Optimizing Print Sequence for Expanded Color Gamut

Liam O'Hara[1] and Bobby Congdon[1] and Brad Gasque[2]

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Abstract

The use of additional inks to augment the reproducible color gamut of CMYK process color sets has been employed for decades now, but the movement towards standardized processes for expanded color gamut (ECG) has only recently gained momentum. To this end, the Flexographic Image Reproduction Specifications and Tolerances document, FIRST 5.0, has established a base set of pigments for Orange, Violet and Green inks, which were employed in this study. However, the issue of print sequence has yet to be addressed in an official manner. In this paper, the authors investigate the print sequence for a FIRST-compliant ECG UV ink set with the goal of achieving the greatest possible gamut of reproducible colors.

This work was conducted on a seven-color OMET Varyflex flexographic printing press using single-pigment UV inks on coated paper. The modular nature of the press allowed the researchers to move entire printing decks around within the press, thus ensuring minimal variation in the production other than ink sequence. Four sequences (KCMYOGV, KOVGCMY, KCGVMOY, and KYOMGVC) were conducted to insert the OGV inks either before, in between, or after their process ink components. Overall gamut volumes were measured, and the two-color overprints were examined with respect to their chroma, opacity, hue angle and lightness. From this analysis, a model for optimizing ink sequence is proposed. This study has bearing on four-color process printing as well as expanded color gamut—gamut expansions of 106% (4/c process comparisons) and 107% (ECG comparisons) were obtained through adjusting print sequence.

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[1] Clemson University; [2] DuPont Advanced Printing

Introduction

Expanded color gamut printing (ECG) offers printers the opportunity to reduce their reliance on spot color formulations to achieve the brand color demands of consumer product companies (CPCs). Today's packaging often employs four-color process printing for photographic elements in the package design and the use of spot colors for high-chroma, high-impact brand colors for logos and brand recognition—three to four spot colors are not unusual in today's packaging. While some spot colors can be replicated with traditional four-color process, the chroma that can be achieved for many hues is limited, and subsequently four-color builds often fail to achieve the desired vividness that is required. The Pantone Color Book is a common reference for spot colors; approximately 40% of the Pantone book can be replicated using the GRACoL2006Coated1v2 printing gamut (Furr, 2014). Pantone claims that 90% of the Pantone book can be replicated using CMYK supplemented with orange, green, and violet ECG (Gundlach, 2015). In testing previously performed at Clemson University, a CMYKOGV ink set yielded 72% of the Pantone library with an average ΔE2000 of 1.39 (Furr, 2014).

The use of ECG enables printers to dramatically reduce makeready and tooling costs, particularly where jobs can be ganged together (Furr, 2014). These economic drivers have bolstered the adoption of ECG in packaging, and with this proliferation, the need for standardization becomes increasingly important to the brand owners to ensure consistent results from printers. Towards this end, the FTA (Flexographic Technical Association) has specified specific pigments and hue angles for CMYKOGV ink sets (depending on the whether the formulations are water-based, solvent or UV inks) in their FIRST specifications (FIRST 5.0, 2015). However, the question remains as to what sequence these inks should be incorporated into a CMYK process.

Prior research into ECG print sequences for flexography is fairly limited. A study at Western Michigan (Sheth, G., et al., 2013) compared YMCKOGV vs YOMGCVK, with both mono-pigmented (single-pigmented) and two-pigmented ECG inks. The study found enhanced gamut with mono-pigmented inks, and found that the YOMGCVK sequence provided a greater gamut (a comparison which held true with both mono- and two-pigment ink sets). The authors state that the YOMGCVK sequence was determined based on the transparency of the overprints. The gamut increases were 5.2% for the single-pigmented inks, and 4.9% for the two-pigment ink sets.

Another print sequence study employing flexographic printing was conducted at RIT on four-color process inks (Patel, 2009). Patel attempted five print sequences (YMCK, MYCK, CMYK, KYMC, and KCMY) and found that while certain sectors (red, green, blue) were enhanced by various sequences, he determined no overall superior gamut, although he notes the greatest black point density was achieved by KYMC.

Looking beyond flexo, there are a number of studies on print sequence for offset lithography, but the wet-on-wet trap of lithography plays a significant role in this, and is not applicable for flexography, which is a dry trap printing method. An optimization of the gravure printing process was performed by Chung and Hsu that employed ink sequencing (along with pigment concentration and gamma adjustments)—they found that they had improved the gamut by printing MYCK rather than the traditional KCMY generally used in gravure printing (Chung and Hsu, 2006).

This study was undertaken to provide a set of reference data for optimized print sequence for expanded color gamut in flexographic printing, focusing on where best to place OGV in relation to their analogous process pairs (for example, green in relation to cyan and yellow: GCY, CYG, CGY or YCG). After the completion of the test trials, the researchers set about finding a predictive model to allow one to optimize the sequence without the time and expense of multiple press trials.

Methodology

Print trials were conducted on an Omet Varyflex 530 flexographic printing press at Clemson University. A set of characterization plates were made using 0.067-inch Dupont Cyrel DPR photopolymer plates using Esko Full HD screening on 4000 dpi RIP using an Esko CDI Spark UV2. This technology creates plates with “flat top” dot profiles by employing a high-intensity bank of UV lights that overwhelm the oxygen inhibition to create flat-top dot features. The plates were imaged at 175 lpi with circular dots and a relief of 0.020 inches. A randomized IT8.7/4 characterization target used to create profiles. The IT8.7/4 was reproduced twice on each plate, with the target in different orientations in order to capture the press variation across the substrate. In addition to the characterization chart, a color bar with solid patches of the seven primaries as well as the various two- and three-color overprints was included. The overprints also overprinted black as well in order to provide a basis for opacity measurements. Figure 1 shows the overprint target, which was used to acquire opacity data

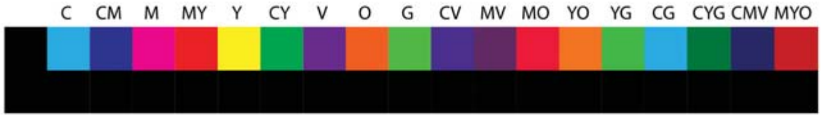


Figure 1. *Overprint Target*

The print trials were conducted using CMYKOGV mono-pigmented UV inks from Siegwerk (L39 series) that conformed to FIRST pigment specifications for ECG printing (FIRST 5.0) which are specified by hue angle. Table 1 shows the FIRST specifications.

UV inks	Hue Angle	Recommended Pigment
Orange	54°	C.I. Pigment Orange 64
Green	181°	C.I. Pigment Green 7
Violet	307°	C.I. Pigment Violet 23

Table 1. *FIRST 5.0 ECG ink specs for UV formulations*

Westrock 10 pt. Printcote paperboard was used for all trials. The press was run at 300 fpm for each of the print sequences tested. The modular nature of the press was ideal for a study of this nature—the individual print decks can be removed and repositioned to create the various ink sequences, so it was not necessary to clean the printing stations between sequence trials. Furthermore, the same anilox and blade was always used with each color, so there was minimal variation between the various sequences; the anilox roll, doctor blade and anilox-to-plate settings remained constant, and the only the plate-to-substrate impression had to be reset. The anilox rolls were ceramic rolls with a 60° angle, and Flexo Concepts Composite blades were employed on each station. The cpi/bcm specifications for the anilox rolls for each station were K: 800/2.0; CMY 1200/1.8; OGV 900/2.2. Lastly, UV inks provide great stability as there are no amines or solvents to monitor and replenish. The solid ink specs between press runs were maintained within 1.0 ΔEab. Once impressions were set and solid ink colors confirmed to match between runs, the press was run at 300 fpm for a minimum of two minutes.

The study employed the Esko Equinox strategy of running four sets characterization targets—CMYK, CGYK, OMYK and CMVK—rather than a single characterization. In this way, each of the ECG primaries is only sampled with its analogous process colors—for instance, orange is only useful in the red sector, so it is only sampled with yellow and magenta for hue and chroma, with black providing tone—Equinox employs a 100% GCR strategy. Due to the constraints of web width and repeat length (20 inches wide and 18-inch repeat), it was not possible to compile all four

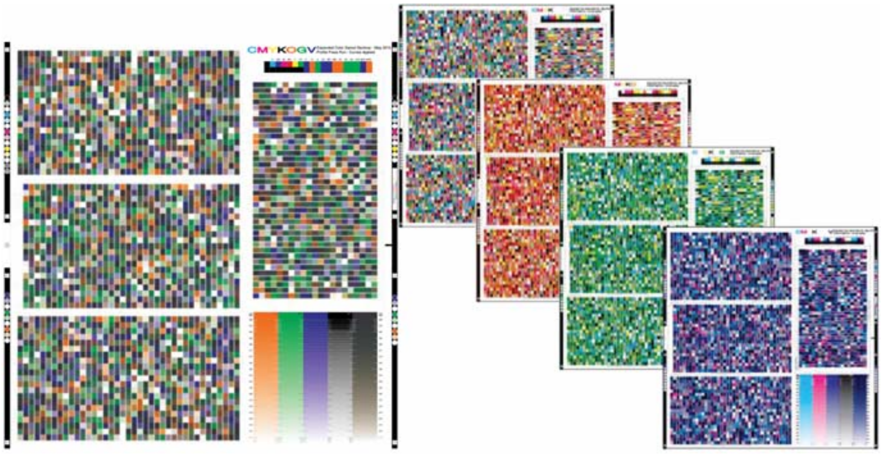


Figure 2. *Four sets of characterizations for CMYK integrated with OGV*

characterization targets on a single set of plates. So the OGV plates were made identical to their complementary process colors, and once a print sequence was set up, the various print stations were turned on and off to create the four sets of characterization targets necessary to create the profile. Figure 2 illustrates how the full 7/c target was "broken down" to create the four sets of targets.

Three print sequences were tested with the aim of placing the OGV primaries before, between, and after their analogous process colors: KCMYOGV, KOGVCMY, and KCGVMOY. It is standard practice at Clemson to print KCMY, and the researchers elected to restrict the print sequence study to the placement of OGV within that sequence, a decision motivated to limit the number of press runs for the experiment. A fourth sequence, KYOMGVC, was added to investigate the "between" strategy with the process colors reversed, to provide data on MOY and YOM (for example). Ten samples were pulled from each of the press runs, and from these, three sets were measured using an X-Rite i1iO table via MeasureTool 5.0.8. The three measurements were then averaged, and the averaged data was used to create ECG profiles via Equinox Profile Creator software. Color Engine Pilot was used to compare the resulting gamut volumes.

Results and Discussion

Figure 3 shows the resulting volumes expressed as a percentage as compared to the smallest gamut. The cubic L*a*b* units are indicated on the y-axis.

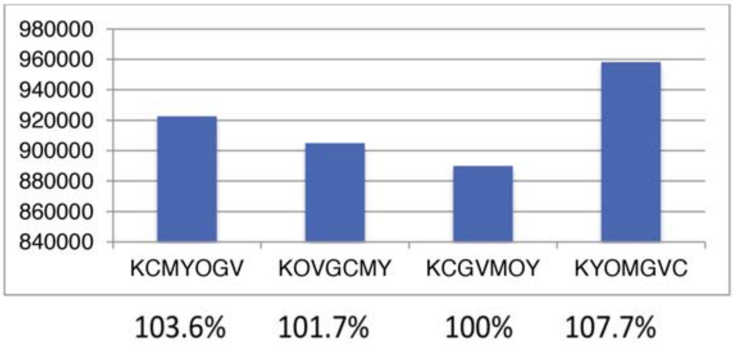


Figure 3. *Gamut volumes for the print sequences*

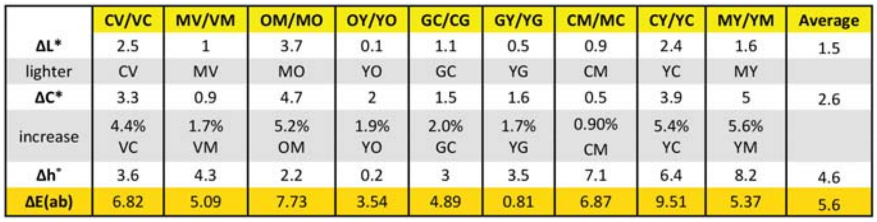
When initiating this project, the researchers' first assumption was that the optimal sequence would be determined by the opacity of the primary colors. The assumption was that more opaque inks should be printed first, with higher transparency inks overprinting them. The opacity of the primaries, from high to low, are as follows: V–15.71, O–10.48, M–6.34, Y–4.83, C–4.06, G–3.76. The closest sequence printed in this study to this scenario was the KOVGCMY, which has violet and orange printing before their process color pairs. Green was the least opaque ink, but the difference in opacity between it and its analogous process colors, cyan and yellow, is far less than than that of violet and orange, which are 2–3 times as opaque as the other inks. Opacity was determined from the printed samples by measuring XYZ tristimulus values with Illuminate C and a 2˚ observer function and using the CIE opacity formula:

$$\text{Opacity} = 100(Y_0/Y_\infty)$$

$$\text{Where: } Y_0 = \text{Black backing and } Y_\infty = \text{White backing} \qquad (1)$$

However, as Figure 3 illustrates, placing orange and violet first yielded one of the smaller gamuts, which suggests that sequencing based on the opacity of the primaries does not yield the optimal gamut. This led the researchers to look for other means to model and predict an optimized ECG print sequence.

The researchers next examined the changes in L*C*h˚ of the various two-color overprints of the CMYOGV color pairs depending on sequence. Table 2 shows the overprint pairs and the resulting ΔL*, ΔC* and Δh˚ results, as well as the overall ΔE_{ab} of the print sequences. In addition, the average difference for the various color pairs is shown on the right; it can be seen that hue angle is color attribute most affected by the print sequence.



	CV/VC	MV/VM	OM/MO	OY/YO	GC/CG	GY/YG	CM/MC	CY/YC	MY/YM	Average
ΔL*	2.5	1	3.7	0.1	1.1	0.5	0.9	2.4	1.6	1.5
lighter	CV	MV	MO	YO	GC	YG	CM	YC	MY	
ΔC*	3.3	0.9	4.7	2	1.5	1.6	0.5	3.9	5	2.6
increase	4.4% VC	1.7% VM	5.2% OM	1.9% YO	2.0% GC	1.7% YG	0.90% CM	5.4% YC	5.6% YM	
Δh˚	3.6	4.3	2.2	0.2	3	3.5	7.1	6.4	8.2	4.6
ΔE(ab)	6.82	5.09	7.73	3.54	4.89	0.81	6.87	9.51	5.37	5.6

Table 2. *L*C*h˚ of the ECG overprints*

The change in chroma due to sequence is more pronounced for some pairs than others. A sequence based on C*, in which the sequenced pair yielding the highest chroma is selected, would yield a sequence of KYGVOCM. Of the sequences actually performed on press, this is closest to the KYOMGVC sequence, which yielded the highest gamut. However, chroma doesn't tell the whole story, as the hue angle also plays a critical role. If the chroma is the same between two overprints, the overprint that is more centered on hue angle between the primaries will create the greatest area. This is illustrated in Figure 4, which depicts a hypothetical set of data in which the chroma is equal but the hue angle changes. Two overprints sequences are depicted, one of which is closer to its primary than the other. When the primaries and the overprints are connected, it is clear that the area of the triangle of the centrally located overprint (OM) is greater than the one that is closer to one of its primaries (MO):

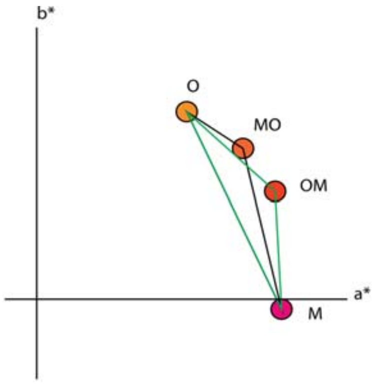


Figure 4. *Hypothetical triangle area of primaries and overprints*

Again, Figure 4 depicts hypothetical data for illustrative purposes. The actual triangle areas can be calculated by determining the length of the sides with a simple ΔEab equation, and then once the lengths of each side are known, the area of the triangle can be calculated using Heron's formula:

$$\text{Area} = \sqrt{[p(p-a)(p-b)(p-c)]}$$

Where p = half the perimeter of the triangle,
and the perimeter of the triangle is the sum of the sides (a+b+c), in which

$a = \Delta E_{ab}$ of Primary 1 to Overprint (i.e. M to MO)
$b = \Delta E_{ab}$ of Primary 2 to Overprint (i.e. O to MO)
$c = \Delta E_{ab}$ of Primary 1 to Primary 2 (i.e. M to O) (2)

Table 3 shows the resulting areas of triangles formed between the primaries and their overprints and the differences (ΔArea) between the print sequences. The largest area for each sequence is highlighted in gray. Some pairs yield much larger changes in area than others; these are highlighted in yellow. The differences in sequence for the others were marginal. This suggests that the sequence for orange in relation to magenta and green in relation to yellow are critical, but the sequence for violet in relation to cyan and magenta is not. The resulting print sequence based on triangle area is KYOMVCG; this is close to the KYOMGVC that had yielded our highest printed gamut volume.

	CM	**MY**	**CY**	**CV**	**MV**	**MO**	**YO**	**YG**	**CG**
	2719.8	2004.8	4240.7	644.9	753.6	734.4	681.4	2015.7	452.6
	MC	**YM**	**YC**	**VC**	**VM**	**OM**	**OY**	**GY**	**GC**
	2721.2	2347.4	4423	664.8	733.7	889	656.9	1777.3	434.5
Δ Area	1.4	342.6	182.3	19.9	19.9	154.6	24.5	238.4	18.1

Table 3. *ΔArea for overprint print sequence.*

The triangle area method is instructive, but the real issue in gamut optimization is volume. In order to predict volume based on two-color overprints, the three points of the triangles are combined with a L^*_{min} and L^*_{max} to create a three-dimensional shape. L^*_{max} is defined by the white point of the paper, but L^*_{min} can be a moving point due to the fact that its commonly a build of black and another color (a rich black rather than 100% black). This could result in the black point of the various color pairs overlapping or leaving "gaps" in the overall gamut. So for this model, a common, neutral black point was selected—$L^* = 9.5$, with a* and b* being 0. The researchers recognize that the true black point may not be captured in this fashion, but the goal of ECG is to expand chroma, not the black point, so we assume that a common black point will serve the purpose of optimizing for gamut expansion.

To calculate the volume of each gamut sector, the sector can be divided into two tetrahedrons: L^*_{max}, L^*_{min}, Primary 1, Overprint and L^*_{max}, L^*_{min}, Primary 2, Overprint. Figure 5 shows the individual tetrahedrons and how they combine to create the volume of an overprint sector, in this case MO. Each of the tetrahedrons shares a common face, L^*_{max}, L^*_{min}, and the overprint, MO.

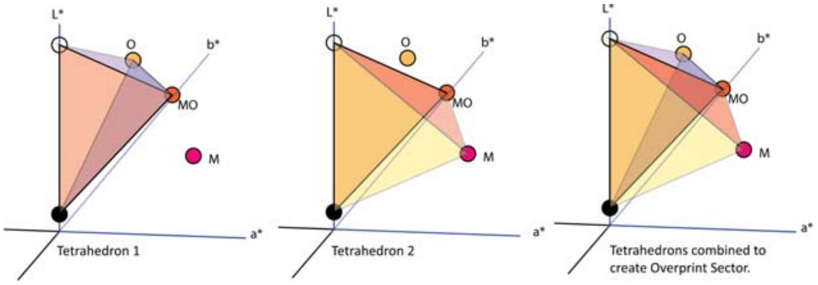


Figure 5. *Tetrahedrons that form an overprint sector volume*

To calculate the volume of each tetrahedron within the overprint sector, one can use the four L*a*b* points of the tetrahedron to extrapolate a parallelpiped, as illustrated in Figure 6:

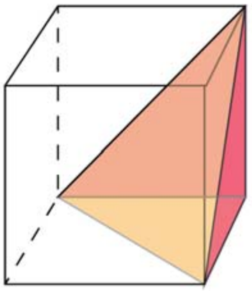


Figure 6. *Extrapolating a parallelpiped from the four points of a tetrahedron.*

The volume of a parallelepiped (Vp) can be calculated from the four L*a*b* points:

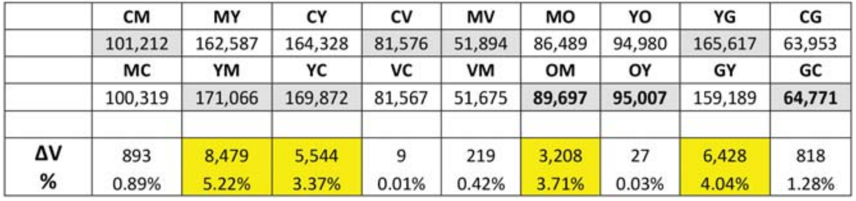
$$\begin{aligned}V_p = {} & (L_4-L_1)[(a_2-a_1)(b_3-b_1)-(b_2-b_1)(a_3-a_1)] \\ & +(a_4-a_1)[(b_2-b_1)(L_3-L_1)-(L_2-L_1)(b_3-b_1)] \\ & +(b_4-b_1)[(L_2-L_1)(a_3-a_1)-(a_2-a_1)(L_3-L_1)] \qquad (3)\end{aligned}$$

Once the volume of the extrapolated parallelpiped has been determined, the volume of the tetrahedron can determined:

$$V_t = \frac{Vp}{6} \qquad (4)$$

To determine the volume of the overprint sector, simply add the two tetrahedrons volumes together. Once the volume of each sector dependent on the print sequence of the overprint has been determined, the larger volume is the optimal sequence for that particular color pair. Of course, this is a simplified model for the gamut sector as it reduces the shape to straight lines and flat planes, whereas the actual shape of a gamut sector is a curved geometry due to factors such as TVI, trapping, and hue error, but the goal of the model is to be able to optimize sequence based the primaries and overprints. To calculate the curved geometry would require far more data, which could be prohibitively complex.

Working from the printed overprints from the various experimental sequences, the overprint sector volumes for each color pair and their differences (ΔV) were determined and shown in Table 4. The largest volume for each sequence is highlighted in gray. Some pairs yield much larger changes in area than others; these are highlighted in yellow. The differences in sequence for the others were marginal. As was true of the triangle area method, this suggests that the sequence for orange in relation to magenta and green in relation to yellow have a relatively high impact, but the sequence for violet in relation to cyan and magenta does not. The resulting print sequence based on overprint sector volume is KOYGCMV.



	CM	**MY**	**CY**	**CV**	**MV**	**MO**	**YO**	**YG**	**CG**
	101,212	162,587	164,328	81,576	51,894	86,489	94,980	165,617	63,953
	MC	**YM**	**YC**	**VC**	**VM**	**OM**	**OY**	**GY**	**GC**
	100,319	171,066	169,872	81,567	51,675	**89,697**	**95,007**	159,189	**64,771**
ΔV **%**	893 0.89%	8,479 5.22%	5,544 3.37%	9 0.01%	219 0.42%	3,208 3.71%	27 0.03%	6,428 4.04%	818 1.28%

Table 4. *ΔV for overprint sector volumes*

Thus, of the four print sequences performed on press, none of them actually match the result of the predictive model. However, the predictive model does accurately rank the volume of the four printed sequences in the same fashion, and a comparison of the predicted volume and the printed volume shows that they are relatively similar. Again, the predictive model is a simplified geometry of flat planes, as opposed to the curved contours of the actual gamut. Figure 7 shows the calculated volumes and actual printed volumes for comparison.

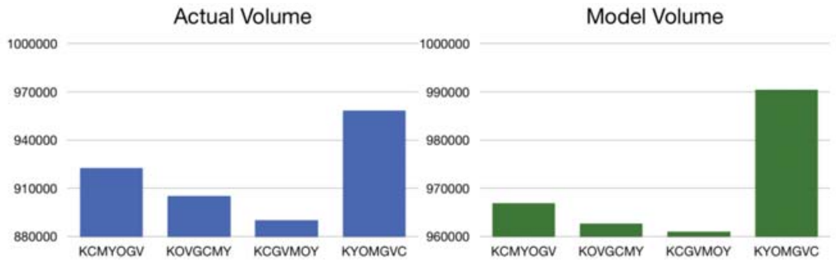


Figure 7. *Actual Volume vs. Model Volume*

In looking at the results of the four printed sequences, it is interesting to isolate the gamut expansion of the KCMY sequence as well. There was a 106.2% increase in gamut volume between running KCMY and KYMC.

Figure 8 shows the gamut expansion between the best of the printed sequences (depicted in green) and the worst printed sequence (depicted in red; the brown is where they overlap) in terms of gamut area of a*b* plots at various L* levels. It can be seen that the greatest expansion is in the green and orange sectors, with little difference in the violet sector. This is due primarily to the sequence of MO and YG (which are shown to have greatest impact on volume in Table 4), and reinforces the observation that violet's sequence with cyan and magenta has minimal impact on the gamut volume. The gamut expansions are most prevalent at L* values below 50.

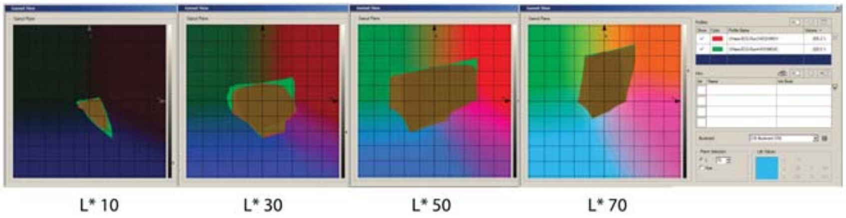


Figure 8. *a*b* Gamut Views at Various L* levels*

Opportunities for further research

Four ECG print sequences were performed on press: KCMYOGV, KOVGCMY, KCGVMOY, and KYOMGVC. The experimental press trials yielded the greatest gamut with KYOMGVC. Subsequent work with the predictive model suggested that KOYGCMV would have yielded a somewhat larger gamut. The researchers intend to perform press trials to confirm this finding.

The research also indicates opportunities to improve four color process work by moving from KCMY to KYMC (a 106% increase). Further exploration of print sequence for KCMY also seems warranted.

The researchers are hopeful that the predictive model developed in this paper will allow printers to work from a set of drawdowns of primaries and their overprints to optimize print sequence without the expense of multiple press runs, regardless of whether they use standardized OGV to supplement CMYK or if they adopt other spot colors into an ECG strategy. Future research will explore the application of this methodology to n-color and modified process situations.

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