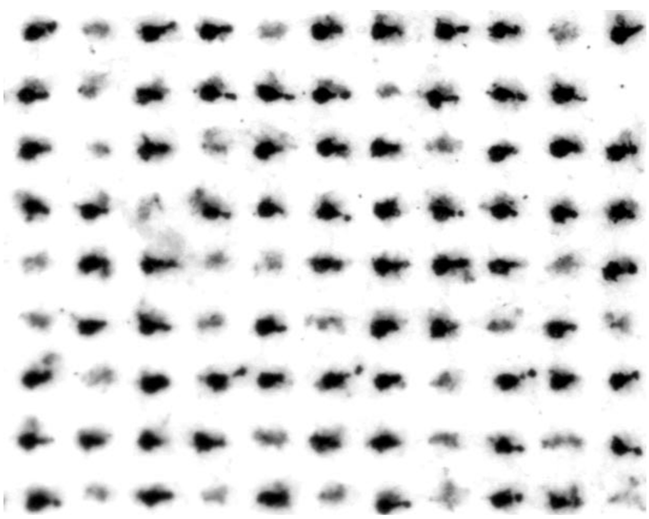

Figure 4. Black dot image for Hewlett Packard printer on Weyerhaeuser paper. *Supplemental Materials—Figure 4 can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

Figure 5. Cyan dot image for Hewlett Packard printer on Weyerhaeuser paper. *Supplemental Materials—Figure 5 can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

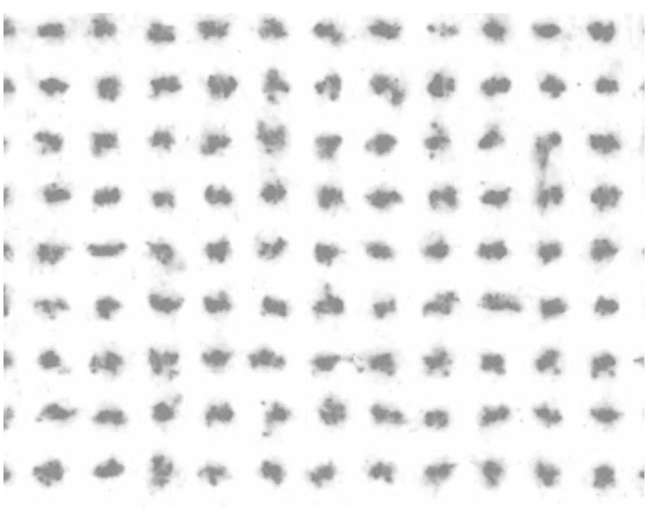

Figure 6. Magenta dot image for Hewlett Packard printer on Weyerhaeuser paper. *Supplemental Materials—Figure 6 can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

Figure 7. Yellow dot image for Hewlett Packard printer on Weyerhaeuser paper. *Supplemental Materials—Figure 7 can be found in color on the IS&T website (www.imaging.org) for a period of no less than two years from the date of publication.*

the other printers. More likely, it reflects a difference in strategy in the printer driver, e.g. a different dithering algorithm, when printing with only black ink. Printing dots with pure cyan, magenta and yellow inks was made difficult[26] because the printer drivers are designed to work with RGB data, despite the fact the printers actually use cyan, magenta and yellow inks. The only way to fully control the CMYK inks for an ink jet printer is to employ a RIP (Raster Image Processor).

The dot area obtained from image analysis can also be used, along with the total area of the analysis window, to estimate the relative area coverage. This can be compared with the coverage estimated using densitometry and the Murray–Davies equation[27]

$$\%\text{Dot Area} = 100(1 - 10^{-D_{tp}})/(1 - 10^{-D_{sp}}) \qquad (6)$$

where D_{tp} is the average optical density of the printed pattern relative to paper and D_{sp} is the density of the solid color relative to the paper.

In estimating the average area per dot in Tables I through IX, small specks and multiple dots connected to one another were excluded from the average. However, to estimate the total coverage, all dots and specks must be included in the analysis, because they would all appear in the average area seen by the densitometers. The estimated area coverages for the different printers on the different papers are shown in Tables X through XVIII.

The dot area coverage estimated by the image analysis is systematically about half of that estimated by densitometry (0.55 with a standard deviation of 0.16). This kind of observation is well known and is attributed to the difference between physical and optical dot gain. The optical dot gain causes the dot sizes to appear larger to the densitometer than their actual physical size. The Yule–Nielsen[28] correction to the Murray–Davies equation was developed specifically to address this issue. This equation is given by

$$\%\text{Dot Area} = 100(1 - 10^{-D_{tp}/n})/(1 - 10^{-D_{sp}/n}) \qquad (7)$$

where n is a correction factor, introduced by Yule and Nielsen, to take into account internal diffusion, i.e. multiple internal reflections, of light in the substrate; n depends on the light trapping property of the substrate and, therefore, the type of coating applied. In practice, $n = 2.7$ has been suggested for uncoated paper and $n = 1.65$ has been suggested for coated paper.[29]

For our analyses, the Yule–Nielsen values given in Tables X through XVIII are all based on $n = 2.7$, the uncoated value. This gives better overall agreement than the coated value, even for the coated samples. This makes sense, since the coated value is more appropriate for glossy coated paper and the matte coated paper is more like uncoated paper in terms of multiple diffuse internal reflections. With this choice, the average ratio of image analysis to densitometry is 0.92 with a standard deviation of 0.24.

As stated earlier, the dot behavior is highly dependant on the paper coating. Here we have discussed only two matte coated samples and plain (copy) paper. Generally, glossy coated samples yield printed dots both rounder and larger than those reported here. We previously reported roundness values on glossy coated papers as high as 0.93,[14,15] and have seen some unreported samples with roundness greater than 0.98, nearly perfect circles. However, the average dot area in our previ-

TABLE X. Dot Area Coverage Data for the Canon Printer on Plain Paper

Color	Dot Area (%) Murray–Davies	Dot Area (%) Yule–Nielsen	Dot Area (%) Image Analysis	Image Analysis/Yule–Nielsen Ratio
Black	26.6	15.3	14.3	.94
Cyan	17.2	9.8	7.9	.80
Magenta	16.7	8.9	7.4	.83
Yellow	9.2	5.8	7.5	1.3
Average	17.4	9.9	9.3	.97

TABLE XI. Dot Area Coverage Data for the Canon Printer on Mead Paper

Color	Dot Area (%) Murray–Davies	Dot Area (%) Yule–Nielsen	Dot Area (%) Image Analysis	Image Analysis/Yule–Nielsen Ratio
Black	15.5	8.6	7.4	.86
Cyan	13.5	7.7	6.9	.89
Magenta	11.4	6.5	4.5	.70
Yellow	10.9	6.7	6.2	.92
Average	12.8	7.4	6.2	.85

TABLE XII. Dot Area Coverage Data for the Canon Printer on Weyerhaeuser Paper

Color	Dot Area (%) Murray–Davies	Dot Area (%) Yule–Nielsen	Dot Area (%) Image Analysis	Image Analysis/Yule–Nielsen Ratio
Black	15.6	8.8	9.9	1.13
Cyan	15.8	9.2	8.9	.97
Magenta	11.7	6.9	5.3	.78
Yellow	10.0	6.4	5.2	.82
Average	13.3	7.8	7.3	.92

TABLE XIII. Dot Area Coverage Data for the Epson Printer on Plain Paper

Color	Dot Area (%) Murray–Davies	Dot Area (%) Yule–Nielsen	Dot Area (%) Image Analysis	Image Analysis/Yule–Nielsen Ratio
Black	19.7	10.1	6.6	.65
Cyan	6.6	3.7	3.1	.83
Magenta	10.0	5.7	4.5	.78
Yellow	5.9	3.7	5.4	1.45
Average	10.6	5.9	4.9	.94

TABLE XIV. Dot Area Coverage Data for the Epson Printer on Mead Paper

Color	Dot Area (%) Murray–Davies	Dot Area (%) Yule–Nielsen	Dot Area (%) Image Analysis	Image Analysis/Yule–Nielsen Ratio
Black	19.6	8.6	13.9	1.62
Cyan	6.0	4.1	3.5	.84
Magenta	9.4	6.1	4.8	.79
Yellow	8.8	6.4	5.8	.91
Average	10.9	6.3	7.0	1.04

TABLE XV. Dot Area Coverage Data for the Epson Printer on Weyerhaeuser Paper

Color	Dot Area (%) Murray–Davies	Dot Area (%) Yule–Nielsen	Dot Area (%) Image Analysis	Image Analysis/Yule–Nielsen Ratio
Black	17.7	8.9	16.0	1.79
Cyan	6.1	3.8	4.8	1.25
Magenta	7.3	4.5	5.6	1.24
Yellow	7.9	5.5	5.4	.99
Average	9.7	5.7	8.0	1.32

TABLE XVI. Dot Area Coverage Data for the Hewlett Packard Printer on Plain Paper

Color	Dot Area (%) Murray–Davies	Dot Area (%) Yule–Nielsen	Dot Area (%) Image Analysis	Image Analysis/Yule–Nielsen Ratio
Black	26.9	15.0	8.2	.54
Cyan	22.0	13.8	10.0	.73
Magenta	27.8	16.8	11.7	.70
Yellow	21.3	13.6	10.4	.77
Average	24.5	14.8	10.1	.69

TABLE XVII. Dot Area Coverage Data for the Hewlett Packard Printer on Mead Paper

Color	Dot Area (%) Murray–Davies	Dot Area (%) Yule–Nielsen	Dot Area (%) Image Analysis	Image Analysis/Yule–Nielsen Ratio
Black	25.0	13.7	5.9	.43
Cyan	18.9	11.8	12.2	1.03
Magenta	23.9	14.0	9.6	.68
Yellow	12.1	7.3	8.9	1.22
Average	20.0	11.7	9.1	.84

TABLE XVIII. Dot Area Coverage Data for the Hewlett Packard Printer on Weyerhaeuser Paper

Color	Dot Area (%) Murray–Davies	Dot Area (%) Yule–Nielsen	Dot Area (%) Image Analysis	Image Analysis/Yule–Nielsen Ratio
Black	21.3	11.5	8.8	.77
Cyan	19.3	12.4	12.4	1.00
Magenta	20.5	12.4	10.3	.83
Yellow	12.6	8.0	9.5	1.19
Average	18.4	11.0	10.2	.96

ous report for glossy papers was about 3 times the ideal dot area for 300 dpi on an HP 820C and more than 13 times larger for 760 dpi on an Epson Color Stylus Pro™.

In addition to single dot fidelity, the image quality depends on the accuracy of placing the dots on the paper. The ImageXpert system can be used to measure the dot placement accuracy (or error) of the ink jet printer mechanism.[30] We used the ImageXpert software to determine the dot placement accuracy. We found the error in dot placement relative to the horizontal and vertical lines to be generally negligible. The average dot to line error was $0.22 \pm 0.18\ \mu$, with a maximum of $2.4\ \mu$. Even this largest value is small compared to typical dot diameters ranging from $50 - 100\ \mu$.

Discussion and Conclusions

We have presented a discussion of dot fidelity for ink jet printer dots. We have introduced the concept of an ideal dot size based on the smallest area covering circular dot. We have also compared dot area analysis with that obtained from densitometry and analyzed dot placement. Our analyses and interpretation are general and are applicable to any printing processes where image quality is governed by the smallest printable dot. The methods reported here form the basis for all evaluation of image quality for both coatings and printing processes in our laboratories.

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