Correlating Changes in Densitometry and Colorimetry in the Context of the Light-Induced Fade of Inkjet Photographic Prints

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Abstract

The current ANSI standard method for evaluating the image stability of photographic prints (ANSI IT9.9-1996) calls for the use of densitometry in order to determine the extent of light-induced fade and to provide an estimate of print-life under real-world conditions. End-of-life criteria based on densitometry can involve monitoring simultaneously as many as 24 different end-points (excluding changes to D_{min}). Conceivably, end-of-life criteria based on colorimetric measures such as ΔE or ΔC could reduce the number of end-points from 24 to as few as 7—one criterion for each primary (cyan, magenta, yellow), secondary (blue, green, red), and neutral (gray/black) test patch. In the context of evaluating inkjet photographic prints based on hundreds of different combinations of various manufacturers' inks and receivers, we have been following the kinetics of dye-fade by both Status A densitometry and CIELAB colorimetry. In this report, we will begin to explore the empirical correlation between densitometric and colorimetric measures of color change.

Introduction

The explosion of digital images available from scanners, digital cameras, and the Internet has driven a commensurate demand for printing those images. Today there are multiple technologies available for printing digital images on the desktop in the home and/or office. "Photo quality" inkjet printers are available for under $100 that can print on media ranging from plain paper to heavyweight photographic stock. There are concerns regarding image stability and physical durability, however, with respect to the long-term storage and/or display of inkjet prints.[1-11] There are several current standards for assessing the image stability of print materials with respect to both light- and heat-induced effects on image stability.[12-14] Another issue in quantifying the image stability of a print has to do with how change is monitored. Although status A densitometry ("ΔD") is recommended in the current ANSI standard,[12] CIELAB colorimetry ("ΔE")[15] has also been used to compare changes in color quality for light-induced fade.[16]

In this report, we explore the relationship between densitometric and colorimetric measures of change in the context of light fade end-points for inkjet photographic prints.

Materials and Methods

Materials

The following printers (and their recommended inks) were used to generate the test targets used for this study: Hewlett-Packard DeskJet 990, Epson Stylus Photo 870, Canon 8200 and S800, Lexmark Z55, and Kodak personal picture maker 200. In addition to the printer manufacturers' recommended photo-quality papers, a variety of third-party papers are also included in this analysis. The inks and papers are representative of commercial products available at retail in 2001.

Methods

The test targets and test methods have been described previously.[4,11] The test targets used in this study comprised step wedges of cyan, magenta, yellow, red, green, blue, and neutral. Each wedge included four coverages of each color: 25, 50, 75, and 100%. Care was taken to ensure that pure colors were printed wherever possible. The test targets were treated under the following conditions: (a) 80 klux, Plexiglas-filtered cool white fluorescent, 23 ± 2°C/50 ± 3% RH, and (b) 5.4 klux, Plexiglas-filtered cool white fluorescent, 23 ± 2°C/50 ± 3% RH. The samples were rotated either manually or mechanically to ensure homogeneous exposure during the course of the study.

The test targets were monitored periodically by status A densitometry and CIELAB colorimetry using a Gretag/Macbeth Spectro Scan T 3.273 spectrophotometer/colorimeter. At each time interval, plots of ΔD and ΔE vs initial density (D_o) were made for each primary color, secondary color, and neutral density. For the ΔD plots of the secondary colors, each of the two primary colors that comprise the secondary color was plotted separately. For the neutral density wedge, all three primary colors were plotted. From these plots, ΔD and ΔE for each color were interpolated to $D_0 = 1.0$ above D_{min} at each exposure interval.

As a means of correlating ΔD and ΔE, densitometric print-life end-points based on guidelines contained in ANSI IT9.9 –1996 (see Table 1) were correlated with ΔE as follows. The cumulative exposures required to reach the various densitometric end-points were determined by plotting ΔD (referenced to $D_0 = 1.0$ as described above) vs cumulative exposure for each ink-paper combination. For almost all cases, either a natural log or linear least squares equation provided a good fit through each data set. To be included in the subsequent analysis, the following criteria were applied to each data set: (a) the correlation coefficient (R^2) must be ≥ 0.97, and (b) the end-point must have been reached after the first reading and before the last reading (no extrapolated end-points). For the 30% end-points (1-12 in Table 1), ΔD was set to 0.30, and the best-fit equation was solved for cumulative exposure. For the 15% differential fade end-points (13-24 in Table 1), the best-fit lines for each primary were mathematically subtracted, the difference in density between the two primaries was set to 0.15, and cumulative exposure was calculated. Using the cumulative exposures thus calculated, ΔE at each densitometric end-point was derived from the best-fit equations of ΔE vs cumulative exposure. For a given ink-paper combination, multiple end-points may be reached, which satisfy the above criteria and all were included in the correlation; however, for the secondary and neutral colors, only the first end-point reached was used in the correlation.

Table 1. End-point criteria based on ANSI IT9.9 – 1996.

No.	Description	ΔD
1	Pure Yellow Patch	0.30
2	Yellow in Green Patch	0.30
3	Yellow in Red Patch	0.30
4	Yellow in Neutral Patch	0.30
5	Pure Magenta Patch	0.30
6	Magenta in Blue Patch	0.30
7	Magenta in Red Patch	0.30
8	Magenta in Neutral Patch	0.30
9	Pure Cyan Patch	0.30
10	Cyan in Green Patch	0.30
11	Cyan in Blue Patch	0.30
12	Cyan in Neutral Patch	0.30
13	Yellow-Cyan Color Balance in Green	0.15
14	Yellow-Magenta Color Balance in Red	0.15
15	Yellow-Cyan Color Balance in Neutral	0.15
16	Yellow-Magenta Color Balance in Neutral	0.15
17	Magenta-Cyan Color Balance in Blue	0.15
18	Magenta-Yellow Color Balance in Red	0.15
19	Magenta-Cyan Color Balance in Neutral	0.15
20	Magenta-Yellow Color Balance in Neutral	0.15
21	Cyan-Yellow Color Balance in Green	0.15
22	Cyan-Magenta Color Balance in Blue	0.15
23	Cyan-Yellow Color Balance in Neutral	0.15
24	Cyan-Magenta Color Balance in Neutral	0.15

Results and Discussion

Overview

In previous studies of light-induced fade of inkjet prints, both densitometry and colorimetry have been used to monitor the extent of dye fade.[1,4,8,9,11] Hofmann, et al., attempted to correlate ΔD and ΔE for a variety of image stability tests, including light, thermal, and pollutant fade.[17] In their light fade example, they concluded that ΔE = 17 correlated well with density changes of 20% magenta, 30% cyan, and 35% yellow, respectively. It was suggested that ΔE of about 15 might be a good approximation for the end-point criteria given in ANSI IT9.9.

One argument for the use of ΔE-based end-points is that the ΔE formula was designed to uniformly evaluate small to medium surface color differences.[18] An additional benefit of ΔE is that only a single end-point criterion would be required for each primary, secondary, and neutral color, resulting in a list of only 7 end-point criteria vs the list of 24 separate densitometric criteria given in Table 1, excluding end-points related to changes in D_{min}.

On the other hand, the correlation of ΔE, as commonly defined (see Eq. 1 below),[16] with perceived color differences has been found to vary greatly depending upon the hue, lightness, and saturation of the reference color.[19] A revised CIE 2000 color difference formula, ΔE_{00}, has been adopted, which reportedly improves the correlation to perceived color differences, especially in the blue and gray color regions.[19] To be consistent with previous work in this field, we have used the following formula for ΔE:

$$\Delta E = \Delta E^*_{ab} = [\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}]^{1/2} \qquad (1)$$

Correlation of Densitometric End-Points with ΔE

Using the methodology described above, we have compiled a correlation table of the densitometric end-point criteria listed in Table 1 with the calculated values of ΔE at those end-points for over 300 different data sets. Table 2 summarizes these results, where n is the number of times that specific end-point was encountered, ΔE_{ave} is the average of the ΔE values calculated for that end-point, and σ is the standard deviation.

Focusing first on the pure primaries (end-points 1, 5, and 9), ΔE_{ave} compiled for these end-points range from a low of 11 for cyan (n = 73) to 18 for magenta (n = 96) and 19 yellow (n = 65). These values for ΔE are reasonably consistent, given the relatively large standard deviations, with those reported by Hofmann, et al.[17] Other workers in this field have postulated that the human observer should be most sensitive to changes in magenta, followed by cyan and yellow, and have weighted the densitometric endpoints accordingly.[20] However, if indeed colorimetric changes based on ΔE are uniformly weighted for the human visual response; these results suggest there is roughly equal visual sensitivity to a 0.30 density loss from a 1.0 initial density for magenta and yellow, with a somewhat lesser sensitivity to 0.30 loss for cyan.

Table 2. Correlation table of ΔE with densitometric end-points. Only end-points for which $n \geq 10$ are included.

No	Property	ΔD	Cyan			Magenta			Yellow			Red			Green			Blue			Neutral		
			n	ΔE_{ave}	σ	n	ΔE_{ave}	σ	n	ΔE_{ave}	σ	n	ΔE_{ave}	σ	n	ΔE_{ave}	σ	n	ΔE_{ave}	σ	n	ΔE_{ave}	σ
1	Pure Yellow Patch	0.30							65	19	2												
2	Yellow in Green Patch	0.30													43	20	2						
3	Yellow in Red Patch	0.30										50	17	2									
4	Yellow in Neutral Patch	0.30																			51	12	6
5	Pure Magenta Patch	0.30				96	18	3															
6	Magenta in Blue Patch	0.30																74	18	4			
7	Magenta in Red Patch	0.30										<10											
8	Magenta in Neutral Patch	0.30																			<10		
9	Pure Cyan Patch	0.30	73	11	2																		
10	Cyan in Green Patch	0.30													<10								
11	Cyan in Blue Patch	0.30																<10					
12	Cyan in Neutral Patch	0.30																			<10		
13	Yellow-Cyan in Green	0.15													10	18	1						
14	Yellow-Magenta in Red	0.15										21	12	3									
15	Yellow-Cyan in Neutral	0.15																			<10		
16	Yellow-Magenta in Neutral	0.15																			<10		
17	Magenta-Cyan in Blue	0.15																<10					
18	Magenta-Yellow in Red	0.15										<10											
19	Magenta-Cyan in Neutral	0.15																			<10		
20	Magenta-Yellow in Neutral	0.15																			<10		
21	Cyan-Yellow in Green	0.15													<10								
22	Cyan-Magenta in Blue	0.15																<10					
23	Cyan-Yellow in Neutral	0.15																			<10		
24	Cyan-Magenta in Neutral	0.15																			<10		

For the secondary colors there are four possible end-point criteria, and for the neutral patch, there are six. For this analysis, only the first one of the multiple end-points per color that is reached for a given test sample is included in Table 2. It can be seen that for each of these color patches one of the multiple criteria tends to occur most frequently.

For red, 0.30 yellow density loss (end-point 3) is the end-point most often encountered, with $\Delta E_{ave} = 17$ (n = 50). Likewise for green, 0.30 density loss in the yellow record (end-point 2) is also the most often encountered, $\Delta E_{ave} = 20$ (n = 43). In the case of blue, 0.30 magenta loss (end-point 6) yields $\Delta E_{ave} = 18$ (n = 74). These ΔE_{ave} values are reasonably consistent with those found for the pure yellow and magenta end-points. For the neutral patch, 0.30 loss of yellow is frequently encountered. In this case, $\Delta E_{ave} = 12$ is much lower; however, $\sigma = 6$ is quite high.

The only other secondary or neutral patch end-points with 10 or more occurrences are the yellow-cyan color balance in green (end-point 13, n = 10) and the yellow-magenta color balance in red (end-point 14, n = 21). Again, given the substantial standard deviations, these values of ΔE_{ave} are generally consistent with those discussed above.

Additional Observations

To gain further insights, we also looked at the ΔD vs ΔE correlation for the 80-klux and 5.4-klux conditions separately. In general, there were far fewer end-points reached under the 5.4-klux condition. For those end-points for which a statistically significant number of end-points were reached under both exposure conditions, the results were in reasonably good agreement.

We also looked at the ΔD vs ΔE correlation separately for porous vs swellable ink-receptive layers. The results were again reasonably consistent. It is interesting to note that σ was consistently lower for the swellable receivers. Further studies are required to better understand the factors responsible for the observed variability in the correlation.

Summary

We were able to correlate changes in colorimetry, as measured by ΔE, with light fade end-points defined in terms of density change, ΔD for over 300 inkjet test targets. A common value for ΔE for each end-point was not obtained, however, and the calculated standard deviations were quite large. Further studies are recommended, including the use of ΔE_{00} in place of ΔE^*_{ab}.

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Biography

Douglas Bugner received his B.S. in Chemistry from the Ohio State University in 1975, a M.S. in Organic Chemistry from UCLA in 1980, and a Ph.D. in Organic Chemistry from UCLA in 1982. In 1982, Dr. Bugner joined the Chemical Technology Laboratory in the Photomaterials Division of Eastman Kodak Company. In 1988, he accepted an assignment in the Photoconductor Technology Laboratory, and in 1991, he was appointed manager of the Chemical Technology Lab. In 1993, Dr. Bugner established a research effort in the area of inkjet materials, and is currently Senior Laboratory Head, Desktop Commercialization Laboratory, Inkjet Materials and Printing Systems Division, Eastman Kodak Company.

In 1994, Dr. Bugner received the Distinguished Inventor Award, and in 1997, he completed the Executive Development Program at the Tuck School of Business at Dartmouth. He currently holds 57 U.S. Patents, and has authored over 20 scientific publications. He is a member of the American Chemical Society, the Society for Imaging Science and Technology, and the Project Management Institute.