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Wimonrat Boonprasit

A Study of Producing Smoother Gradients in the Flexographic Process on Oriented Polypropylene with UV Ink by Varying Screening Techniques, Gradient Lengths and the Surrounding

By

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School of Print Media in the College
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Abstract

Printers find that producing smooth gradients in the highlight area is a great challenge for flexographic printing. Screening technology vendors claim that hybrid screening technologies produce smoother gradients and enhance reproducible dots in the highlight areas. This study was designed to investigate if hybrid screening technologies can achieve better gradient results than other screening technologies—conventional screening and FM screening—with the flexographic process.

A single test form was printed on oriented polypropylene with UV ink, as these are common materials used in flexible packaging. The first objective was to see how different pressure settings impact tone reproduction of each screening technique. There were three pressure settings—kiss impression, moderate pressure and high pressure. Tone reproduction curves of all three screening techniques were evaluated to see the change due to the different pressure settings. The results show that FM screening had a high sensitivity to change in pressure, while AM and hybrid screenings were more forgiving to variations in pressure settings. In the highlight areas, hybrid screening is the least sensitive to changes in pressure.

The second objective was to study whether smoother gradients can be produced by altering three variables: screening techniques, gradient lengths and the impact of the

surrounding. These variables were used to create a gradient matrix. Printed sheets from different points in the press run were collected for data analysis. There were two types of data analysis, measurement based evaluation and visual evaluation.

Because of difficulty in the methodology for analyzing the measured data, the conclusions were then based on the results from the visual evaluation. There are three aspects to the problems with gradient smoothness: highlight breaking in AM screening, graininess of FM screening, and a disjunction at the transition point of hybrid screening. When minimum dot size, transition point, and transfer curve are set correctly, hybrid screening would be the best selection to use with the flexographic process. The surrounding, or solid frames around the gradients, did not truly enhance gradient smoothness at kiss impression.

Chapter 1

Introduction

A demand on flexible packaging design is to produce packages that catch the consumer's attention. One technique, which packaging designers use, is to create a three-dimensional effect by placing a shadow around an object or type. To generate the three-dimensional effects, designers use blends, vignettes, ramps or gradients. However, in order to generate gradients with the flexographic process, there are critical issues that are of concern since flexographic printing cannot reproduce highlight dots very well. As a result, professional designers and pre-media operators in the flexographic process avoid and prevent this unpleasant appearance by using low contrast colors and/or using lower screen rulings. However, to remain competitive in the market place, screen rulings tend to become finer; thus, using a lower screen ruling is not desirable.

Producing highlights with small dots is a challenge in the flexographic process; highlight tone breaking may occur harshly or dots may be lost at a lower percentage. Because of the elastic nature of flexographic plates, when pressure is applied to the plates during printing, the highlight dots being much smaller and therefore mechanically weaker get squashed more than the larger dots. This causes uneven tone reproduction, especially in the highlight areas.

Many screening technology vendors claim that hybrid screening methods can be used to decrease and/or prevent these highlight problems. Typically, hybrid screening is a simple combination of conventional (AM) screening for the larger dots, and frequency modulated (FM) screening for the highlights.

To get an idea on the extent to which flexographic printers adopt hybrid screening technology, an informal sampling of flexographic printed packaging was conducted at a local supermarket. No flexo printed products were found using hybrid screening. This was also corroborated by a plate manufacturer, who said that all of their customers still use AM screening and they never have an order to make a plate with hybrid screening.

Consequently, the researcher was interested in studying whether or not hybrid screening can produce better print quality as claimed by screening technology vendors. What was learned from this experiment could be a help to designers and pre-media operators when choosing a method for producing gradients.

Accordingly, the following aspects were investigated:

1. Sensitivity of three screening techniques to different amounts of pressure during printing.
2. Which screening technique reproduces smoother gradients?
3. When printing a gradient, does the length of gradient make a difference in the visibility of poor highlight rendition?
4. Does the surrounding of a gradient make a difference? A solid area close to the highlight areas might absorb printing pressure and thereby shield the highlight dots from excessive pressure.

These aspects were studied both by measurements and visual evaluation.

Chapter 2

Theoretical Basis of the Study

Screening Technology

Continuous Tone and Halftone Screen

Continuous tone refers to a method to represent tonal values used in photographs, drawings and paintings. In photography, these tones are created by varying silver amounts. As the silver amounts increase, the tone values of the images will become darker. For (flexographic) printing, the varying tones of the images were reproduced by using halftone screens. Before the halftone is made, there are many factors that must be considered in order to produce a printable dot size such as printing process, printing condition, ink, and substrate (Adams, Faux, & Rieber, 1996). Halftone screens are made by converting the continuous tone of images into a pattern of tiny dots that can then be reproduced on printing presses. The image is rendered in a grid-like pattern that is called a halftone. Traditionally, the halftone image uses different dot sizes with fixed space (screen resolution) to create tones. This halftone screening approach is called conventional screening or amplitude modulated (AM) screening (Riordan & Romano,

2003). The gradation tones of full color images are produced by arranging each of the color dots along straight lines at different screen angles. The screen angle of each color (cyan, magenta, yellow, and black) must be set carefully in order to lessen the appearance of moiré patterns. Rosette dots will appear properly if the dots of every color align in their appropriate angles (Hardesty, 2002).

Frequency Modulated Screening or Stochastic Screening

Stochastic is a Greek word which means “random” or “probabilistic”. It is used to describe frequency modulated (FM) screening (Bury, 2004). Unlike AM screening, stochastic screening generates tone values by varying the occurrence, or frequency, of microdots. In other words, gradation tones are generated by varying dot spaces with equal dot size throughout the range of tone (Broudy, 2001 & McDougall, 1994). The fundamental concept of randomness has been around since 1963. However, it was not widely used in the analog age until digital technology became available and also the cost of image setters and powerful computer systems became affordable (GATF, 2004). In 1993, stochastic screening, or frequency modulated screening, developed by German technicians (McDougall, 1994) was introduced to the market by Agfa Corporation as Crystal Raster (Campbell, 2003) and Diamond Screening was announced by LinotypeHell. During this time, some vendors provided their own versions of raster image processors. As a result, two printers, New York City based World Color Press and

R.R. Donnelley & Sons, began to integrate FM screening into their operations (McDougall, 1994 & Campbell, 2003).

FM screening will affect not only offset lithography, but also non-heatset web offset and flexography because of the continuation of research and development (Romano, 1995). Two generations of FM screening have been developed: first-order and second-order FM screening. First-order FM screening is the screening method that varies only the frequency of equal-size dots; this technology produces images that are grainy (Bury, 2004). First-order FM screening performs poorly in shadow areas and is not acceptable in packaging printing (Hamilton, 2004). Therefore, this technology is further developed to second-order FM screening, which not only varies the frequency of the dots, but also varies the dot sizes. This revised screening technology eliminates the graininess and produces smoother blends and solids (Bury, 2004).

FM screening requires more process control and reliable color proofs, which are expensive. However, if printers have good process control, printing with stochastic screening will be successful (Bury, 2004). The improvements in the pressroom lead to more efficiency since every process in the workflow needs to be optimized, calibrated, and benchmarked—this is a huge advantage. For offset printing, FM screening reaches the required color quicker, and also decreases production spoilage and waste (Bury, 2005). FM screening also allows greater ink densities, improving tone reproduction and contrast in offset printing (Romano, 1995). In general, FM screening does not have screen angles and it also eliminates the moiré effect and rosette patterns; this allows more color to be printed without worrying about the moiré effect. Thus, FM screening is ideal

for printing more than four colors, a benefit for flexographic printing as packaging usually prints more than four colors, and also provides sharper details (McDougall, 1994).

As the technologies of photopolymer plates and computer-to-plate workflows have been developed, they make FM screening more applicable for flexography. Flexographic printing can hold 2 percent dots of 150 lpi or around 26 microns. (Broudy, 2001) Using FM screening in flexographic printing raises concerns about the relationship between dot size and the resolution of the anilox rollers (White, 1999). It is claimed that FM screening achieves a finer screen with flexographic printing, which leads to higher quality products (White, 1999).

Comparison of AM vs. FM Screening

Moiré. As dots in AM screening were generated along grid lines, the grid of each color must lie on a different screen angle when printing multicolor jobs. If the screen angles are not set properly, a moiré effect will appear when adding more colors. Whereas, FM screening was not designed to set dots at different angles and so, the moiré effect will be eliminated. Poorly registered FM screening will not affect color shifts as does AM screening (Romano, 1995). According to Steve Kendrick, press manager of Colour Innovations of Toronto, moiré is an issue with AM screening but should not be a problem if printers set the screen angles correctly (Bury, 2005).

Color gamut, resolution and details. Not only is FM screening able to eliminate unwanted patterns such as moiré, it also produces a larger color gamut for offset printing.

This larger gamut for offset printing is achieved because of the un-sharp dots and the lower density of very fine dots. Therefore, flexographic printing, which cannot print such small dots, will not show this benefit. FM screening not only increases color gamut in offset printing, but it also reduces the need for spot color usage (Hamilton, 2004).

Moreover, FM screening can produce higher resolution images, finer detail, brighter, and more saturated colors and is also more stable on an offset press. In other words, FM screening produces more consistent colors (Bury, 2005). Since FM screening extends tone value range and produces full tonal range, images appear more dimensional than in AM screening (American Press, LLC., 2002). However, printed images are darker in FM screening due to higher dot gain than in AM screening (Bury, 2004 & McDougall, 1994). An increase in dot gain causes the reduction of shadow details by 20 percent in print contrast (GATF, 2003). This, however, can be compensated by using a transfer curve in the RIP process.

In addition, FM screening produces graininess in the middle tones of printed images. This grainy effect also depends on dot placement calculations, the algorithms specific to the software. Therefore, to use FM screening to its full potential, printers should fingerprint their presses and build compensation curves. These compensation curves can then be used to decrease dot gain. Although printing processes work well through the use of FM screening, to do minor adjustments on press is not as easily done as with AM screening (Campbell, 2003). The difficulty of on press adjustments with FM screening is the result of the tiny dots that cannot accept and transfer more ink from the inking unit. Again, this was observed in offset printing.

Ink consumption. According to PIA/GATF research in 2004, FM screening consumes less ink than AM screening, particularly on offset presses, because FM screening gives a thinner ink film thickness. However, Jeff Taylor of Hamlock states that they run more ink to get greater color intensity. In agreement with Taylor, Al Kelly of Quebecor says that they use more ink with FM screening for some high quality projects (Bury, 2004). However, because the dot diameter of FM screening was smaller, leading ink to lay more evenly on printed images, the inking fluctuation with FM screening is less than with AM screening (Campbell, 2003).

Miscellaneous. Using FM screening with a four-color process and two special colors claims to deliver any proprietary color within the Pantone standard range. This technology is called FMsix (“My Cartons”, 2002). Contrary to FMsix color processing, the Pantone Matching System (PMS) produces colors based on conventional screening, therefore sometimes PMS colors do not match with FM screening colors (Bury, 2005).

Another disadvantage of FM screening is that microdots of FM screening affect the longevity of the offset plate’s life. In FM screening, the print run per plate is shorter than that of AM screening (Campbell, 2003 & Bury, 2004). Dots in FM screening are very small and require a precise plate production; mis-registration and dust can damage its capability to produce the fine dots required in film-based workflow (Campbell, 2003).

There are other differences between AM and FM screenings that should be mentioned. For example, ink-balance in lithography is easier to achieve and maintain with FM screening (Romano, 1995) and digital proofers are not able to generate FM screening dots (McDougall, 1994). The gray scales for both AM and FM screening are

similar (Romano, 1995), however, FM screening can make printing on textured substrates more effective because it does not form halftones on a grid (McDougall, 1994).

Flexography

Flexography, or flexo, is a relief printing process, which is similar to the letterpress process. In other words, flexographic plates have two levels. The higher level is the image area, while the lower level, called the floor, is the non-image area. It is a direct printing process; thus the image on the plate is wrong reading. Generally, flexo plates are made from flexible materials such as rubber and polymer (FFTA, 1991). Inking units of the flexographic presses are less complicated than those of the lithographic presses (Hardesty, 2002).

A printing unit in flexographic presses typically consists of a rubber-fountain or metering roller, anilox roller, doctor blade, plate cylinder, and impression cylinder. Inks in flexography are low-viscosity and can be water-based, solvent-based, or UV. Plates can be made by etching rubber or polymer, while higher quality plates can be done with computer-to-plate or CTFlex technology (FFTA, 1999).

Blends, Vignettes, Gradients

Blends, vignettes, and gradients refer to a gradual change from a higher percentage to a lower percentage of density or from one color to another color in printing. Gradients may show unpleasant banding, or steps, especially in flexographic printing due

to gear streaks. Good planning during the design stage can minimize this problem. There are several points to consider when dealing with blends, vignettes, and gradients:

- The longer the blends, the more invisible the unpleasant banding at a certain range of different percentages across the blends.
- The shorter the range of different percentages across its length, the higher the unpleasant banding.
- The darker the color used, the more visible the banding.
- The higher the screen ruling, the more banding effect (FTA, 2003).

Glossary

Amplitude modulated (AM) screening is a conventional screening technique, which produces print images by varying the dot size with fixed spaces between the dots.

Blends, vignettes, gradients refer to a gradual change from a higher percentage to a lower percentage of dot areas/density or from one color to another color.

Continuous tones refer to a method of representing tonal values by varying silver or dye amounts found in photographs, drawings, and paintings.

Frequency modulated (FM) screening or stochastic screening is a screening technique that produces different tones by varying dot spaces, or dot frequency, with fixed dot size.

Halftone images allow images to be printed by converting continuous tone images into a tiny dot pattern that can be reproduced on printing presses.

Moiré is the interference pattern between two frequencies, for example, the screen ruling of AM screening printed at different angles.

Rosettes are a form of a moiré, which occurs at a screen angle of 30 degrees.

Chapter 3

A Review of Literature in the Field

Introduction

Many flexible packages that are purchased come with some type of packaging printed by the flexographic process. Flexography has the opportunity to grow in the packaging industry over other printing processes because of its advantages in production versatility; lower plate costs than gravure printing, lower waste in make-ready and more consistency across product types (Mix & Bonawandt, 2005). Packaging is an advertising media that not only carries the product, but also provides self-promotion and offers an opportunity for brand recognition. To make products more attractive to customers, a higher quality of packaging is critical. Therefore, increasing resolution and print quality are methods used to improve print products. Screening technologies play a role in improving print quality and decreasing production costs. To produce dot patterns, there are four primary variables in screening technologies: dot size, dot frequency, dot shape, and dot formation (Polischuk, 2004). A description of these variables can be found in the glossary at the end of this chapter. These variables are utilized to develop new screening technologies, or hybrid screening, which have been introduced into the current market.

To understand the manner in which these variables are used by screening technology vendors, they are discussed within this literature review.

Hybrid Screening

Hybrid screening, or transitional screening, offers the advantages of both AM and FM screening technologies. Typically, it is a combination of AM and FM screening that produces the best output. Claims were made by many screening technology vendors that the idea of this screening technique grants a better dot gain curve (White, 1999). It also improves print production by giving better detail in fine lines and produces smoother shades. Moreover, it allows printing operators to adjust ink levels on offset printing presses as done with AM screening (Campbell, 2003).

This new screening technology provides printers with a better approach to achieve greater print quality with less effort (“Hybrid screening”, 2002). In addition, the reasons to use hybrid screening are to achieve rich details in the highlight and shadow areas and to decrease graininess in the midtones (Campbell, 2003). It is also developed to avoid highlight breaks in flexographic printing (Artwork Systems Group, 2004). Vendors claim that hybrid screening helps package printers to run solids, lineworks and halftone images on the same plate (Hamilton, 2004). An accuracy benchmark of printing presses is the first requirement in achieving optimum dot size when printing with hybrid screening (“Screen suppliers”, 2003).

Since flexographic printing requires bump curves to compensate for dot deformation in highlight areas and cutback curves to compensate for dot gain in midtone and shadow areas, hybrid screening will be the way to improve print quality for full tone reproduction by using standard-level equipment. Thus, hybrid screening will save the print shops time and money (Struchil, 2004). Simply combining AM and FM screening will create a problem, which is a visible transition point from one screening to another. Thus, the following vendors have developed and offered their own hybrid screening products.

Agfa Corporation: :Sublima

:Sublima is claimed to be hybrid screening that combines the strengths of AM and FM screening. This combination was called XM or Cross Modulated screening. FM screening generates better detail in the highlight and shadow areas, whereas AM screening generates smoother midtones. :Sublima is designed to utilize the smallest dot size that each particular press can handle safely. When :Sublima reaches the smallest reliably printable dot size, the dot size will not become any smaller, instead, dots are randomly removed to generate a lower density percentage. However, the dots are still aligned along the normal screen angles. Higher dot areas than this smallest dot size are regular AM halftone dots. This is shown in Figure 1 (Agfa Corporation, 2005).

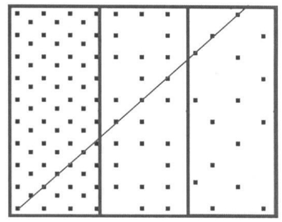

Figure 1. :Sublima: Agfa Corporation

The transition point at which the screening switches from AM to FM and FM to AM screening is frequency dependent and predetermined. With this technology, although it still uses rosette pattern dots, the pattern is claimed to be unnoticeable to the naked eye because the :Sublima hybrid screening can achieve higher resolution. The higher resolution is achieved because the resolution has less limitation from irreproducible dots in the highlight areas. In addition, use of this screening technology relies on the particular printing conditions the press can handle; it will not change any printing conditions, especially those of anilox rollers. Also, using :Sublima technology does not require extra work for prepress operation (Agfa Corporation, 2005). Terry Copeland of The Midas Press, Hampshire, England, states that they use :Sublima effectively for certain jobs in their offset printing plant. Mauric Grainger of Alpine Press, Hertfordshire, England, agrees with Copeland that the results are so good that they use :Sublima specifically to add value for their special jobs in their offset companies ("Campaign", 2005). However, since :Sublima is different from AM screening only in the highlight areas, and offset printing has no problem printing small dots, :Sublima offers no advantage for offset. It can offer a big advantage for flexographic printing.

In traditional flexographic applications, the screening resolution depends on the resolution of the anilox rollers. Typically, a ratio of 1:4 is acceptable to prevent the dot dipping effect that will result in losing highlight dots. In other words, the anilox rolls should have four times higher resolution than the resolution of the plates. Substrates, inks, and complete press characteristics are also considered when selecting screening frequency. With :Sublima, using "minimum dot" strategy will not only give higher detail quality in the highlight and shadow areas, but also prevent the dot dipping effect. As an accomplishment, :Sublima won the "2004 Technological Innovator of the Year" award at the 7th Flexographic PrePress Platemakers Association (FFTA) conference (Agfa Corporation, 2005).

Esko-Graphics: Sambaflex / Groovy Screens / FlexRip

SambaFlex is designed by combining AM and FM screenings. It takes advantage of AM screening's lower dot gain and cleaner image aspect through AM grid alignment as well as FM screening's lack of dot percent limitation and optimum dot size, which can be adjusted to each individual printing process. Moreover, Esko-Graphics claims that integrating FM screening into SambaFlex produces better print quality in flexography. SambaFlex technology allows the user to customize seven transition points for each resolution. When screening reaches transition points, dots will be moved away from the screen angles to avoid artifacts (Figure 2). This technology was designed especially for flexography and silk-screen printing (Esko-Graphics, 2003).

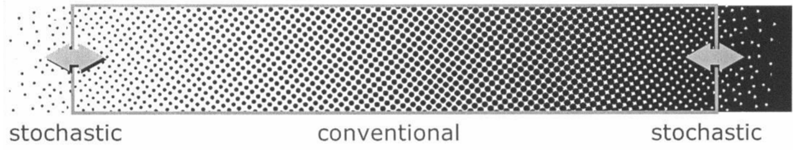

Figure 2. SambaFlex: Esko-Graphics

Groovy Screens is a combination of circular dot shapes and line (groovy) patterns used in the same job to optimize print quality on each individual object (Figure 3). It claims to gain a higher density in the shadow areas and solid areas with less ink. However, it still keeps the same highlight and midtone areas as in AM screening. The ideal transition point to activate Groovy Screens is controlled by IntelliCurve. The benefits of this screening technology are a smoother transition from circular dots to Groovy Screens and more saturated colors due to better ink distribution. Esko-Graphics claimes that Groovy Screens uses less ink to produce the same density, leading to better quality (Esko-Graphics, 2003).

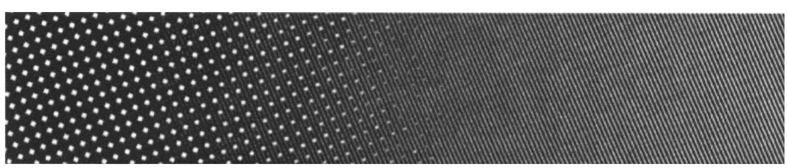

Figure 3. Groovy Screens: Esko-Graphics

FlexRip is a RIP software used for combining multiple screening types for specific purposes (Figure 4). It produces clear centered rosettes, which are less visible in the midtone areas. FlexRip also allows combining up to sixteen different screenings, which can be ripped per separation (Esko-Graphics, 2003).

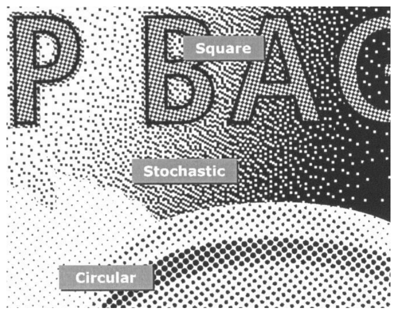

Figure 4. FlexRip: Esko-Graphics

Creo Inc.: Maxtone and HyperFlex

Creo Inc. has developed its own solution to conquer limitations in flexographic printing. *Maxtone* is a hybrid screening technology that uses FM screening to enhance details in the highlight areas and uses AM screening for the other areas. It allows prepress operators to define transitional points corresponding to flexographic platemaking and particular printing conditions. This technology reduces the tone break effect in flexographic printing, which usually occurs in blends and vignettes. Maxtone also saves time in prepress because it does not require applying bump curves during the platemaking process. The

benefits of using Maxtone are better image details, smoother gradients, better solid ink coverage, and more flexibility in managing the digital workflow (Figure 5).

HyperFlex is a plate resolution enhancement technology, which is used to improve the quality of screening. It uses UV light filter technology to extend the imaging capability of the flexographic plate. HyperFlex raises the floor of the flexographic plates, which helps make the microdots strong enough to withstand the print process (Figure 5). The ability to produce tiny dot sizes with support dots by using HyperFlex makes flexographic plates more effective and allows highlights to be produced more efficiently. Therefore, using Maxtone and HyperFlex will not only improve quality in flexographic printing, but also increase prepress speed, predictability and consistency (Creo, Inc., 2005).

Figure 5. Maxtone and HyperFlex: Creo Inc.

Phototype: NuDot™

NuDot™ screening technology was designed specifically for printing on film in the flexographic process by combining three different dot shapes. The standard round

dots are used in the first few screen percentages of tone reproduction. In the highlight area, this screening technology uses exactly the same round dots as in AM screening. It also uses a dot shore line that resembles a cross with arrowheads on the end of each arm after the first few percentages through the midtones. NuDot™ screening is said to improve ink transfer and produce diamond sharp dots to diminish the donut dot effect. In the shadow areas, it uses a honeycomb dot structure. Ink clumps and spreads are used to form a uniform solid, as ink is transferred to the substrate surface. Therefore, solids are smoother and more saturated than solids in AM screening. This can be seen in Figure 6 (Phototype, 2002).

According to Chris Deye, the marketing director at Phototype, ink deposits more uniformly, dot gain is more consistent and makeready is faster when using this technology (Polischunk, 2004). Density is leveled up to twenty-five percent, while harder highlight dots have less dot gain. NuDot™ also extends tonal range and benefits both the cost and quality advantages for flexography. Additionally, Nudot™ does not require changing the existing workflow.

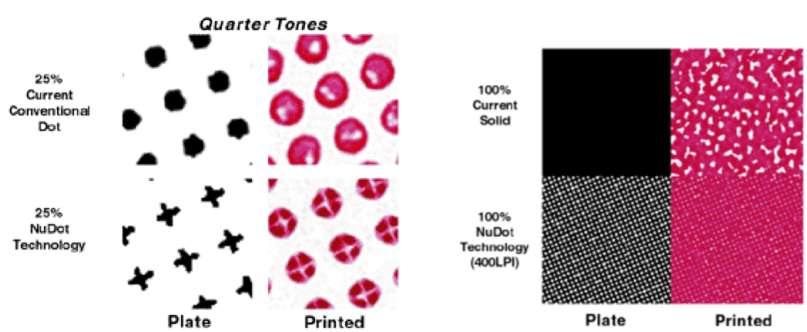

Figure 6. NuDot™: Phototype

Artwork Systems Group: Classic^{TM} and Quantum^{TM} Hybrid Screening, Concentric^{TM} Screening

Artwork Systems Group offers two types of hybrid screening, which are *Classic^{TM} hybrid screening* and *Quantum^{TM} hybrid screening* (Figure 7). Classic^{TM} hybrid screening is a simple combination of AM and FM screenings. The transition point can be determined freely by the users; however, the transition point from one screen to another screen will occur over a range of gray levels in such a way that is unnoticeable to the observers.

Another hybrid screening from Artwork Systems Group was Quantum^{TM} hybrid screening. It is the second generation of hybrid screening in this product line. It was designed to reduce the graininess of print images, which is an effect of using FM screening even when used only in highlight areas. Thus, Quantum^{TM} hybrid screening is designed to use dots in AM screening to generate images. When the dot size reaches the smallest size that the press can handle, the size of the dots is maintained. Then, the highlight area uses that dot size to produce highlight dots. Quantum^{TM} hybrid screening produces highlight tone by removing dots randomly, but it still keeps dots aligned on screen angles. The transition point can also be defined freely by the user (Artwork Systems Group, 2005). Mark Samworth of Artwork Systems Group also states that Quantum^{TM} hybrid screening lowers the volume of anilox rollers, or finer resolution, about ten to forty percent due to the larger highlight dots leading to less consideration to

prevent dot dipping effect. Also, the Quantum™ hybrid screening can lower ink consumption (Hamilton, 2005).

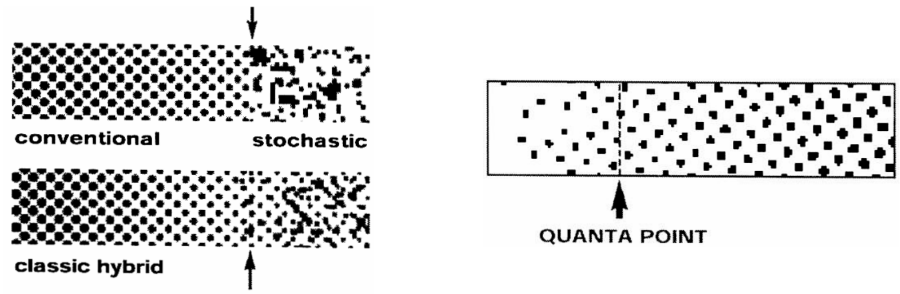

Figure 7. Classic™ and Quantum™ Hybrid Screening: Artwork Systems Group

Artwork Systems Group launched a new screening technology, *Concentric™ screening*, at their Print 05 exhibit in Chicago, Illinois. Concentric™ screening is an alternative screening technology. To generate Concentric™ screening, AM screening dots are divided into thin concentric rings with certain ring width and space width (Figure 8). A concentric ring is said to offer the benefits of both AM and FM screening. A benefit of AM screening is smoother midtones, while the tiny dots of FM screening limit the ink film thickness on offset plates, resulting in greater details. Thus, in combining the advantages of both screening methods, Concentric™ screening is a combination of effectively using tiny dots from FM screening to control ink film thickness and the uniform distribution of AM screening for smoother midtones. Also, it enables dots to be aligned uniformly, which is similar to AM screening, but controls dot size in a way similar to FM screening.

It is claimed that Concentric™ screening provides greater press latitude than either AM or FM screening, and also allows the dots to gain in size inside the concentric rings. Thus, printers can print with higher AM line screens and produce better quality, particularly in offset printing. Artwork Systems Group claims that many printers can double their screen ruling by using Concentric Screening. Printers can double screen rulings without facing mottle, dot gain and other problems associated with high screen rulings (Artwork Systems Group, 2005).

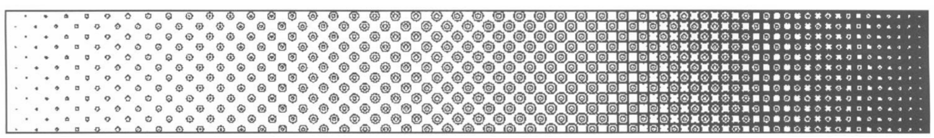

Figure 8. Concentric™ Screening: Artwork Systems Group

Trends in Flexographic Printing

Printers want to serve the best quality that their environment can deliver (American Printer, September 2002). Flexography is cost-effective and has considerably improved since computer-to-plate and other related technologies have become available and/or affordable for flexographic printers to use. As a result, flexography market shares started to increase due to its penetration into markets dominated by other printing processes, such as lithography and especially gravure (Birkenshaw, 1999). From recent studies, 75 percent of the business volume in the US packaging industry is represented by the flexographic printing process. It is obvious that flexography has become a major

printing process of the packaging industry, from rigid to flexible packaging, with 20,000 new food products produced each year (Lowden, 2004). In addition, according to the growth of packaging and label printing, improving print quality is the way to add value to printed products. Since packaging provides self-promotion and advertisement, demand for higher quality packages at the lowest possible price makes flexographic printing more competitive than other printing processes (Mix, 2005). The demand for process improvements in packaging applications continues to grow. Mechanical systems and capabilities will improve the flexographic process to achieve lower plate costs, faster press speeds and quicker changeovers (Alexandria, 2003).

Due to the flexibility of the printing plate, flexographic printing has difficulties in producing highlight dots. This leads researchers to pursue and develop new screening technologies to solve this critical problem. According to the development of electronic pre-media and CTP, screening technology has been developed to take advantage of these developments (Redman, 2004). Thus, screening technologies have been developing in packaging printing to gain better results, more stable processes, and reduced operating costs (Hamilton, 2004). This developing trend is also supported and stated at the FPPA 7th annual convention in 2004. In summary, the next generation of flexographic screening technology will increase the ability of output resolution without additional cost (FPPA 7th annual convention, 2004).

Glossary

Dot formation is a term that refers to the quality of halftone dots such as dot sharpness or softness, edge smoothness, and uniformity of the density across dots, as influenced by different techniques of output devices.

Dot frequency refers to the distances between dots. AM screening uses a constant screen ruling (frequency) to position the dots. Whereas, FM screening uses different spaces between dots to vary tones, therefore, dot frequency of FM screening is changed as tone value changes.

Dot shape refers to the various shapes of dots used to produce AM halftones. The dots can for example be circular, elliptical, or square. Some screening vendors combine multiple dot shapes to generate new screening technologies. Dot shapes can influence second order problem such as midtones jump and dot gain sensitivity to inking changes. Midtone jump happens when dots touch each other in the corner, resulting in an obvious dot gain jump. Also, different dot shapes have different perimeters. The more dot perimeters, the more possible dot gain.

Dot size refers to the size of the halftone dots. For AM screening, dot size varies to produce different tone values. The distance between the dots remains constant. For FM screening, the dots have a constant size, while the distance (frequency) is changed between them to obtain the different tone values.

Chapter 4

Research Statement

For three types of screening technologies—AM, FM, and hybrid screening—the following questions were investigated;

1. How much does tone reproduction change when pressure changed?
2. When printing a gradient, does its length make a difference in the visibility of poor highlight rendition?
3. Does the surrounding of a gradient make a difference? A solid area close to the highlight areas might absorb printing pressure and thereby shield the highlight dots from excessive pressure.

Chapter 5

Methodology

Introduction

The first research objective was to determine which of the following three screening technologies could produce smoother gradients—AM (or conventional) screening, FM screening, and hybrid screening. A gradient matrix was established with three variables, which were screening technologies, gradient lengths, and the surrounding. In addition, visual evaluation targets were created similar to the gradient matrix. The visual evaluation data was compared with the measured data to see if the observers noticed the differences observed in the measured data. If the observers did notice a difference, did it matter to them?

Limitations

This research was limited by time constraints and financial factors. It focused on three specific variables under particular printing conditions, which were Kohl & Madden UV ink and Exxon Mobil Oriented polypropylene. For different printing conditions, the results might be different.

To study the characteristic of each screening without having other variables interfere with its tone reproduction, each screening was linearly generated and compared. In other words, there was no transfer curve applied to any screening techniques.

Lastly, the analysis of the gradient smoothness and the impact of the surrounding were analyzed by using printed samples at kiss impression setting. Therefore, the data for the other pressure settings would need more measurements.

Part 1. File Preparation and Plate Specification

Test targets used in each of the following sections were imposed on a 14.75" x 19.5" page using Adobe InDesign CS2. The file was converted to EPS and sent to Vertis Incorporation, Texas, to generate all three screening technologies and to make the plates. The plates were made by using computer-to-plate processing.

Plate specifications

- Plate thickness: 0.067"
- Backing thickness: 0.020"
- Plates: Digitally Imaged Photopolymer Plates
- No curves apply to any screening techniques
- Addressability of the output: 2,540 spots per inch
- The CtP system makes plates by ablating a black carbon coating in the image areas. A photopolymer plate is light sensitive. An exposure through the ablated coating crosslinks the photopolymer in the image areas. The non-image areas are washed out to make a three-dimension relief image.

Part 2. Plate Evaluation

There were two plates used in the experiment; an ablated plate and a finished plate, both using the same test form. The ablated plate intermediate, not washed out, was used to obtain dot area measurements before the wash-out process. Every step of the step wedge targets on both plates was captured as an image by using BetaFlex 334 Flexo Analyzer and Flexo Eye Software. The percent dot areas of the images were then measured by using the Image Pro system. Dot areas on the finished plate could not be measured because no reliable measurement method was available; image contrast on the finished plate was so low that the dot area measurement was not reliable. Therefore, to get a measurement of dot area on the finished plate, it had to be first printed at kiss

impression, and then the dot areas were measured on the prints. Data from the ablated plate is shown in Appendix B.

Part 3. Test Target

The Mark Andy LP 3000 flexographic printing press at RIT was used in this experiment. The first requirement for generating FM and hybrid screening is to establish the minimum dot size that the Mark Andy LP 3000 can handle for this particular printing condition. Since this study was limited to one press run maximum, dot size capability was determined from previous experiments. Dot sizes of 25, 30, and 35 micron were selected for this test.

Because flexible plates are used, pressure settings are critical. Pressure is defined as the amount of force per unit area. Therefore, the lower the area, or the lower the number of dots, the higher the pressure; the likelihood that highlight dots will be squeezed is higher when pressure is applied. One of the research questions in this study was to observe whether the surrounding affects dots in the highlight areas. A method of answering this question was simply to create solid frames around the gradients; this disperses the pressure from the gradient dots and places it on the surrounding. The gradients were then observed to see the differences due to the surrounding.

Three pressure settings were used in the experiment, kiss impression (or the lightest pressure), moderate pressure, and high pressure, to show the sensitivity of each screening technique at different pressure settings. Part 4 documents how the pressures were set.

The test form consisted of the following items:

1. Solid and 75 percent tint patch targets: These targets were used to determine ink densities.
2. Doubling targets: These targets were used to indicate possible gear streaks and to observe the resolution of the output.
3. Visual evaluation targets: Artistically typographic images, in the shape of the letter "I", were created to correspond with the gradient matrix. Few lengths were used; 0.25" 0.5", 1", 2". These visual evaluation targets were limited to four different gradient lengths due to the limitation of the printing area.
4. Surrounding evaluation targets: Gradients with and without the surrounding (solid frames) were used to study the impact of the surrounding to the gradients.
5. Step wedges: These targets were used to determine full tone reproduction of all screening types utilized.
6. Gradient matrix targets: There were three variables, dot sizes, gradient lengths, and screening methods that were used to create the gradient matrix targets.
   - Screening methods: AM screening 150 lpi, 25-micron FM screening, 30-micron FM screening, 35-micron FM screening, 25-micron hybrid screening, 30-micron hybrid screening, and 35-micron hybrid screening
   - Gradient lengths: 0.25", 0.5", 1", 2", 3", 4"
   - The gradients cover a dot area range from 0–30 percent

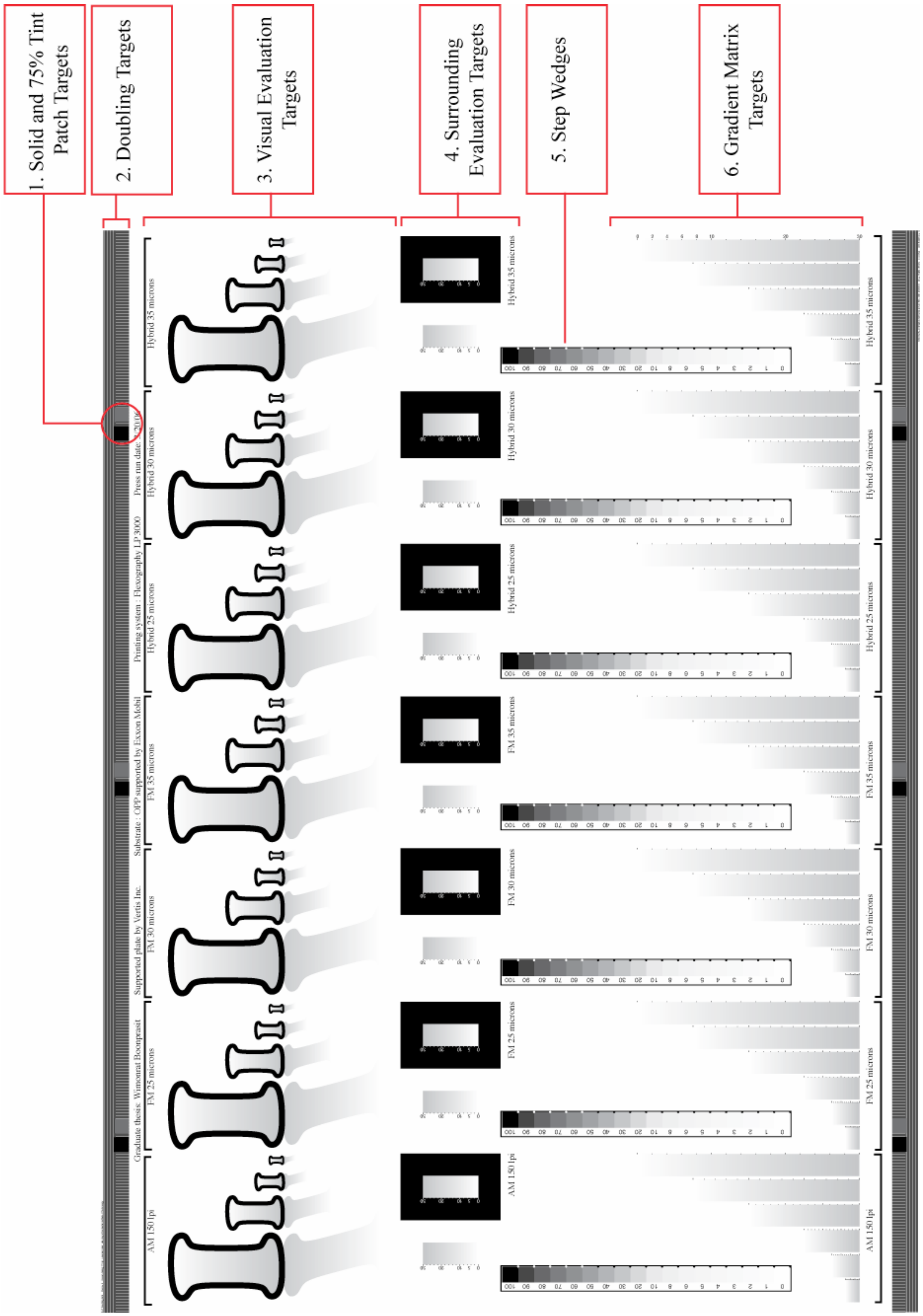

Figure 9. Test Targets

Part 4. Press Run

The finished plate was mounted on the fourth unit of the press. The press was run with Pharmaflex Process black ink from Kohl & Madden on Exxon Mobil 150LL302 Oriented Polypropylene (OPP), width 15". The OPP was chosen for this study as a representative of substrate used widely in the flexible packaging industry.

The press run setting was standardized as follows:

- Speed: 150 feet per minute
- Sticky backing of the plate: 3M 1120
- Anilox roll: 900 / 2.15 Harper 1022780
- Environment control: 70° F ± 2° F / RH 50%± 5%
- UV light level: Intensity level 3 at 150 feet per minute
- Target density of black ink: 1.30 ± 0.07 at kiss impression, 1.40 ± 0.07 at moderate pressure setting, and 1.50 ± 0.07 at high pressure setting.

The target densities at each pressure setting were adjusted to apply pressure evenly on both an operator side and a gear side by measuring densities of both solid and 75 percent tint patches. Even though densities of solid patches of both sides are in the tolerance, 75 percent tint patch, which is more sensitive to the pressure than solid patch, may differ more than ± 0.07. Therefore, to set the pressure evenly on both sides, the densities of both tint patches need to be within 0.07 density units of one another. After the desired pressure settings were reached, ten samples were pulled.

Part 5. Data Analysis

Two methods were used for data analysis, measurement based evaluation and visual evaluation.

Measurement

First, the samples were measured to define the smallest producible dot size under the defined printing conditions by measuring the size of the dots and comparing them with the data from Part 1. The gradients were measured by using the Gretag SpectroScan Spectrophotometer with 0.5 millimeter step increments. Since the normal aperture of the SpectroScan is a three-millimeter circular shape, the measurements would overlap a lot. Therefore, to reduce aperture size, the aperture was covered with black tape, which had a 0.7 millimeter slit cut into it. Each gradient was measured in 0.5 millimeter increments across its length. Then, the data from the measurements were placed in an Excel sheet in order to do mathematical analysis.

Since the ideal tone reproduction of the highlight areas is expected to be nearly linear, a straight line from zero to thirty percent was used as reference for the highlight tone reproduction. The measured data was compared with this reference. The difference is taken as a measure of the gradient smoothness; the further away from the reference, the less smooth the gradients. Then, the smoothness data of all three screening technologies was compared.

For the surrounding variable, the surrounding targets were measured with the same methodology of gradient smoothness. The measured data from the targets with and without the surrounding were then compared to see the difference and indicate if the surrounding could affect the highlight dots.

Visual Evaluation

The four gradient lengths in the shape of an artistic letter "I" were evaluated visually. This evaluation was done through a paired comparison method. Thirty observers were used because this sample size gives a reasonable approximation to the statistical normal distribution curve. The thirty observers for this study were students from the College of Imaging Arts and Sciences. These observers have some training in evaluating printed images. The observers were asked to choose the smoother gradient from a pair of presented samples and to complete the survey form (Appendix A). To control other variables that may affect the observation, the observers were asked to do the observation at a viewing booth under a D50 light source with a viewing distance of twelve inches. Also, the observed samples were framed with neutral gray paper to decrease interferences that may impact the observation.

Before combining all data into the Excel sheet, inconsistent data was eliminated. The inconsistent data was data that did not have a logical relationship. For example, if an observer said "A" is better than "B"; "B" is better than "C"; and then "C" is better than "A", then this relationship is not logical since if "A" is better than "B", and "B" is better

than “C”, then, “C” cannot be better than “A”. Such inconsistently logical relationships were eliminated before counting data frequencies. The data was then counted to define frequencies of the three screening techniques. The absolute frequencies were then calculated to determine fractional frequencies, which in turn were converted to z-scores. All z-scores of each screening technique, that was chosen as it produced smoother gradients over the other two screening techniques, were averaged. The average z-score of each screening technique was analyzed further by calculating the observed standard deviation. To see whether the differences of three screening techniques were statistically significant, the data were calculated by using Monte Carlo simulation (Montag, 2004).

Equation 1: $$\sigma_{observed} = 1.76(n-(-3.08))^{(-0.613)} * (N-2.55)^{(-0.491)}$$ (Montag, 2004)

$\sigma_{observed}$ represented the observed standard deviation that would be calculated from the above equation. “n” was replaced with the total number of the samples that were used in the visual evaluation. Since this study was trying to compare three screening techniques and there were three samples used in the visual evaluation, “n” was replaced with three. Also, “N” referred to the number of valid observers. The maximum number of “N” in this study was 30 according to the total number of the observers. However, since there were some logical inconsistencies in the observers’ choices, the valid numbers of the observers varied.

Equation 2: $95\%\ confidence\ interval = Scale\ value \pm 1.96\ \sigma_{observed}$ (Montag, 2004)

To calculate 95 percent confidence interval, the average z-score is used as a scale value. The value of error bars refers to an interval of the calculated $\sigma_{observed}$ multiplied by 1.96 (Equation 2).

After the average z-scores and the error bars were calculated, both of these numbers were used to plot a column chart to analyze and define whether or not the differences were statistically significant. If the error bars of any pair of screening techniques overlapped, the difference of that pair was statistically insignificant. Ultimately, the results were also compared with the measured data.

Chapter 6

The Results

This study was designed to verify if hybrid screening technologies can achieve better gradient results than other screening technologies (conventional screening and FM screening) with the flexographic process, when using oriented polypropylene substrate and UV inks. Since each screening technique may react differently with different pressure settings, the three pressure settings for the press run—kiss impression, moderate pressure, and high pressure—were evaluated.

The printed samples showed that the highlight dots at 25-micron and 30-micron in both FM screening and hybrid screening were not reproducible below three percent dot area at the kiss impression setting, while the dots at 35-micron of both FM and hybrid screening were reproducible below three percent dot area. Therefore, only 35-micron dot sizes were compared and analyzed further with AM screening at the kiss impression setting in this study (Appendix C).

Tone Reproduction at Three Different Pressure Settings

Pressure setting is critical in the flexographic process. Ideally, images should be printed with the lightest pressure, or kiss impression. However, if pressure is set too low, some details in the highlight areas might not be transferred onto the substrate. On the other hand, if pressure is set too high, dots would be squeezed more resulting in higher dot gain. Therefore, setting the correct pressure is a compromise, which depends on operators' experience. The increased pressure can shift the entire tone reproduction curve, which may also affect the gradient smoothness. The impact of pressure on the tone reproduction of each screening technique can be seen in Figures 10–13. The tone reproduction of the printed samples was determined by measuring the density of step wedges with the X-Rite 530 densitometer.

Figure 10 shows the tone reproduction curves of each screening at three pressure settings. Percent PostScript dot area (Glossary), or percent dot area of the input digital file, was plotted against percent Murry Davies dot area (Glossary), showing a tone reproduction curve. According to Figure 10, tone reproduction above 10 percent dot area of FM screening was affected much more than either AM or hybrid screening. Whereas, tone reproduction below 10 percent dot area of FM and hybrid screening showed a similar sensitivity, which was less than the sensitivity of AM screening. Tone reproduction above 10 percent dot area of AM and hybrid screening showed an identical sensitivity.

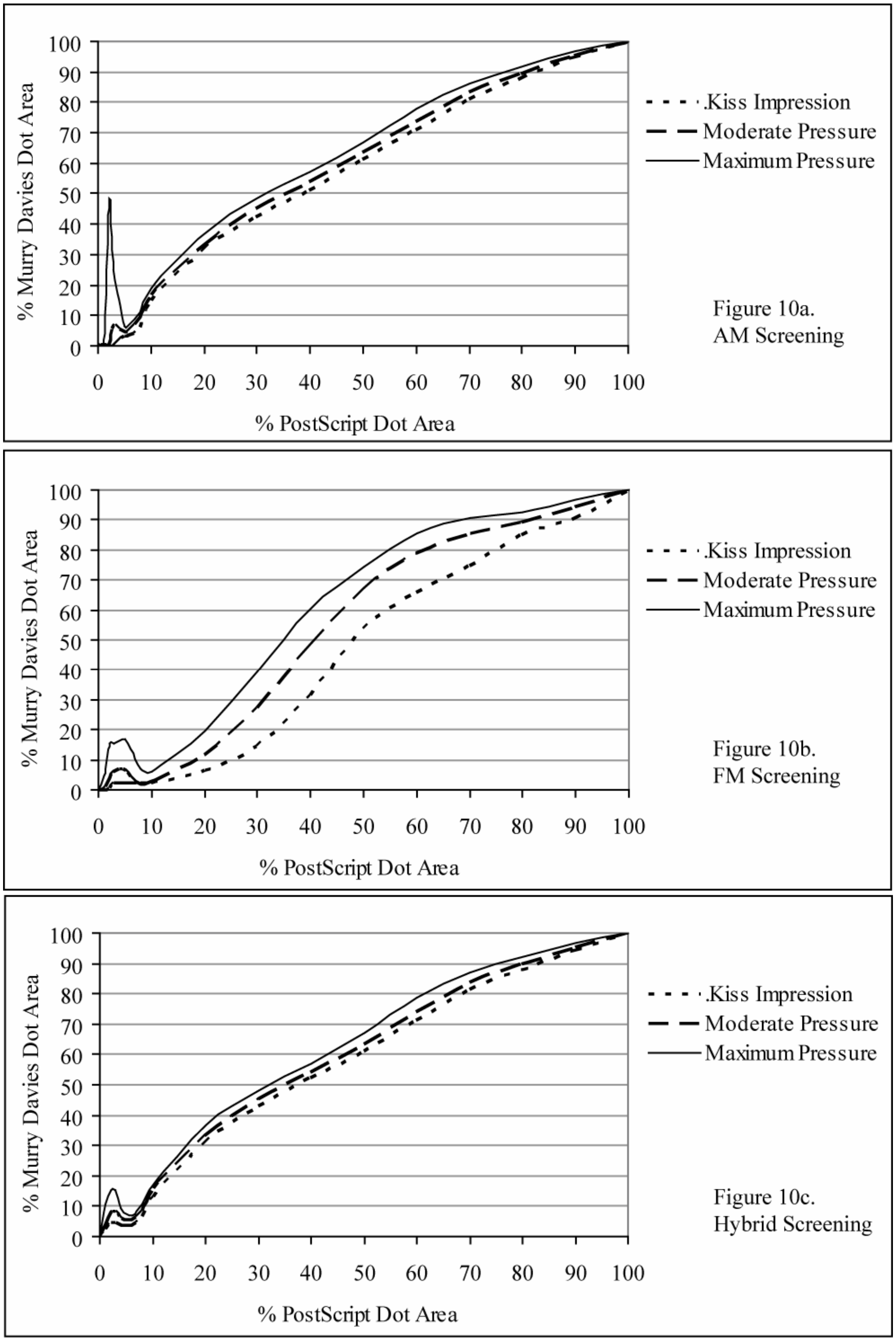

Figure 10. The Effect of the Pressure on the Tone Reproduction of AM Screening, 35-micron FM Screening, and 35-micron Hybrid Screening

The comparison of the tone reproduction as shown in Figure 10, used linear data; there was no transfer curve applied to any screening technique. Therefore, tone reproduction is different and the curves cannot be compared directly. To analyze the data regardless of the differences in tone reproduction, the higher pressure setting was plotted relative to the tone reproduction at kiss impression (Figure 11).

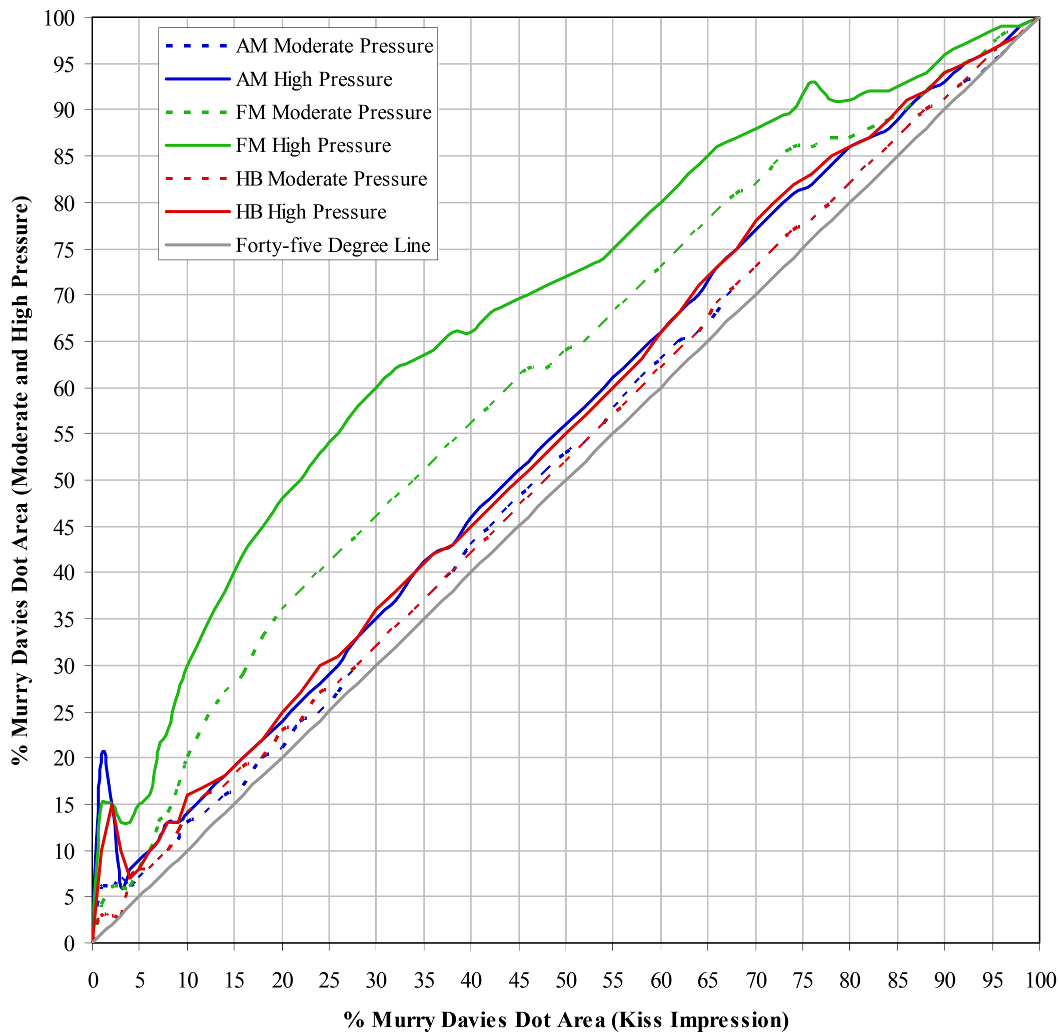

Figure 11. Tone Reproduction as a Function of Changes of Pressure

Figure 11 shows the change of the tone reproduction of three screening techniques when pressure is changed. The forty-five-degree line indicates tone reproduction of the samples when there is no change due to the higher pressure relative to the kiss impression. In Figure 12, the same data was plotted as the one from Figure 11, but this time the forty-five degree line became the x-axis.

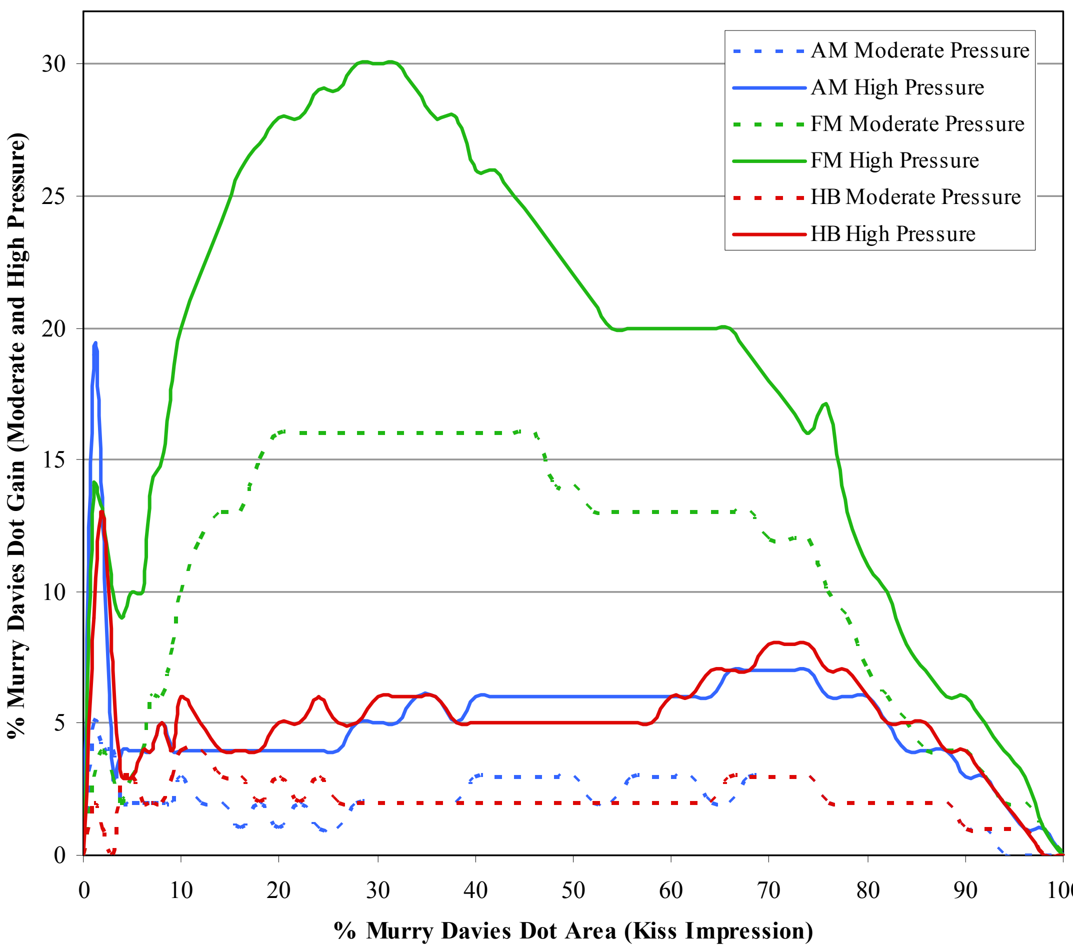

Figure 12. Comparison of Percent Murry Davies Dot Gain between Kiss Impression and Higher Pressure for All Three Screening Techniques

Figure 12 shows the differences of the tone reproduction change due to the change of higher pressure based on the tone reproduction at kiss impression. The higher the curves, the greater the change of the tone reproduction. FM screening shows larger differences as higher pressure is applied. Even though a transfer curve can compensate the higher tone reproductions of FM screening, the curve only corrects for one pressure setting. If pressures vary, the tone reproduction of FM screening is also varied.

In addition, even though AM and hybrid screening show similar curves above 10 percent dot area, AM screening shows a higher spike below 5 percent dot area. To make the differences in the highlight area between AM and hybrid screening more visible, Figure 13 shows the data without FM screening and an expanded scale of x-axis.

According to Figure 13, hybrid screening showed less sensitivity to pressure changes than AM screening especially below 4 percent dot area. For instance, at moderate pressure and at one percent dot area at kiss impression, AM screening shows more than twice the dot gain of hybrid screening. The higher sensitivity of AM screening in the highlight areas was even more obvious at high pressure. The spike in AM screening in Figure 13 may not show as high as in Figure 10 because of differences in interpolation.

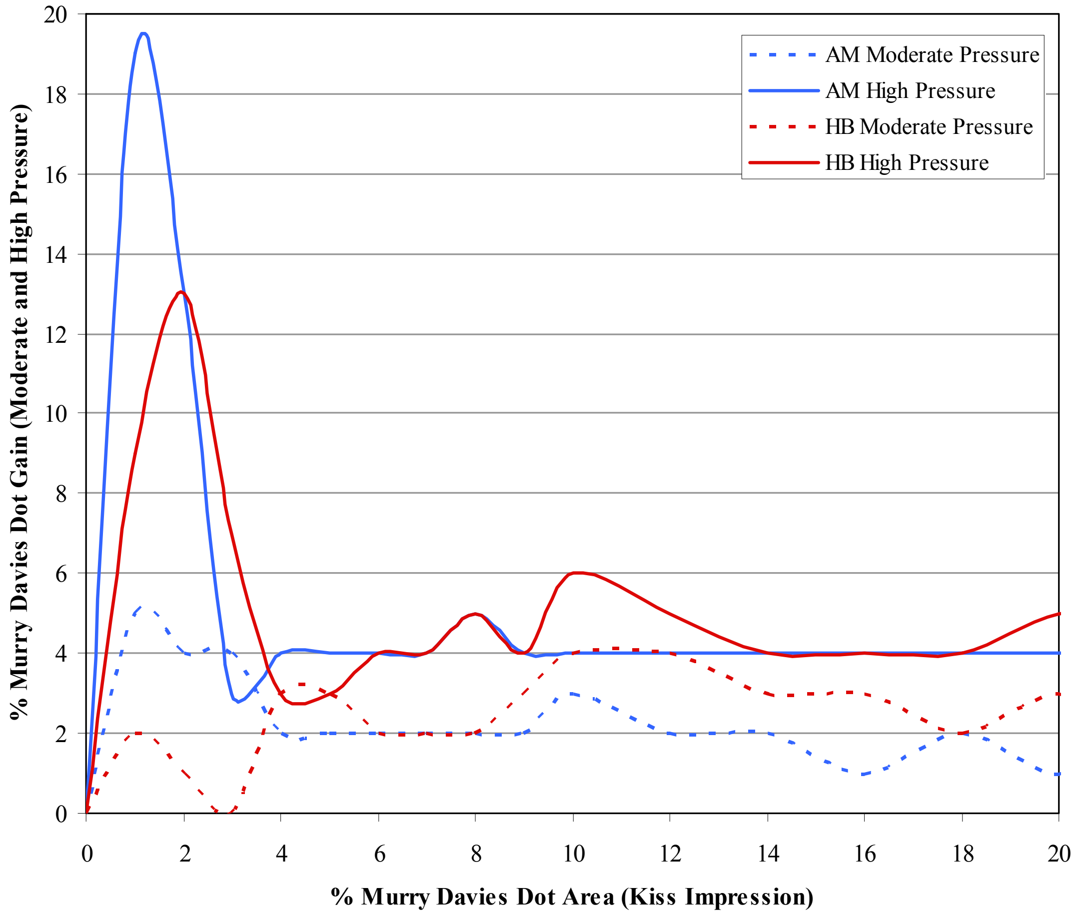

Figure 13. The Comparison of % Murry Davies Dot Gain between Kiss Impression and Higher Pressure of AM and Hybrid Screening Focusing in the Highlight Area

For the following discussion, only printed samples at kiss impression were used in analyzing gradient smoothness because highlight dots were reproducible at this pressure setting without over-squashed dots.

Smoothness

In this study, smoothness was evaluated using two methods. One based on measurement and another based on visual evaluation. The methodology to evaluate smoothness by measurement turned out to be problematic. The basic idea was to find out the deviation between the measured data and a straight line as a measure of smoothness. The assumption being that tone reproduction in the highlight area is normally close to a straight line and any bump in the curve, deviating from the straight line, is a measure of smoothness. The area between the tone reproduction line and the straight line was used as a measure of unsmoothness.

The problem arose because no transfer curve was used to make the average tone reproduction of the three screening techniques the same. Therefore, the deviation between the straight line and the tone reproduction line was not only a measure of unsmoothness but also a measure of the different tone reproduction curves.

The data for the measurement method is still presented in the following section, even though the conclusion will be based on the visual evaluation method.

Measurement Data

The measurement data was divided into two sections; gradient matrix and the effect of the surrounding on gradient smoothness.

Gradient Matrix

Since FM screening was too sensitive to changes in printing pressure, only AM and hybrid screenings were analyzed in this section. Figure 14 shows the comparison of the tone reproduction and the smoothness of AM and hybrid screening of 0.25" gradients. The densities of the gradient of each screening technique were plotted against percent PostScript dot area. A straight line from 0–30 percent was used as a reference line. A dashed line was determined by calculating the differences in density of the tone reproduction of each screening technique from the reference line. This curve is referred to as a smoothness curve.

The sum of the differences for each measurement divided by the number of measured fields of each gradient length represented an unsmoothness index. The unsmoothness index could, therefore, be used as a measurement of the gradient smoothness (Figure 15); the higher the index number, the less gradient smoothness.

The results of 0.25" gradients showed that 35-micron hybrid screening produced less gradient smoothness at 0–30 percent dot area range than AM screening. The dots in the highlight areas, below 4 percent dot area, could not be produced with any screening technique at 0.25" length. Therefore, there was no difference in the unsmoothness index at the 0–5 percent dot area range (Figure 14–15). The comparison figures of other gradient lengths can be found in Appendix D.

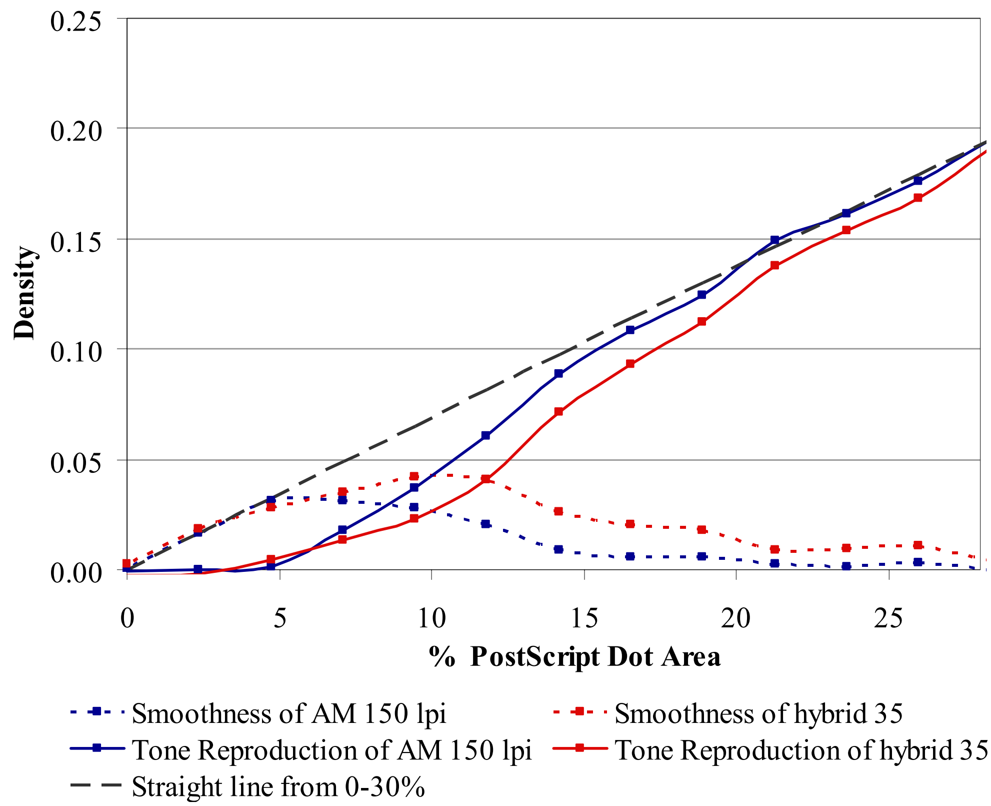

Figure 14. The Comparison of the Tone Reproduction and the Smoothness of AM and Hybrid Screening of 0.25" Gradients

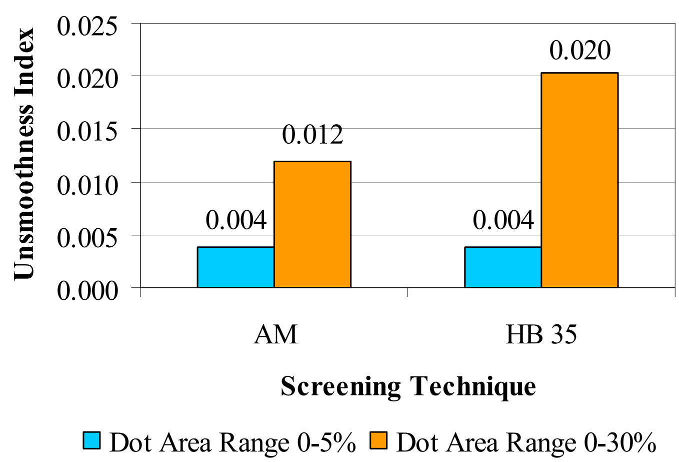

Figure 15. The Comparison of the Unsmoothness Index of AM and Hybrid Screening of 0.25" Gradients in 0–5 and 0–30 Percent Dot Area Range

The Effect of the Surrounding on Gradient Smoothness

Theoretically, the halftone dots of the gradients without the surrounding would be squeezed more due to the pressure of the printing process. The results in this section were analyzed through the same methodology of measuring the gradient smoothness as in the previous section.

Figure 16–17 show that the highlight areas below five percent PostScript dot area of the gradients were most affected by the surrounding for all three screening techniques. The change in tone reproduction of AM screening of the gradients without the surrounding was increased more than the other two screening techniques. For FM screening, tone reproduction of the gradients without the surrounding seemed to flatter more than the ones with the surrounding. Tone reproduction of hybrid screening was minimally affected by the surrounding.

Even though the measured data showed that there were differences between the gradients with and without the surrounding at kiss impression (Figure 16–19), the differences were difficult to observe visually without using a magnifier. Therefore, using the surrounding to improve the smoothness of the gradient was not truly useful. Also, using the surrounding can limit products' designs.

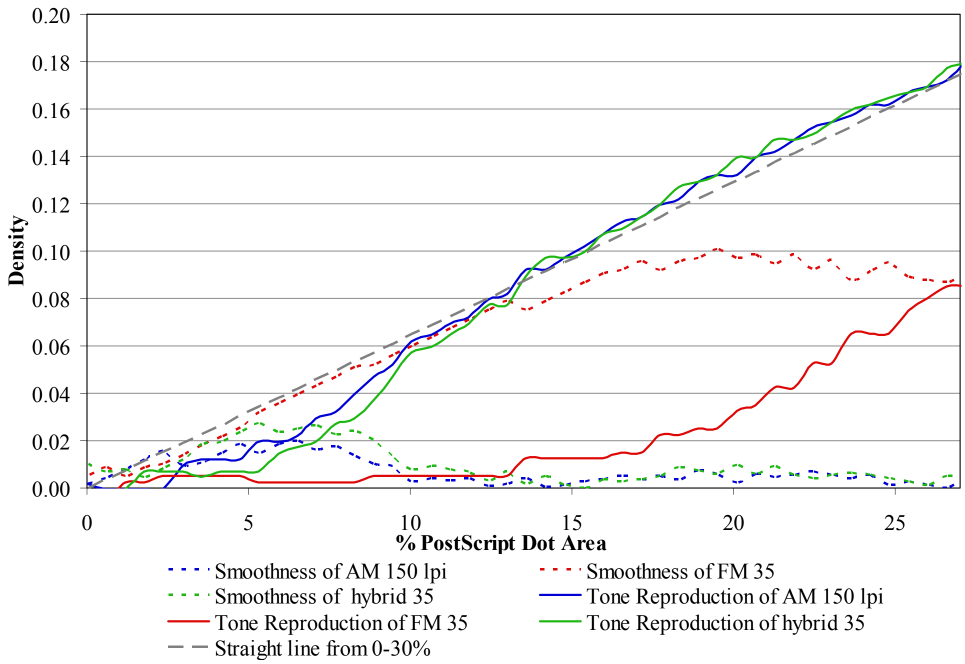

Figure 16. The Comparison of the Tone Reproduction and the Smoothness of AM, FM, and Hybrid Screening of the Gradients with the Surrounding

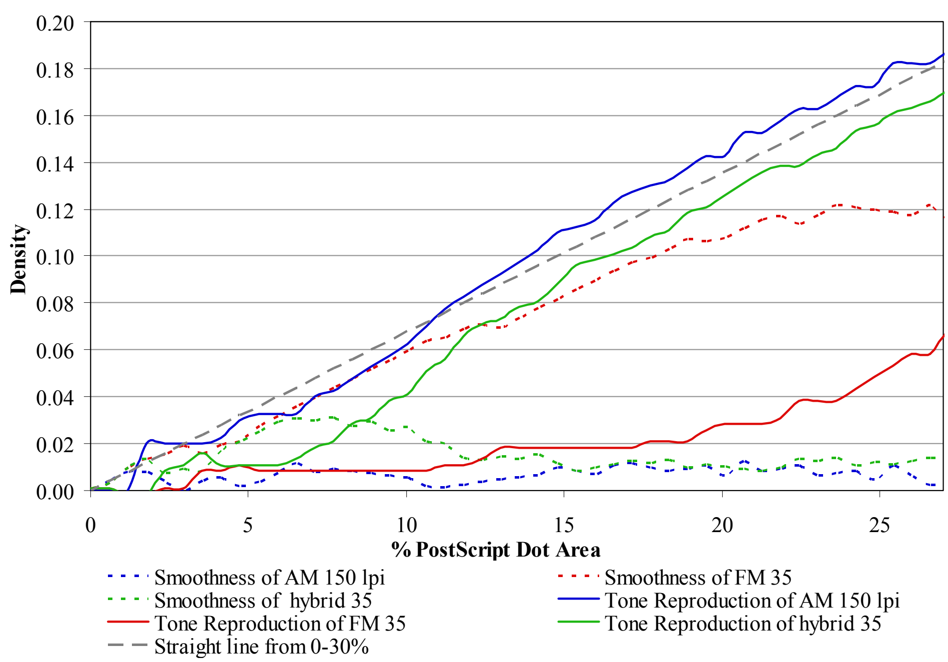

Figure 17. The Comparison of the Tone Reproduction and the Smoothness of AM, FM, and Hybrid Screening of the Gradients without the Surrounding

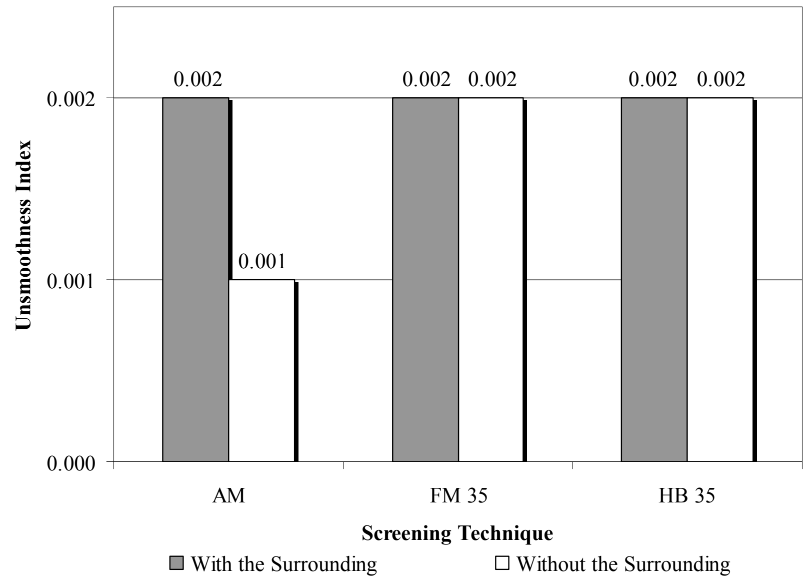

Figure 18. The Comparison of the Unsmoothness Index of the Gradients with and without the Surrounding in AM, FM, and Hybrid Screening from 0–5 Percent Dot Area Range

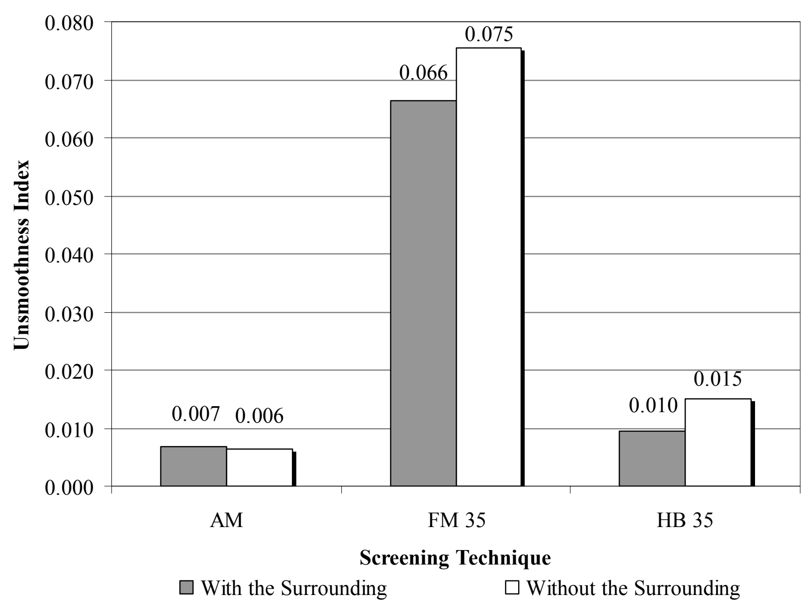

Figure 19. The Comparison of the Unsmoothness Index of the Gradients with and without the Surrounding in AM, FM, and Hybrid Screening from 0–30 Percent Dot Area Range

Visual Evaluation

The visual targets, or letter "I", were used to validate the measured data. Although thirty observers were selected to complete the survey, some inconsistent logical judgments were eliminated before doing the paired comparison analysis. Therefore, the valid number of observers did not always end up being thirty. The data were then analyzed statistically using the Monte Carlo simulation procedure. The data processing for 0.25" gradients is explained here as an example; the data for the other gradient lengths is given in Appendix E.

Table 1. Data Analysis of 0.25" Targets with Outline

		AM	FM 35	HB 35
Absolute Frequencies	AM	-	4	10
	FM 35	25	-	24
	HB 35	19	5	-
Fractional Frequencies		AM	FM 35	HB 35
	AM	-	0.14	0.34
	FM 35	0.86	-	0.83
	HB 35	0.66	0.17	-
z-scores		AM	FM 35	HB 35
	AM	-	-1.08	-0.41
	FM 35	1.08	-	0.95
	HB 35	0.41	-0.95	-
	Average	0.75	-1.02	0.27

One observer of 0.25" targets with outline was eliminated because its judgment was not logically consistent. Therefore, the final number of the valid observers was 29 instead of 30. The frequencies table can be explained as the number of observers that

selected one screening technique, that they believed produced smoother gradients, over another screening technique. For example, of the 0.25" targets with outline of the AM and FM screening pair, 25 observers said that the AM screening produced smoother gradients than the targets of the FM screening. Therefore, only four observers said that FM screening targets were smoother than the AM screening targets.

The fractional frequencies were calculated by dividing the absolute frequencies by the total number of valid observers. The fractional frequencies were used to look up the z-scores from the z-score table of the statistical normal distribution. The average z-scores of each screening were then calculated.

In order to analyze data statistically, the observed standard deviation was calculated using Equation 1; "n" is the total number of the screening methods that were used in the visual evaluation; "N" is the total number of valid observers;

Equation 1: $$\sigma_{observed} = 1.76(n-(-3.08))^{(-0.613)} * (N-2.55)^{(-0.491)}$$ (Mortag, 2004)

The $\sigma_{observed}$ for the above example would therefore be as shown below, where n = 3 , N = 29

$$\sigma_{observed} = 1.76 \times (3-(-3.08))^{-0.613} \times (29-2.55)^{-0.491}$$

$$= 0.117$$

The observed standard deviation for 0.25" targets with outline was 0.117.

By following the above method, the data of 0.25" targets without outline were also calculated and shown in Table 2.

Table 2. Data Analysis of 0.25" Targets without Outline

		AM	FM 35	HB 35
Frequencies	AM	-	2	9
	FM 35	24	-	20
	HB 35	17	6	-
p -observed proportions		AM	FM 35	HB 35
	AM	-	0.08	0.35
	FM 35	0.92	-	0.77
	HB 35	0.65	0.23	-
z-scores		AM	FM 35	HB 35
	AM	-	-1.41	-0.39
	FM 35	1.41	-	0.74
	HB 35	0.39	-0.74	-
	Average	0.90	-1.08	0.18

Four of the observers for the 0.25" target without outline were eliminated because they had logical inconsistencies. By following Equation 1, where "n" = 3 and "N" = 26, the calculated $\sigma_{observed}$ for 0.25" target without outline was 0.124.

The average z-scores have a statistical uncertainty due to randomly occurring experimental errors. The magnitude of the errors can be expressed by confidence interval, using error bars in the following column graphs. Ninety-five percent confidence intervals for average z-scores were calculated by using Equation 2.

Equation 2: $95\%\ confidence\ interval = Scale\ value \pm 1.96\ \sigma_{observed}$ (Montag, 2004)

The scale value of Equation 2 is just a different term for the average z-scores. From the previous example, the error bar value for the 0.25" target with outline equaled 0.117 × 1.96 = 0.23, while the error bar value of 0.25" target without outline equaled 0.124 × 1.96 = 0.24.

To present the visual evaluation data effectively, the average z-scores were plotted in column graphs with the error bars. The more positive the average z-scores, the smoother the gradients. The error bars represented 95 percent confidence intervals, which were used for all screening techniques at particular gradient specification. If two error bars of any pair do not overlap, the difference of that pair is statistically significant at 95 percent confidence interval. On the other hand, if two error bars of any pair overlap, the difference of the pair is not statistically significant.

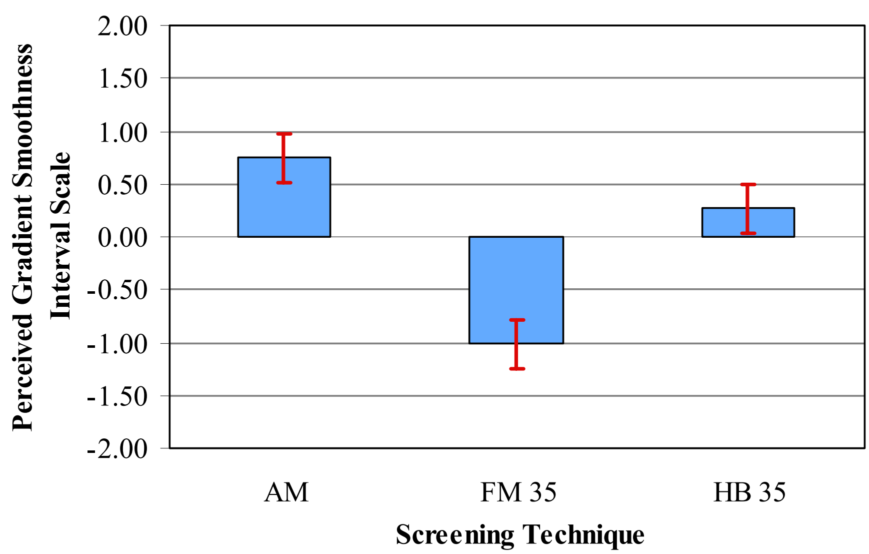

Figure 20. Perceived Gradient Smoothness Interval Scale and the Error Bars at 95 Percent Confidence Interval of 0.25" Targets with Outline

All three 0.25" gradient targets with outline—AM screening, 35-micron FM screening and 35-micron hybrid screening—were statistically different at 95 percent confidence interval. AM screening was visually evaluated to have smoother gradients, followed by hybrid screening and FM screening respectively. The least visually smooth gradient was the FM screening as the average z-score was negative (Figure 20).

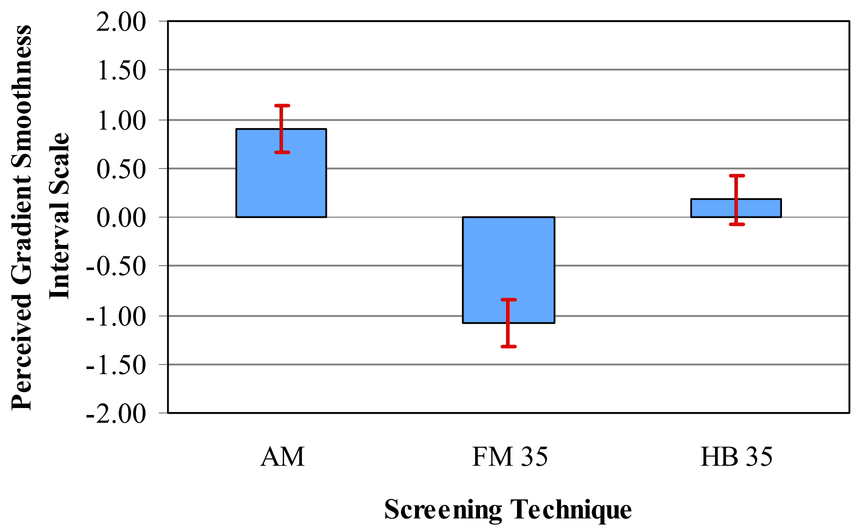

Figure 21. Perceived Gradient Smoothness Interval Scale and the Error Bars at 95 Percent Confidence Interval of 0.25" Targets without Outline

There were statistical differences at 95 percent confidence interval for all three screening techniques. The results were similar to the 0.25" targets with outline (Figure 21).

The numeric data of the other gradient lengths (0.5", 1", and 2") is in Appendix E, Table E1–E6. Appendix E contains the numeric data and Figure 22 shows the same data in graphical form. In Figure 22, it is not always easy to see which error bars overlap. Table E7 and E8 show the numeric data, from which it is easier to see the overlaps.

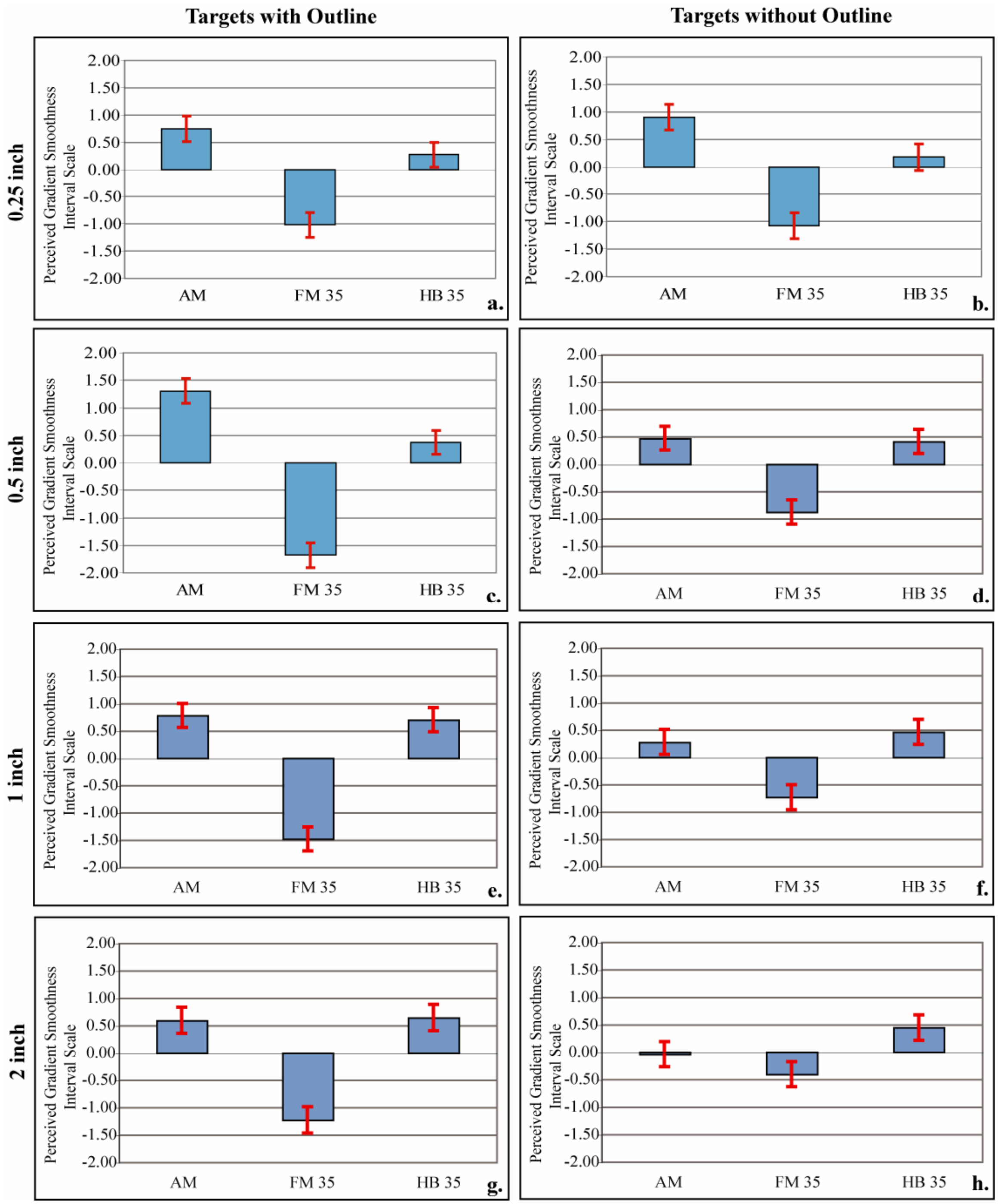

Figure 22. Perceived Gradient Smoothness Interval Scale and the Error Bars at 95 Percent Confidence Interval of the Targets with and without Outline of 0.25", 0.5", 1", and 2" Gradients.

For the targets with outline, the difference between AM and hybrid screening tended to decrease when the gradients were longer. As shown in Figure 22a, 22c, 22e, and 22g, the difference of AM and hybrid screening of the 0.5" targets with outline is statistically significant, while the different of 1" and 2" targets with outline is statistically insignificant.

For the targets without outline, the difference of AM and hybrid screening is statistically significant at 0.25" targets, and slightly significant at 2" targets. The differences are not statistically significant for 0.5" and 1" targets.

The average z-scores of the targets with and without outline with FM screening were negative for all gradient lengths. Therefore, it can be concluded that FM screening was visually the least smooth screening techniques.

Comparison of Results between the Measured Data and the Visual Evaluation Data

To verify the measured data, the results from both the measured data and the visual evaluation data were compared. The results of both data sets were ranked in order to define levels of smoothness; the best smoothness was ranked as number 1; the second and the third smoothness was ranked as number 2 and 3 respectively. The ranking order of the results from both the measured and the visual evaluations are shown in Table 3 and 4.

Table 3. The Ranks of the Measured Data at 0–5 Percent Dot Area Range

Gradient Length	Measurement (0-5%)	
	AM	**HB 35**
0.25"	1	1
0.5"	2	1
1"	2	1
2"	2	1
3"	2	1
4"	2	1
Total	**11**	**6**

The measured data were ranked using the smoothness comparison data from Appendix D. The sum of the ranks (total) in Tables 3 shows the highest and lowest ranks between two screening techniques. The lower the number, the smoother the gradients.

For over all ranking scores, although AM screening produced smoother gradients in the 0–30 percent dot area range, tone reproduction and halftone dot formation of AM and hybrid screening were really the same in the range of 5–25 percent dot area. The difference of the tone reproduction curves was more obvious below five percent dot area. As shown in Table 3, the 35-micron hybrid screening produced smoother gradients below 5 percent dot area range than AM screening.

In Table 4, the visual evaluation data was ranked in the same manner as the measured data.

Table 4. The Ranks of the Visual Evaluation Data of the Targets with and without Outline

Gradient Length	**Targets with outline**			**Target without outline**		
	AM	**FM 35**	**HB 35**	**AM**	**FM 35**	**HB 35**
0.25"	1	3	2	1	3	2
0.5"	1	3	2	1	3	2
1"	1	3	2	2	3	1
2"	2	3	1	2	3	1
Total	**5**	**12**	**7**	**6**	**12**	**6**

Ranking of the visual evaluation data was done by comparing the z-scores of each gradient length (Table 1–2 and Appendix B). For all gradient lengths, the targets with or without outlines for AM screening and 35-micron hybrid screening were indirect competition with each other for the highest ranking. The targets either with or without outlines of 35-micron FM screening were visually evaluated to have the poorest gradient smoothness when compared to both AM screening and 35-micron hybrid screening.

Although the targets with outline of the AM screening were judged by the observers to produce smoother gradients among the screening techniques, the differences were not significant. The total ranking number of AM screening was followed closely by that of the 35-micron hybrid screening. However, the AM screening and 35-micron hybrid screening switched rank position at 2" gradient length. Although the total ranking number of

the targets with outline of AM screening and 35-micron hybrid screening were different, the total ranking numbers of the targets without outline for both screenings were identical.

For less than 5 percent dot area, particularly for long gradients, hybrid screening was better than AM screening. The difference between AM and hybrid screening was minimal. Also, having an outline was not really making a difference at kiss impression.

Summary of the Results

The results were divided broadly into two sections; the tone reproduction at different pressure settings and the smoothness results with and without the surrounding. In the first section, the results showed that the 35-micron hybrid screening was the least sensitive screening to the change in pressure. It preserved its tone reproduction better than AM screening and 35-micron FM screening respectively. The second section of this chapter was divided into a measurement and a visual evaluation subsection.

Firstly, the measured data showed that AM screening produced smoother gradients at almost every gradient length in the 0–30 percent dot area range except for the 4" gradients. Even though AM screening produced smoother gradient at the range of 0–30 percent dot area, the tone reproduction of both AM and hybrid screening were similar, except the tone reproduction below 5 percent dot area. The tone reproduction curves below 5 percent dot area of hybrid screening produced smoother gradients than AM screening. The results in this section were not truly valid due to tone reproduction differences of each screening method.

The differences between the targets with and without the surrounding at kiss impression of all three screening techniques were not noticeable without a potential magnifier. Therefore, using the surrounding did not improve the gradient smoothness.

Secondly, the results from the visual evaluation show that FM screening targets was the least smooth. The difference between AM and hybrid was relatively small.

Glossary

Percent Murry Davies dot area is percent dot area per certain area, which is calculated from an equation of Murry Davies dot area below.

$$\%dot\ area = \frac{1-10^{-Dt}}{1-10^{-Ds}} \times 100$$

Percent PostScript dot area in the context of this report is percent dot area of the original data file that is sent to the RIP.

Chapter 7

Conclusions

Three screening techniques, which were AM, FM, and hybrid screening, were investigated. For hybrid screening, there is a transition point in the highlight areas, where FM screening changes to AM screening for the rest of the tone scale. Therefore, above the transition point, AM and hybrid screening should have the same tone reproduction except for small differences due to system noise.

Different Pressure Settings

The first research question was; "How much does tone reproduction change when pressure changed?" Because the press does not have a scale for pressure settings, pressure was evaluated relative to kiss impression for the different screening techniques. FM screening showed a high sensitivity to change in pressure, while AM and hybrid screenings were more forgiving to variations in pressure settings (Figure 10-13).
For practical works, press operators tend to apply a little higher pressure than kiss impression, to make sure that all image areas are transferred onto the substrate. The

results showed that in the highlight areas, hybrid screening was the least sensitive to changes in pressure (Figure 13).

Smoothness

The abrupt breaking of highlight dots is a basic problem for the flexographic process. This is caused because flexography cannot print dots that are smaller than about three percent dot area, resulting in “unsmooth” tone reproduction. Smoothness in this study was investigated by looking at tone reproduction curve in the highlight areas.

However, as we discovered during the study, unsmoothness can also be seen as a grainy appearance as shown in FM screening. When doing the visual analysis with the 30 observers, no clear definition of unsmoothness was provided, in order not to influence their judgments. After the experiment, it was recognized that what they called unsmoothness of FM screening is really graininess of FM screening.

According to this study, FM screening had two problems: very sensitive to changes in pressure and a grainy appearance. Either one of these problems makes it an inferior screening technique, compared to AM or hybrid screening.

The linear transfer curves used for all screening methods caused the FM screening tints to be lighter in the highlights and midtones than AM or hybrid screening. However, changing to a different transfer curve would not alter the above conclusion.

This type of study cannot really be done disregarding tone reproduction curves. For hybrid screening, the transition point between AM and FM screening is a critical

area. As we observed from this study for hybrid screening, the four percent dot area (FM) was darker than the six percent dot area (AM). The density difference between the four and six percent dot areas is more obvious at longer lengths because for shorter gradients the difference is averaged out by the measuring aperture of Spectrolino (See Appendix D, Figure D3, D5, D7, and D9). This indicates that a transfer curve is necessary and/or the transition point should be chosen in another way.

There was no transfer curve used in this study, because the researcher wanted to study the basic nature of these screening techniques. For instance, to find out the smallest reproducible AM dots, one cannot apply curves. It was found that the minimum reliable dot size for FM and hybrid screening for this printing condition should be 35 microns.

Using hybrid gradients with a dot size limitation set at 35 microns, did result in improved highlight rendition from 0 to 5 percent dot area, when compared to AM screening. However, for certain gradient lengths, the observers preferred AM over hybrid screening in terms of smoothness, because they saw what visually appeared to be a too light area in the six to ten percent dot area region in hybrid gradients. This indicates that the transition point between AM and FM screening was not optimally set: the FM dots should have been further apart from one another. From this we learn that although hybrid screening has a potential to produce better tone reproduction in the highlight areas, this can only be achieved when using optimized dot size, correct transition point, and optimized transfer curves.

Therefore, there are three types of unsmoothness: highlight breaking in AM screening, graininess of FM screening, and a disjunction at the transition point of hybrid screening.

Gradient Lengths

The second research question was: “When printing a gradient, does its length make a difference in the visibility of poor highlight rendition?” According to the results from the measurement and visual evaluation, when the length of the gradients increased, the smoothness of the AM screening targets seemed to decrease, while hybrid screening produced smoother gradients at longer lengths. This could be explained by considering percent dot area increments in each gradient length. The 0.25" gradient target has 4.72 percent dot area increments at every one millimeter, while the 4"gradient target has 0.30 percent dot area increments at every one millimeter. These increments are calculated by dividing 30 percent dot area with the lengths of the targets in millimeters. The calculated numbers represented the percent dot area of those targets at every one-millimeter increment. The difference of the percent dot area increment of each gradient length can be used to explain why hybrid screening produced smoother gradient at longer lengths.

Assuming that the highlight breaking point is five percent dot area in AM screening, the distance to produce 0–5 percent dot area range for the 0.25" gradient targets is less than one millimeter. Whereas, the distance to produce the same dot area range for 4" gradient targets is around 17 millimeters. That means, if the highlight breaks

at five percent dot area, there is only one millimeter where the dots are not reproducible for 0.25" gradient length, while there is 17 millimeters where the dots are not reproducible for 4" gradient targets. However, the highlight dots in hybrid screening were more reproducible below five percent dot area. Therefore, the 0.25" targets of both AM and hybrid screening were not much different, while the differences in producing highlight dots were most obvious with longer gradient lengths, or 4" gradient targets in this scenario. As a result, it can be summarized that the longer the gradients, the more noticeable the highlight breaks and the less smooth the gradients appear. Therefore, to produce smoother gradients AM and hybrid screening could be used for shorter gradient lengths, while hybrid screening, with optimum settings, would be the best selection to produce smoother gradient with longer lengths.

The Surrounding

The last research question was: "Does the surrounding of a gradient make a difference?" The results show that the surrounding did not truly improve the smoothness of the gradients, since the difference between the targets with and without the surrounding at kiss impression were unnoticeable with the naked eye. Also, using the surrounding with gradient would limit designers. It is not practical to use the surrounding around the gradient if designers want to show gradient ends. However, the effect was more obvious with the naked eye at higher-pressure settings.

The surrounding does not have to be a solid. It could be other halftone dots. This is nicely shown in Figure 10. For FM screening where all dots have the same diameter, the ones at the beginning of the scale that do not have neighbors, are squeezed and get much darker. The dots at the 10 percent dot region were not squeezed and printer sharper.

Recommendations for Further Investigation

– Since the dot sizes in this study were predetermined from previous experiments, the dot size selection should have included one more larger dot size.

– Instead of specifying minimum dot size in terms of round micron numbers, dot size should be specified in terms of multiples of addressability spots. When the one-bit tiff images of the test form were investigated to verify that the requested dot size were actually obtained, it was noticed that sometime the dots are rectangular like 2×3 spots for the 25-micron dots. Rectangular dots are undesirable because they are less stable and have directionality. To avoid rectangular dots, it is necessary to specify dot size using a full number of spots. For instance, one spot is 10.6 microns at 2400 spi (spot per inch), thus, halftone dot size can be 21 μ, 31.5 μ, and/or 42 microns.

– Now that we know about the importance of selecting optimum screening settings for hybrid screening, such as minimum dot size, transition point, and transfer curve, the documentation of these variables needs to be more carefully done than it was in this study.

– A better methodology for measuring smoothness needs to be developed. The simple straight line method was not adequate when comparing screening with different tone reproductions.

– This study was limited to study gradient smoothness in the range of 0–30 percent dot area. However, once healthy dots are obtained in the highlight region, no more nonlinearities are expected. Therefore, a better criterion to choose the dot area range might be to simply select a range that goes from zero to twice of the dot area of the transition point.

– Since there are many more hybrid screening technologies available in the market, they could be compared with one another. Each one could have different ways to define transition point and transfer curve.

– Furthermore, applying curves to normalize the tone reproduction of each screening would be more appropriate in order to validate the comparison. At least two press runs are needed. The first run is a calibration run to determine optimum dot size, transition point, and find out what transfer curve is needed for those conditions. The second press run could be done using these optimized parameters to compare performance of these different screening techniques at different pressure settings.

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Appendices

Appendix A

Appendix A

Survey Form

General Information

Name……………………………………………………… Age…………………..

Major……………………………………………………… Year………………….

Please circle the letter that shows the smoother gradient of each pair.

A vs. B

Letter "I" with outline

- 0.25" A vs. B
- 0.5" A vs. B
- 1" A vs. B
- 2" A vs. B

Shadow of letter "I"

- 0.25" A vs. B
- 0.5" A vs. B
- 1" A vs. B
- 2" A vs. B

A vs. C

Letter "I" with outline

- 0.25" A vs. C
- 0.5" A vs. C
- 1" A vs. C
- 2" A vs. C

Shadow of letter "I"

- 0.25" A vs. C
- 0.5" A vs. C
- 1" A vs. C
- 2" A vs. C

B vs. C

Letter "I" with outline

- 0.25" B vs. C
- 0.5" B vs. C
- 1" B vs. C
- 2" B vs. C

Shadow of letter "I"

- 0.25" B vs. C
- 0.5" B vs. C
- 1" B vs. C
- 2" B vs. C

Appendix B

Appendix B

Plate Specification

There were two plates in the experiment; the finished plate and the ablated plate. The ablated plate was the plate that was imaged but did not pass through the washout process. The thickness of the finished plate was measured before printing. Table B1 shows the raw data of plate thickness. Plate size was 14.75" x 19.5".

Table B1. Plate Thickness

No. of Measurement	**Thickness (inch)**	**Floor (inch)**
1	0.0675	0.0200
2	0.0675	0.0195
3	0.0675	0.0205
4	0.0680	0.0195
5	0.0680	0.0160
6	0.0680	0.0200
7	0.0680	0.0205
Average	0.0678	0.0194
Standard deviation	0.00027	0.00157

The Comparison of the Tone Reproduction at Three Production Stages

The three production stages are referred to as the ripping stage, the imaging stage and the printing stage. Measurement of tone reproduction at the ripping stage was the measurement of the digital one-bit tiff file. Then, the ripped file was output through the platesetter to create the image areas on the flexible plates; this stage was referred to as the imaging stage. The measurement of the tone reproduction at this stage was done by measuring the ablated plate. Each patch of the step wedges on the ablated plate was captured by using BetaFlex334 and FlexoEye Software. The captured images were then measured with Image Pro System to define percent dot areas of each screening condition.

The final stage was the printing stage. The printed samples were measured with an X-Rite 530 densitometer to calculate and define the tone reproduction of the printing stage. Since the accessible equipment was not able to measure the finished plate, it was not possible to measure dot area on the final plate directly. This is why dot area was measured on the prints (Figure B1–B7).

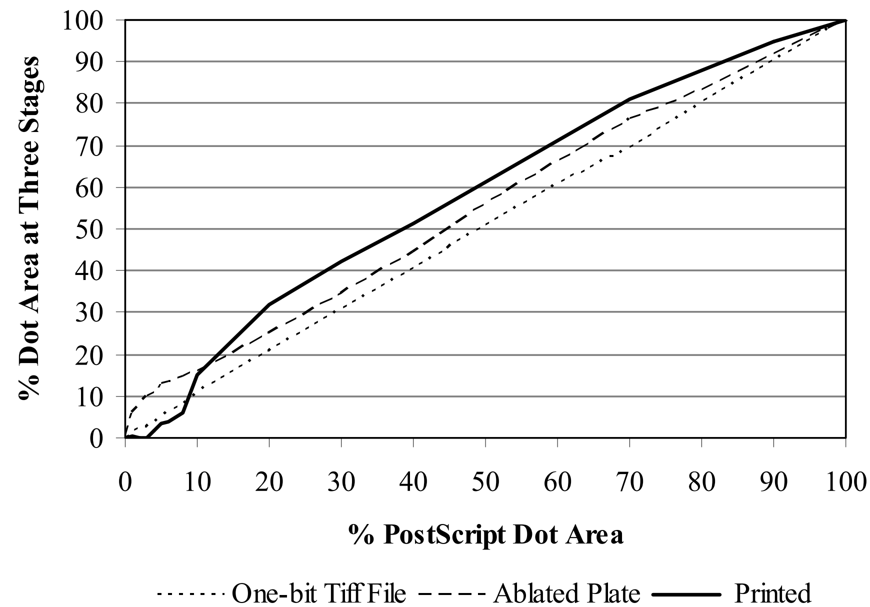

Figure B1. The Comparison of the Tone Reproduction of Three Production Stages of AM Screening 150 lpi

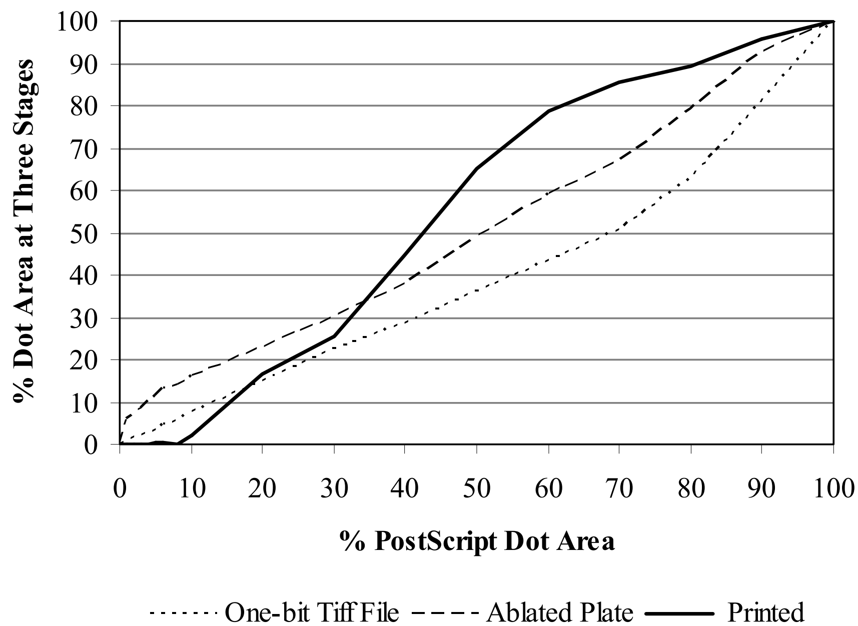

Figure B2. The Comparison of the Tone Reproduction at Three Production Stages of 25-micron FM Screening

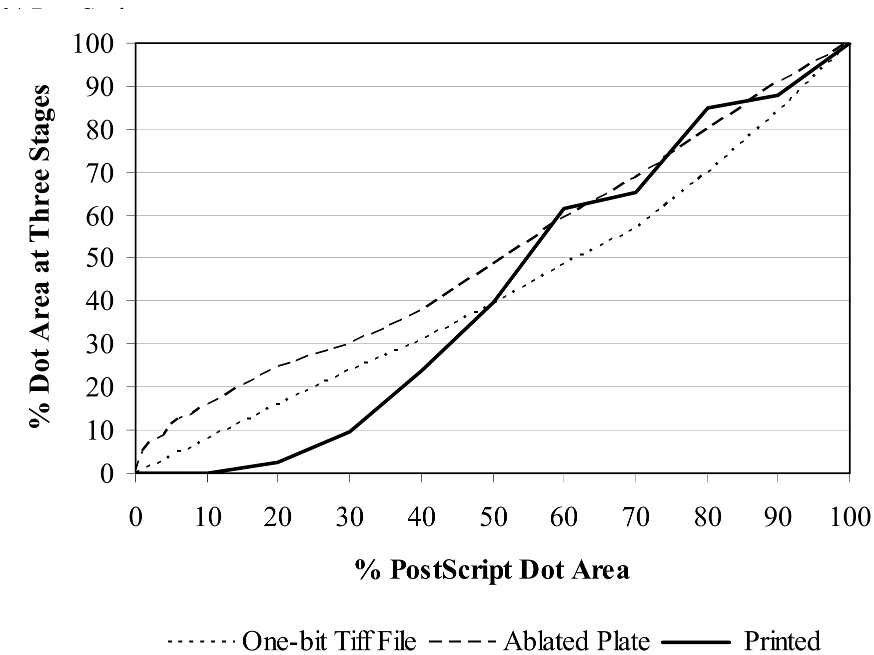

Figure B3. The Comparison of the Tone Reproduction at Three Production Stages of 30-micron FM Screening

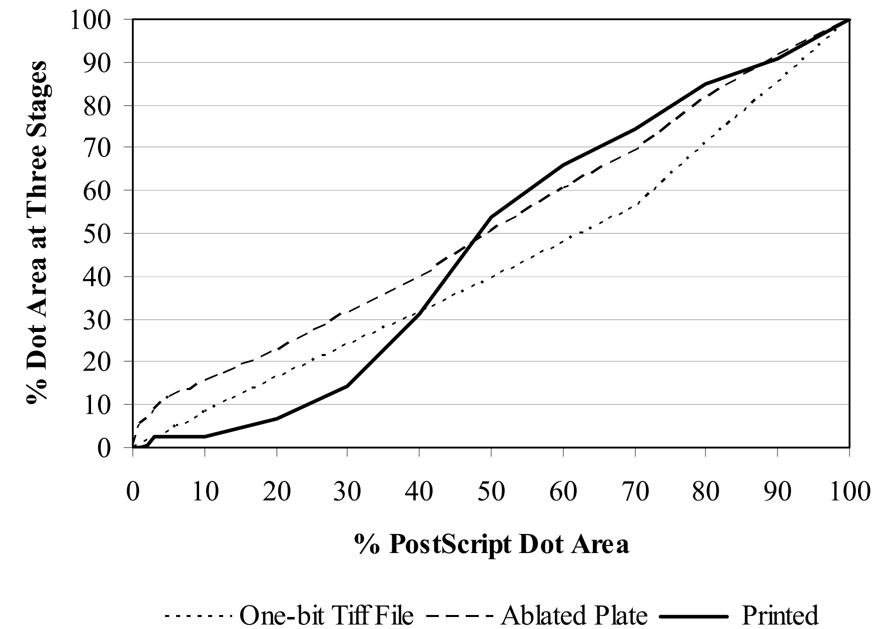

Figure B4. The Comparison of the Tone Reproduction at Three Production Stages of 35-micron FM Screening

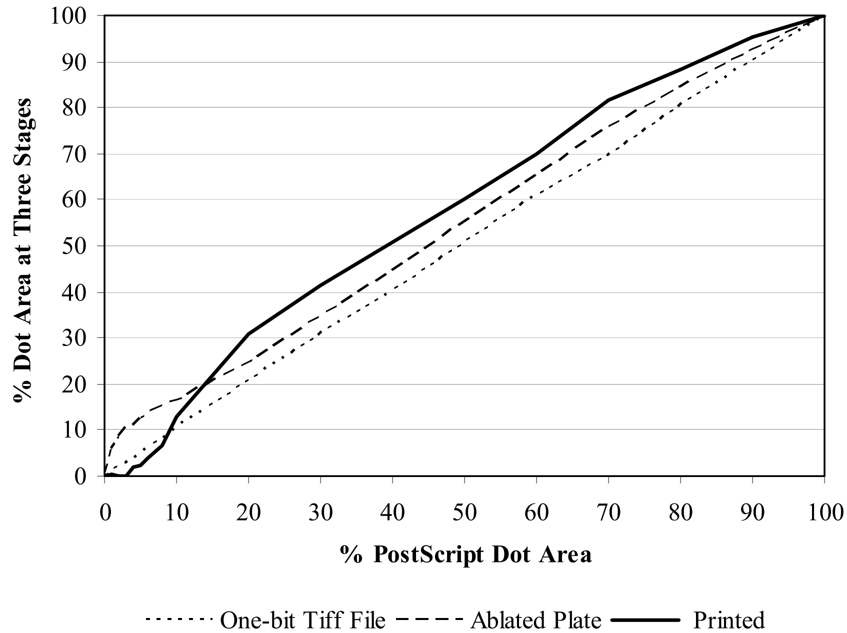

Figure B5. The Comparison of the Tone Reproduction at Three Production Stages of 25-micron Hybrid Screening

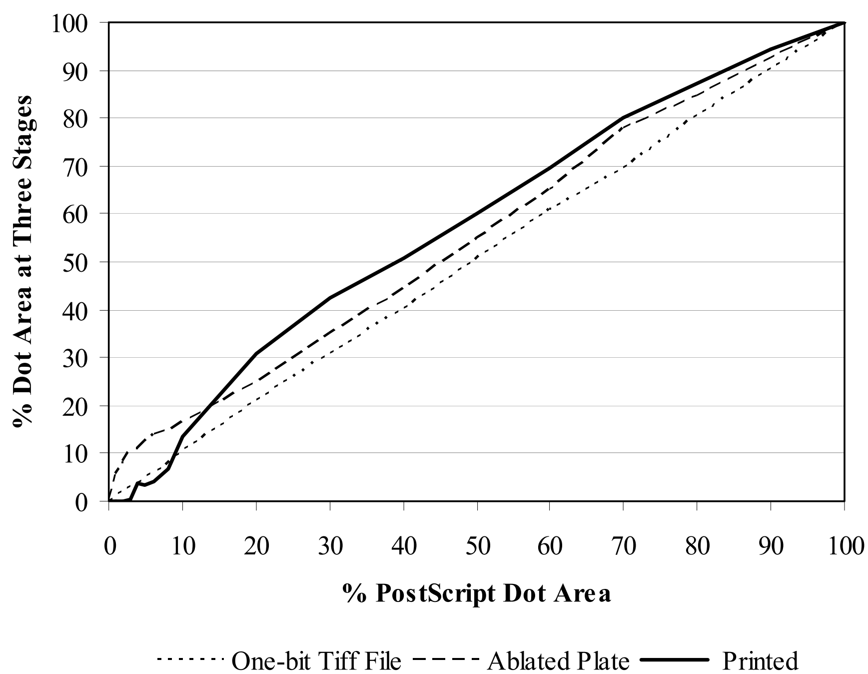

Figure B6. The Comparison of the Tone Reproduction at Three Production Stages of 30-micron Hybrid Screening

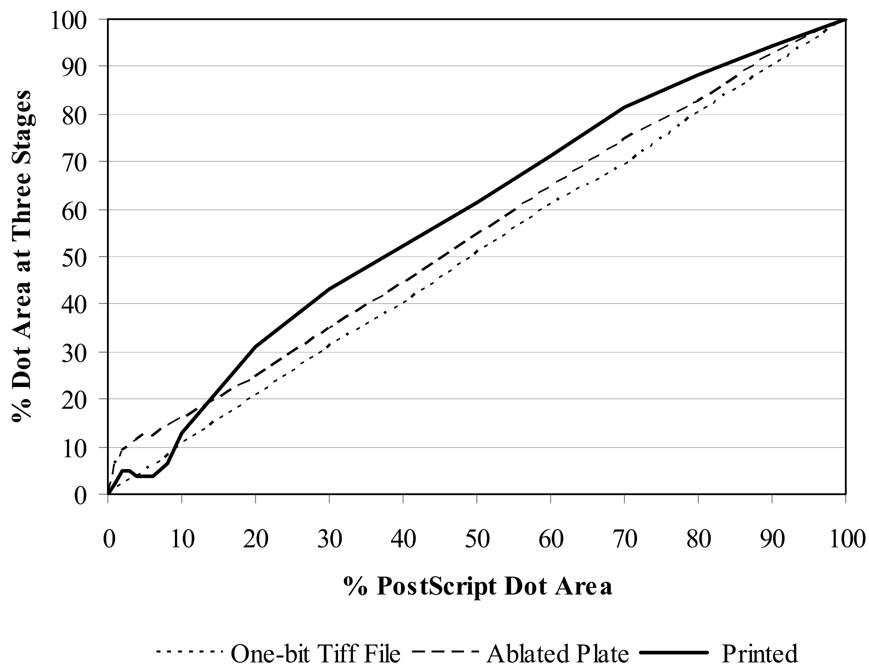

Figure B7. The Comparison of the Tone Reproduction at Three Production Stages of 35-micron Hybrid Screening

The tone reproduction of the one-bit tiff file in all screening techniques was slightly different. The tone reproduction of AM screening and hybrid screening had almost identical and nearly linear results, while tone reproduction of FM screening was different from the other screening techniques. When image areas were created on the ablated plate, the entire tone reproduction curves of three screening techniques were higher than tone reproduction of the one-bit tiff file, especially in the highlight areas.

The highlight areas below 5 percent in the AM screening were not reproducible on the printed sample. However, the AM screening tone reproduction above 10 percent was higher in the printed sample than of the ablated plate. The tone reproduction in AM screening on the printed sample was higher than both one-bit tiff file and the ablated plate

above 12% dot area. The AM screening tone reproduction curve of the printed sample was visually smoother from the 10 percent dot area to the shadow areas than that of the FM but it was similar to the hybrid screening.

Also, the highlight dot areas of the 25-micron FM screening below 9 percent dot areas were not reproducible on the printed sample; from 35 percent and above, the tone reproduction of the printed sample exceeded that of the tone reproduction of the one-bit tiff file and the ablated plate. With a larger dot size, the highlight dots below 10 percent were not reproducible with the 30-micron FM screening, whereas its tone reproduction from the midtone to the shadow areas above the 60 percent dot area fluctuated around the tone reproduction of the ablated plate. Since the dot size of the 35-micron FM screening was higher than the 25- and 30-micron FM screening, the dots below 10 percent of the 35-micron FM screening were better reproduced on the printed sample. Although the printed sample's tone reproduction of the 35-micron FM screening from the highlight to the midtone areas was lower than the ablated plate, its tone reproduction above 50 percent tended to be slightly higher than the tone reproduction of the ablated plate.

The tone reproduction of both the ablated plate and the printed sample from the hybrid screening, at all dot sizes, was similar to the tone reproduction of the AM screening. However, since there were three different dot sizes used in the hybrid screening, there were differences at the highlight areas below 10 percent. The highlight dots in the first few percentages of both 25-micron and 30-micron hybrid screening were not reproducible on the printed sample because the dots were too small. The highlight dots of the 35-micron hybrid screening were producible due to the larger dot size in the

highlight areas. Although the tone reproduction of the printed sample at all micron sizes from the hybrid screening was lower than the tone reproduction of the ablated plate, they were higher above 12 percent dot area.

Appendix C

Appendix C

Tone Reproduction at Three Different Pressure Settings

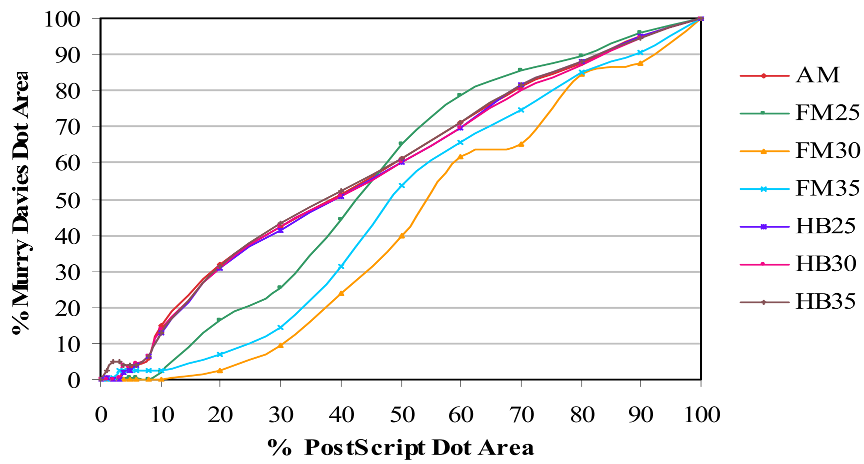

Figure C1. Tone Reproduction of All Screening Techniques at Kiss Impression Setting (Lightest Pressure)

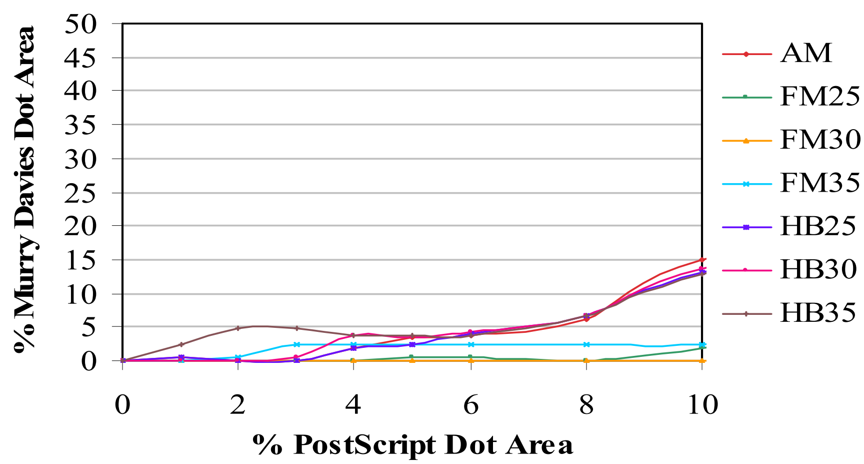

Figure C2. Tone Reproduction Below 10 Percent Dot area of All Screening Techniques at Kiss Impression Setting (Lightest Pressure)

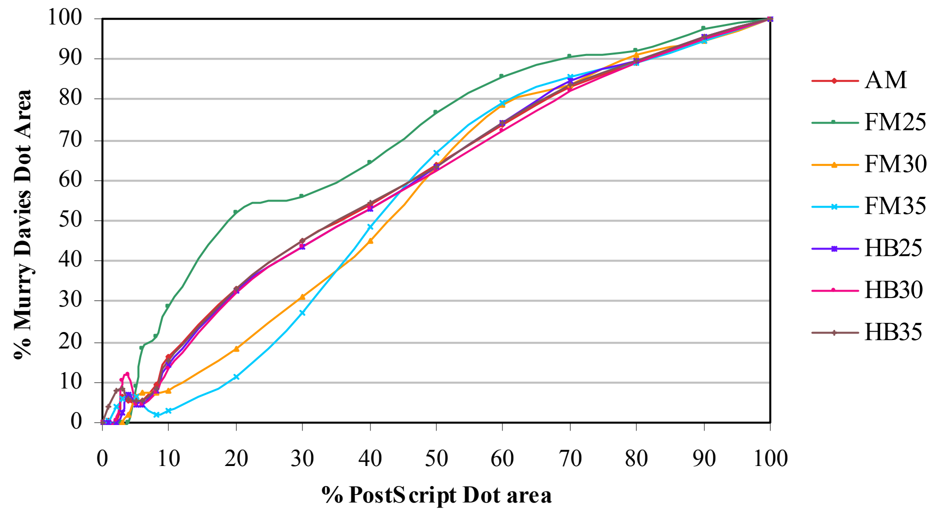

Figure C3. Tone Reproduction of All Screening Techniques at Moderate Pressure Setting

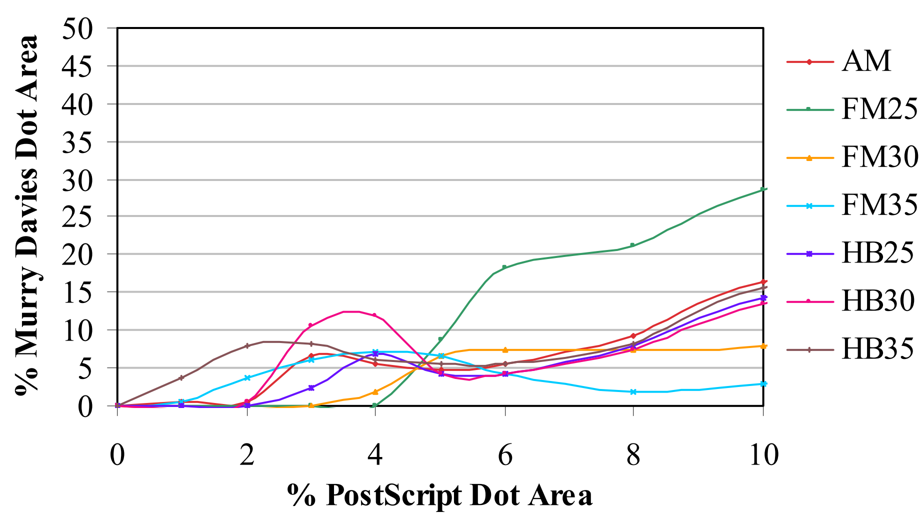

Figure C4. Tone Reproduction Below 10 Percent Dot Area of All Screening Techniques at Moderate Pressure Setting

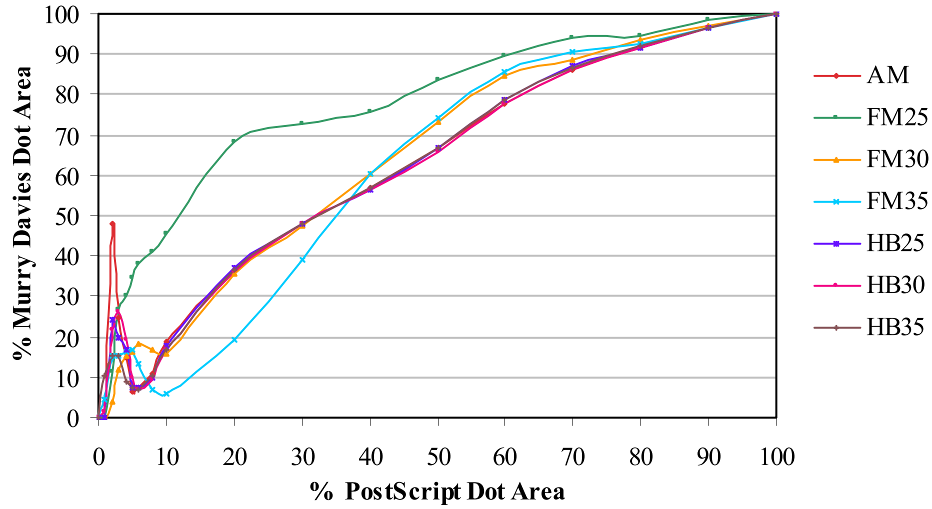

Figure C5. Tone Reproduction of All Screening Techniques at High Pressure Setting

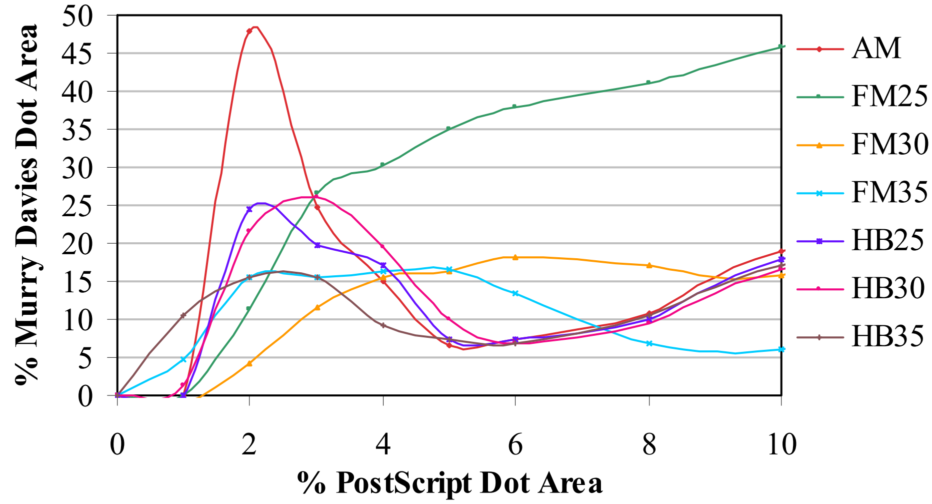

Figure C6. Tone Reproduction Below 10 Percent Dot Area of All Screening Techniques at High Pressure Setting

Appendix D

Smoothness

0.5" Gradients

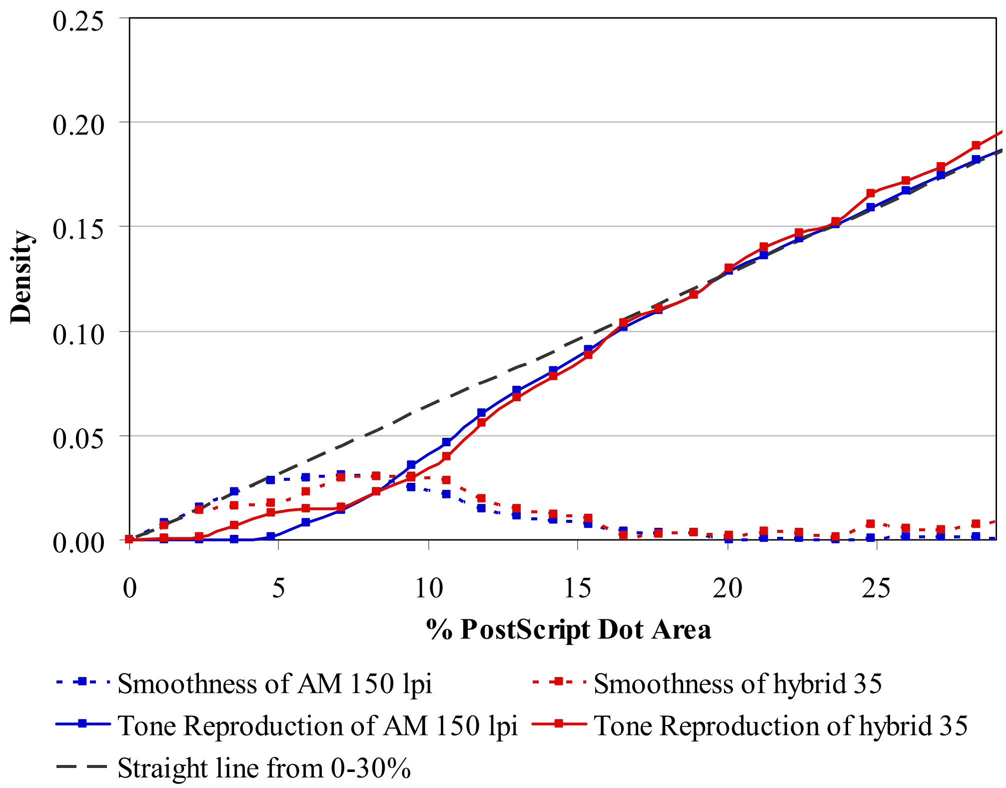

Figure D1. The Comparison of the Tone Reproduction and the Smoothness of AM, FM and Hybrid Screening of 0.5" Gradients

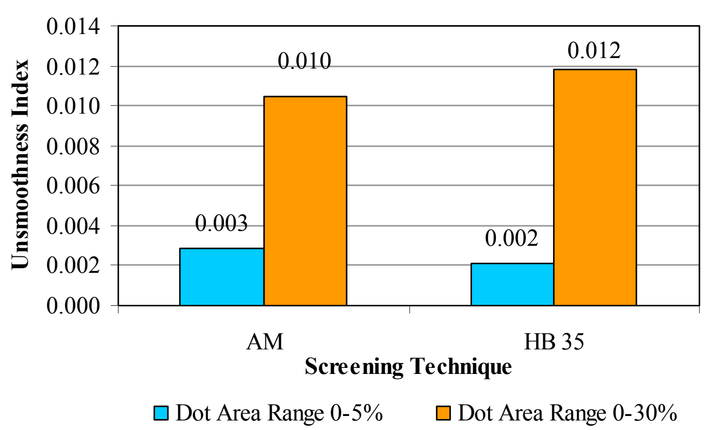

Figure D2. The Comparison of the Unsmoothness Index of AM, FM and Hybrid Screening of 0.5" Gradients in 0–5 and 0–30 Percent Dot Area Range

1" Gradients

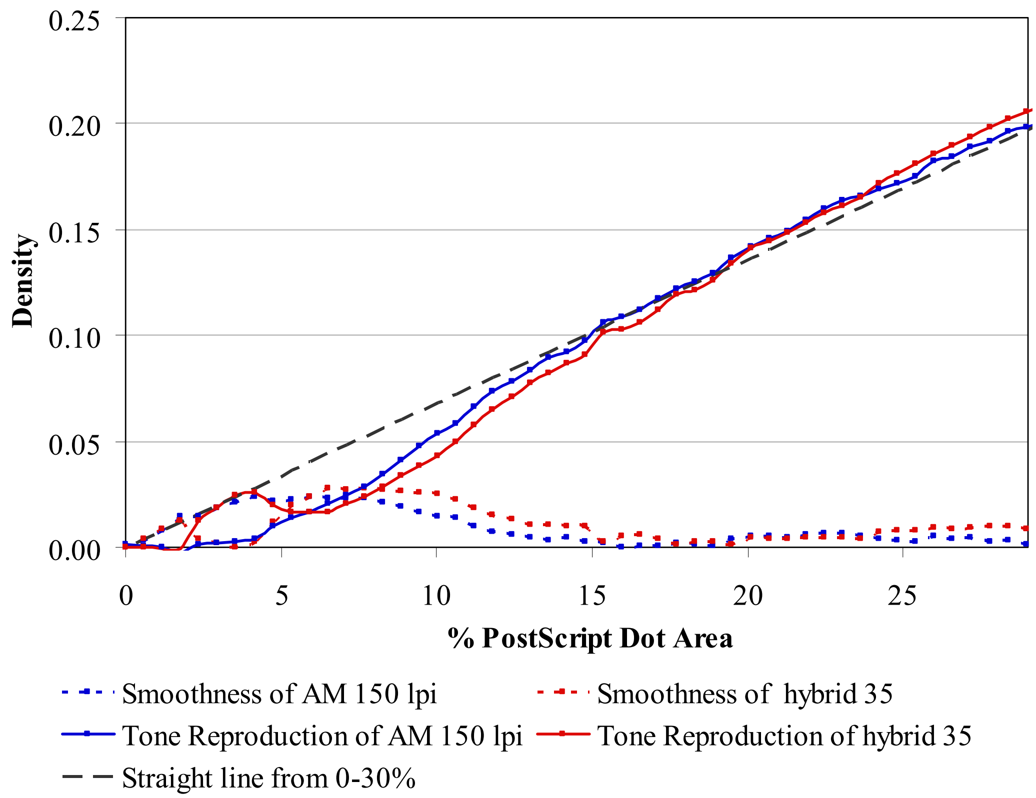

Figure D3. The Comparison of the Tone Reproduction and the Smoothness of AM, FM and Hybrid Screening of 1" Gradients

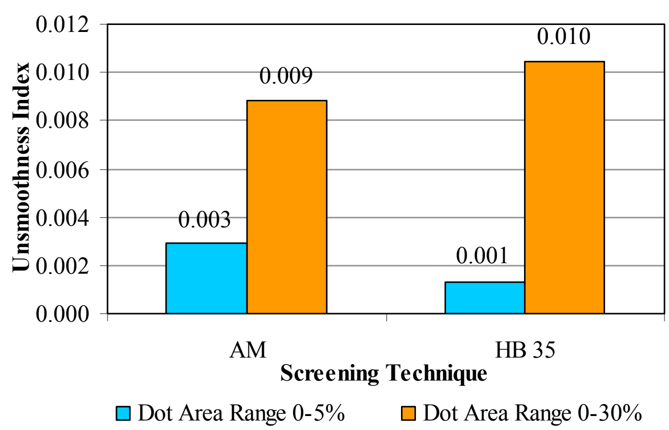

Figure D4. The Comparison of the Unsmoothness Index of AM, FM and Hybrid Screening of 1" Gradients in 0–5 and 0–30 Percent Dot Area Range

2" Gradients

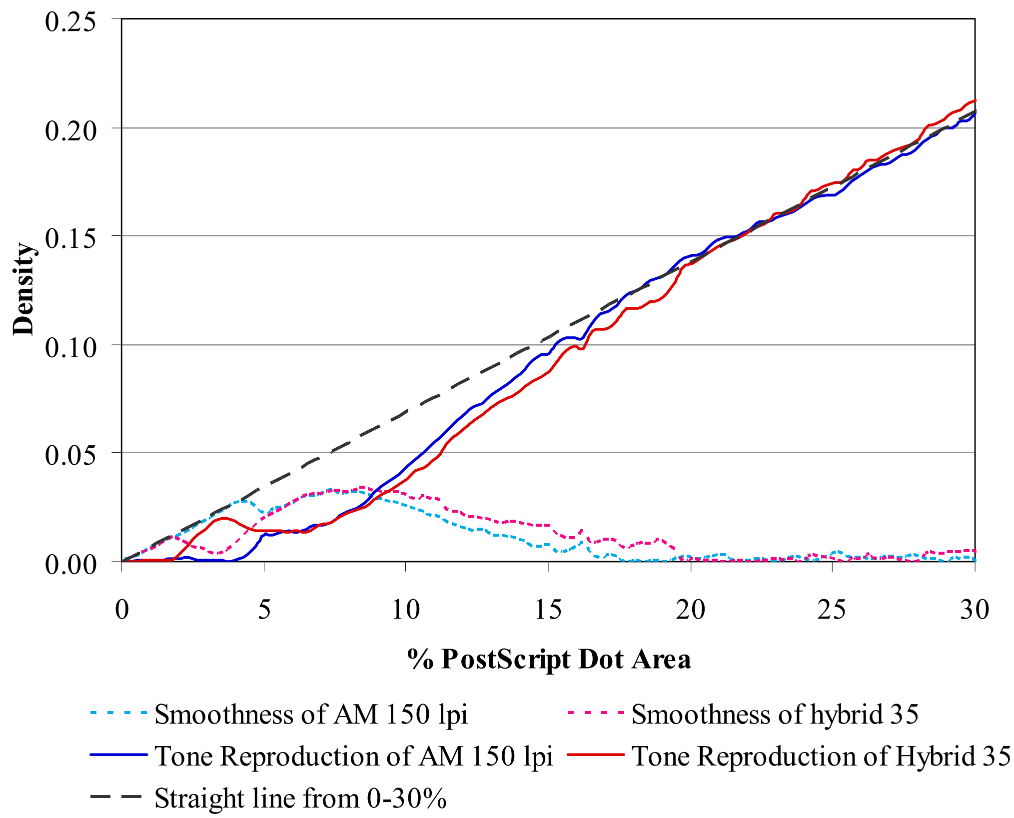

Figure D5. The Comparison of the Tone Reproduction and the Smoothness of AM, FM and Hybrid Screening of 2" Gradients

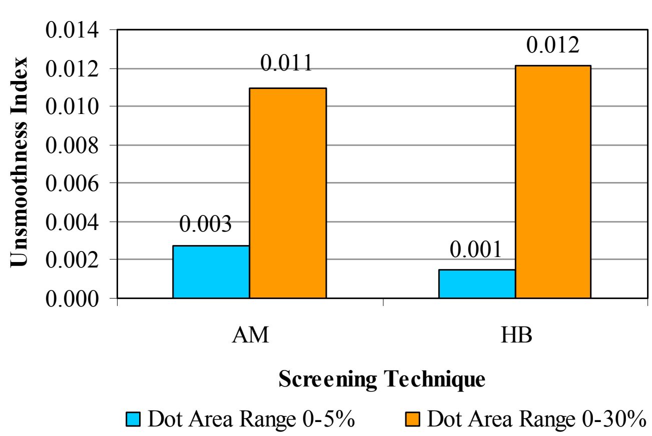

Figure D6. The Comparison of the Unsmoothness Index of AM, FM and Hybrid Screening of 2" Gradients in 0–5 and 0–30 Percent Dot Area Range

3" Gradients

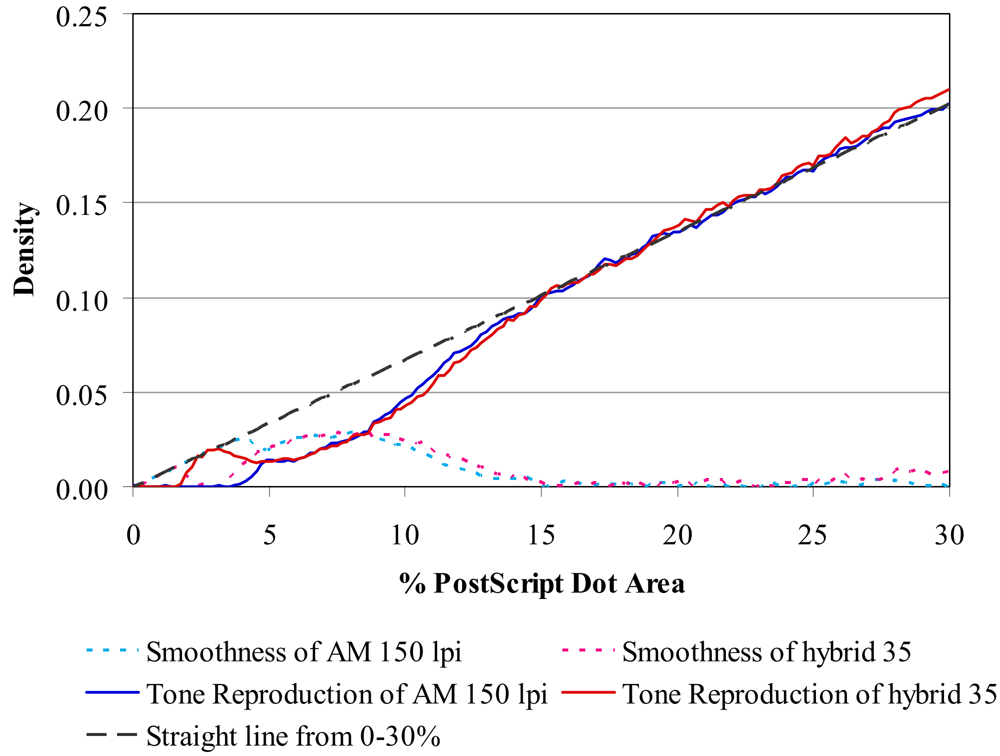

Figure D7. The Comparison of the Tone Reproduction and the Smoothness of AM, FM and Hybrid Screening of 3" Gradients

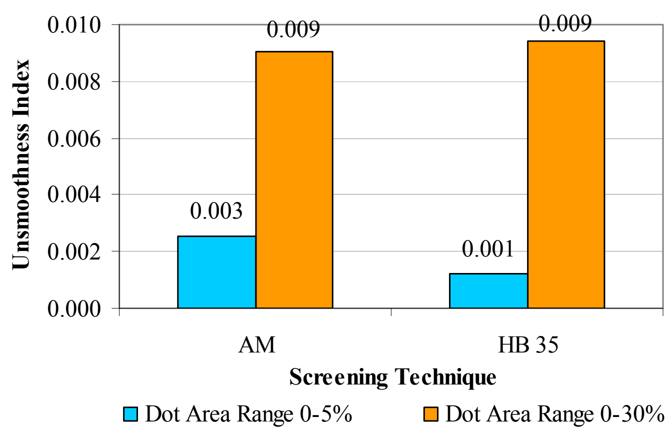

Figure D8. The Comparison of the Unsmoothness Index of AM, FM and Hybrid Screening of 3" Gradients in 0–5 and 0–30 Percent Dot Area Range

4" Gradients

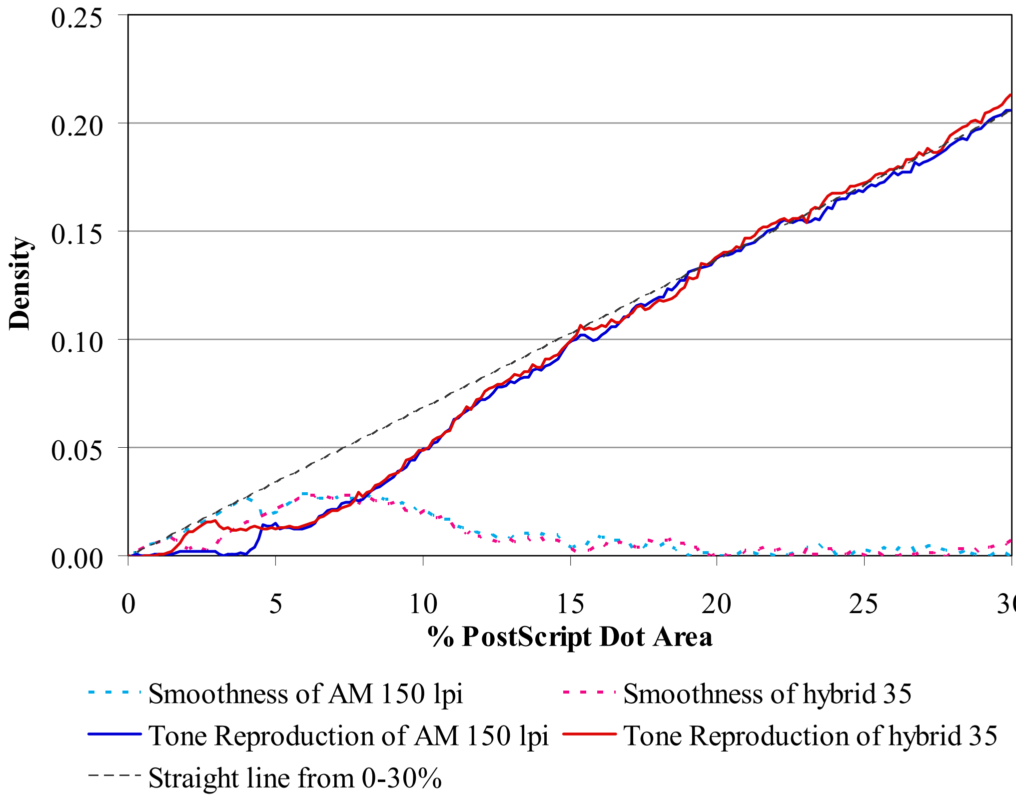

Figure D9. The Comparison of the Tone Reproduction and the Smoothness of AM, FM and Hybrid Screening of 4" Gradients

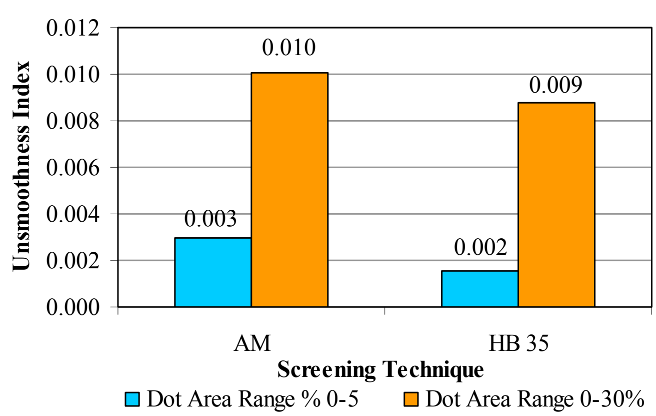

Figure D10. The Comparison of the Unsmoothness Index of AM, FM and Hybrid Screening of 4" Gradients in 0–5 and 0–30 Percent Dot Area Range

Appendix E

Appendix E

Analyzed Data from Visual Evaluation

0.5" Gradients

The data in Tables 12 and 13 were calculated using the same method used for the 0.25" gradients. There was no observer elimination in this data set since there was no logical inconsistency. Therefore, the total number of the valid observers was 30. To calculate standard deviation of the observation, "N" was replaced with 30. Therefore, the standard deviation used to define the error bars for 0.5" targets with and without outlines was 0.114.

Table E1. Data Analysis of 0.5" Targets with Outline

		AM	FM 35	HB 35
Frequencies	AM	-	1	7
	FM 35	29	-	28
	HB 35	23	2	-
p -observed proportions		AM	FM 35	HB 35
	AM	-	0.03	0.23
	FM 35	0.97	-	0.93
	HB 35	0.77	0.07	-
z-scores		AM	FM 35	HB 35
	AM	-	-1.88	-0.74
	FM 35	1.88	-	1.48
	HB 35	0.74	-1.48	-
	Average	1.31	-1.68	0.37

Table E2. Data Analysis of 0.5" Targets without Outline

		AM	FM 35	HB 35
Frequencies	AM	-	7	13
	FM 35	23	-	25
	HB 35	17	5	-
p -observed proportions		AM	FM 35	HB 35
	AM	-	0.23	0.43
	FM 35	0.77	-	0.83
	HB 35	0.57	0.17	-
z-scores		AM	FM 35	HB 35
	AM	-	-0.81	-0.13
	FM 35	0.81	-	0.95
	HB 35	0.13	-0.95	-
	Average	0.47	-0.88	0.41

<u>1" Gradients</u>

There was no observer inconsistency in the observation of the 1" target with outline, thus the total number of the observers was exactly 30. Whereas, there were two observers, that had logical inconsistencies for the 1" targets without outline, leading to the total number of observers to be 28 (Table E3–E4).

Table E3. Data Analysis of 1" Targets with Outline

		AM	FM 35	HB 35
Frequencies	AM	-	2	14
	FM 35	28	-	28
	HB 35	16	2	-
p -observed proportions		AM	FM 35	HB 35
	AM	-	0.07	0.47
	FM 35	0.93	-	0.93
	HB 35	0.53	0.07	-
z-scores		AM	FM 35	HB 35
	AM	-	-1.48	-0.08
	FM 35	1.48	-	1.48
	HB 35	0.08	-1.48	-
	Average	0.78	-1.48	0.70

Table E4. Data Analysis of 1" Targets without Outline

		AM	FM 35	HB 35
Frequencies	AM	-	8	14
	FM 35	20	-	23
	HB 35	14	5	-
p -observed proportions		AM	FM 35	HB 35
	AM	-	0.29	0.50
	FM 35	0.71	-	0.82
	HB 35	0.50	0.18	-
z-scores		AM	FM 35	HB 35
	AM	-	-0.55	0.00
	FM 35	0.55	-	0.92
	HB 35	0.00	-0.92	-
	Average	0.28	-0.74	0.46

2" Gradients

Table E5. Data Analysis of 2" Targets with Outline

		AM	FM 35	HB 35
Frequencies	AM	-	3	14
	FM 35	24	-	24
	HB 35	13	3	-
p -observed proportions		AM	FM 35	HB 35
	AM	-	0.11	0.52
	FM 35	0.89	-	0.89
	HB 35	0.48	0.11	-
z-scores		AM	FM 35	HB 35
	AM	-	-1.23	0.05
	FM 35	1.23	-	1.23
	HB 35	-0.05	-1.23	-
	Average	0.59	-1.23	0.64

Three logically inconsistent observers were eliminated from the data of 2" targets with outline. Therefore, there were only 27 valid observers used in the calculations. Also, there was one observer that was pulled from the data of 2" targets without outline, as its judgment result was not logically consistent. Therefore, the final number of the valid observers of 2" targets without outline was 29 (Table E5–E6).

Table E6. Data Analysis of 2" Targets without Outline

		AM	FM 35	HB 35
Frequencies	AM	-	12	18
	FM 35	17	-	21
	HB 35	11	8	-
p -observed proportions		AM	FM 35	HB 35
	AM	-	0.41	0.62
	FM 35	0.59	-	0.72
	HB 35	0.38	0.28	-
z-scores		AM	FM 35	HB 35
	AM	-	-0.23	0.31
	FM 35	0.23	-	0.58
	HB 35	-0.31	-0.58	-
	Average	-0.04	-0.41	0.45

Summary Table for Visual Evaluation

Table E7. The Numeric Data of Targets with Outline

Length	Error Bars	Confidence Interval	AM		FM 35		HB 35		AM
	Upper	z-score + 0.23	0.98		-0.79		0.50		0.98
0.25"	**0.23**	**Average z-score**	**0.75**	Sig.	**-1.02**	Sig.	**0.27**	Sig.	**0.75**
	Lower	z-score - 0.23	0.52		-1.25		0.04		0.52
	Upper	z-score + 0.22	1.53		-1.46		0.59		1.53
0.5"	**0.22**	**Average z-score**	**1.31**	Sig.	**-1.68**	Sig.	**0.37**	Sig.	**1.31**
	Lower	z-score - 0.22	1.09		-1.90		0.15		1.09
	Upper	z-score + 0.22	1.00		-1.26		0.92		1.00
1"	**0.22**	**Average z-score**	**0.78**	Sig.	**-1.48**	Sig.	**0.70**	**---Insig.---**	**0.78**
	Lower	z-score - 0.22	0.56		-1.70		0.48		0.56
	Upper	z-score + 0.24	0.83		-0.99		0.88		0.83
2"	**0.24**	**Average z-score**	**0.59**	Sig.	**-1.23**	Sig.	**0.64**	**---Insig.---**	**0.59**
	Lower	z-score - 0.24	0.35		-1.47		0.40		0.35

Table E8. The Numeric Data of Targets without Outline

Length	Error Bars	Confidence Interval	AM		FM 35		HB 35		AM
	Upper	z-score + 0.24	1.14		-0.84		0.42		1.14
0.25"	**0.24**	**Average z-score**	**0.90**	Sig.	**-1.08**	Sig.	**0.18**	Sig.	**0.90**
	Lower	z-score - 0.24	0.66		-1.32		-0.07		0.66
	Upper	z-score + 0.22	0.69		-0.66		0.63		0.69
0.5"	**0.22**	**Average z-score**	**0.47**	Sig.	**-0.88**	Sig.	**0.41**	**---Insig.---**	**0.47**
	Lower	z-score - 0.22	0.25		-1.10		0.19		0.25
	Upper	z-score + 0.23	0.51		-0.51		0.69		0.51
1"	**0.23**	**Average z-score**	**0.28**	Sig.	**-0.74**	Sig.	**0.46**	**---Insig.---**	**0.28**
	Lower	z-score - 0.23	0.05		-0.97		0.23		0.05
	Upper	z-score + 0.23	0.19		-0.18		0.68		0.19
2"	**0.23**	**Average z-score**	**-0.04**	Sig.	**-0.41**	Sig.	**0.45**	Sig.	**-0.04**
	Lower	z-score - 0.23	-0.27		-0.64		0.22		-0.27