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Image Permanence Evaluation by Color Gamut Volume Changes*

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Abstract. *Gamut volume is one of the parameters generally used for the characterization of printers and other imaging devices. However, it can also be used for monitoring color print fading. Relative gamut volume changes plotted as a function of the exposure dose can be conveniently used to determine the fading rate and corresponding lifetime. Calculation of the gamut volume is a challenge on its own, as a set of isolated points in three-dimensional space does not define a unique body in any obvious way. This problem has been addressed using the quick-hull algorithm combined with a non-linear convexing transformation of the measured data points and subsequent determination of the convex hull. In this article, the optimal degree of convexing is determined empirically on an extensive set of 19 samples including essentially all presently used photoprinting techniques. The actual use of gamut volume changes for monitoring of color print fading is illustrated on selected samples. © 2012 Society for Imaging Science and Technology.*
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INTRODUCTION

Until recently, all color photographs were produced by optical exposure of photosensitive silver-halide-based paper or film. During the evolution of color photography, many photographic processes have been developed, all of which share the same fundamental principle of image forming based on the changes of crystal structure of AgX upon irradiation. These processes include, but are not limited to, the chromogenic (i.e., dye creating) processes C-41, RA-4, E-6, K-14 and R-3, the dye bleaching process known as Cibachrome/Ilfochrome, the dye diffusion processes utilized in Polaroid, Fuji and Kodak instant films and the dye imbibition transfer processes employed for fine-art printing.[1]

The boom of digital photography brought major changes into the imaging industry. As a consequence, most of the traditional optical processes have been discontinued or have shrunk to a mere fraction of the market share. As the only exception, the RA-4 process proved to be a viable form of color print production in the digital era. Nowadays, a significant fraction of both consumer and professional photographs are produced on this type of paper. Digital image files are optically exposed by LCD, LED or laser recorders and the digitally exposed paper goes through the standard wet processing sequence.

The number of digitally recorded images is increasing constantly and so is the demand for high-quality digital printing techniques that would enable the digital photographer to leave the dark room entirely and use a purely digital photographic workflow. Following this trend, we have witnessed a huge breakout of digital photorealistic printing technologies in the past two decades.

As the traditional silver-halide color photographic media have been around for the past 70 years, consumers are well aware of their properties. They usually have some idea or at least personal experience of the image permanence in various conditions. Therefore, informed users know how to handle, store and display their valuable images. However, there is neither such a general knowledge nor experience with the new digital printing techniques. Moreover, it has become obvious that both the lightfastness and/or dark storage stability of at least some of these new printing technologies are questionable. Therefore, it is important to provide the consumer community with sufficient information on this topic so that the new technology can be used optimally.

PRESENT PRACTICES AND CHALLENGES OF PRINT PERMANENCE TESTING

At present, there are several standard practices and ISO standards, which deal with the lightfastness testing of color photography and prints. These regulations include information about test conditions, methodology and end-point criteria. Among these, the ISO 18909 standard[2] is especially worth mentioning. This standard sets the methodology for testing the image permanence of traditional silver-halide materials of different types. However, this standard is not

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suitable for testing images produced by the new digital printing techniques. A new standard is necessary for multiple reasons.

1. A fundamental problem arises from the use of densitometric measurements with a status A filter set for the monitoring of color reflection print fading. While the spectral characteristics of this filter set are well suited for silver-halide photographic materials, they need not match the absorption maxima of the dyes and pigments used in digital printing. The problem was clearly demonstrated at Wilhelm Imaging Research by inequal density readings on visually neutral composite gray patches printed by various inkjet printers.[3]
2. The limited number of test patches given in ISO 18909 poses a further problem. Modern inkjet printers utilize more than the four traditional primary colors. Printers with eight to 12 ink types are widely used for demanding tasks such as photorealistic printing or certified digital proofs. In such an imaging system, e.g., green color is reproduced by direct printing of a green ink rather than overprinting cyan and yellow ones. If the green ink suffers from low permanence, one may not be able to notice it with the ISO 18909 methodology because only CMY and composite gray patches are monitored in this case. It is obvious that many more test patches are needed in order to get reliable data about these sophisticated imaging systems utilizing more primary colors than the traditional CMY triplet.
3. The problem of catalytic fading of inkjet prints brings further complications to the process of permanence determination. Catalytic fading commonly refers to the phenomenon when a dye fades faster in the presence of another dye than when it is present on its own.[4] Strictly speaking, the process is not catalytic, but rather photo-catalytic, and the roles of hydrogen donors and singlet oxygen sensitizers are crucial. Anyway, the process results in uneven fading across the density scale and therefore preferably the whole tonal scale should be monitored.
4. Ground-level ozone is a common part of the ambient atmosphere in homes and offices and has a strong oxidative effect, mainly on inkjet dyes. The susceptibility of, in particular, inkjet prints to ozone-induced degradation is given by the gas absorption capacity of the ink receiving layer, although the sensitivity of dyes to oxidation varies greatly.[5] The ground-level ozone concentration is usually small, from 20 to 80 mg m^{-3} of air. In spite of such a low concentration, it can cause total print deterioration in the course of several weeks of display. Naturally, ozone damage testing should be included in the permanence evaluation standards of digital printing technologies.

These problems have been addressed by several research teams and many new test methods have been proposed based on densitometric measurements of extended test targets,[6] colorimetry[7] or image analysis.[8] Worth noting is the comparative study of Fenech et al.[9], who justified the fitness of colorimetric measurements of dye degradation by direct comparison with rigid analytical chromatographic methods. However, none of these proposals has received a general acceptance articulated in the form of a new ISO standard for the evaluation of digital print permanence.

It is quite surprising that despite the general awareness and recognition of the above mentioned problems, industrial practice still relies on rather obsolete evaluation techniques and advanced testing methods seem to find their acceptance very slowly. Although perhaps the most innovative standard, the Japanese JEITA CP-3901,[10] includes multiple density patches, colorimetric evaluation of base yellowing and indoor ozone effect testing, it still monitors only CMY primary colors by traditional reflection densitometry. The highly productive Wilhelm Research group suggested several alternative approaches to print permanence testing. Yet, their own print permanence reports are still made using a relatively conservative method[11] based on a proprietary end-point criterion set and densitometric monitoring of print fading. However, a fully functional and practical colorimetry-based print fading test methodology was later completed by the primary author of reference 8, Mark McCormick-Goodhart, and the resulting I^* metric[12] is in routine use at the Aardenburg Imaging & Archives test facility.

The authors of this article recently proposed a general method for the monitoring of color print fading, suitable for any color printing technology. It is based on the determination of gamut volume of a freshly printed extensive test chart and subsequent measurement of gamut volume changes during accelerated fading.[13] Relative gamut volume changes plotted as a function of exposure dose can then be used to determine the fading rate, which can further be used to compare the lightfastness of different media or to predict their lifetime if the end-point criteria are established.[14] However, the question of gamut volume determination is a challenging problem on its own. This article reports on our recent findings related to optimization of the gamut volume calculation method and its empirical evaluation using a representative set of 19 samples including essentially all presently used photoprinting techniques. Proprietary software for batch gamut volume calculation and fading data analysis is also presented. The actual use of gamut volume changes for monitoring of color print fading is illustrated on selected samples.

GAMUT VOLUME CALCULATION

The color gamut of a device is usually defined as follows. Gamut is a certain connected subset of a color space encompassing all the colors that can be accurately reproduced by the device. Gamuts are commonly represented as areas in the CIE 1931 chromaticity diagram; however, a full gamut must be represented in a 3D color space. CIE Lab color space is preferred to visualize the gamut of a certain device, often accompanied by 2D cross-section plots for various L levels. Gamut plots are usually constructed from data

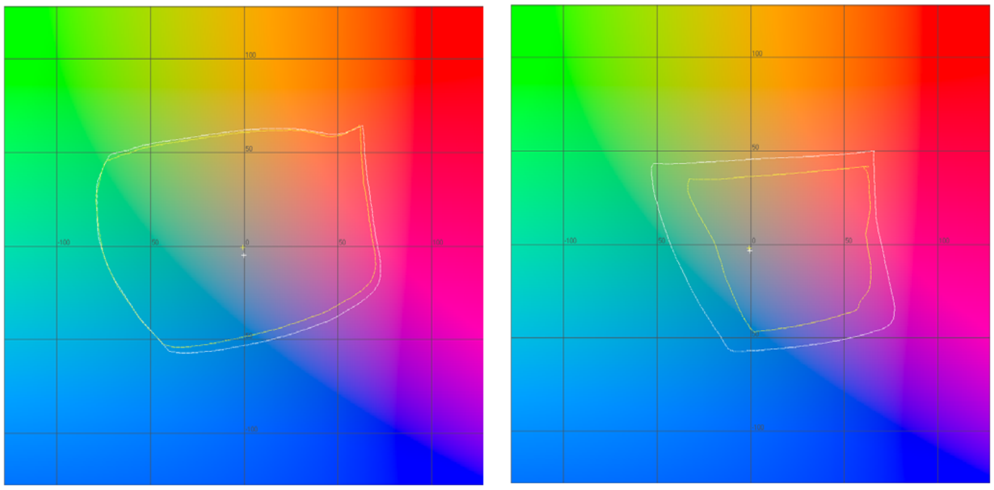

Figure 1. Most gamuts of real printers are not convex. The departure from convexity may further be enhanced during print fading. Screenshots from GretagMacbeth Profile Editor illustrate this behavior. Left: Epson R2400 + Ilford Smooth Pearl paper, right: HP 500 PS + Ilford Smooth Pearl paper. The interior areas represent gamuts after a two-year indoor display.

obtained by reflection colorimetric measurements of suitable testcharts, although attempts based on mathematical modeling have been published. Printer profiling targets containing a sufficient number of patches can be conveniently used for determining gamut volume. Most of the commercial software capable of gamut visualization actually uses ICC profiles rather then measured Lab values.

From the mathematical (and practical!) point of view, there is a need for a more precise definition of a gamut. The use of profiling testcharts results in datasets containing a list of coordinates of the colors of the measured points in the Lab space. A set of isolated points in three-dimensional space does not define a unique body in any obvious way. The convex hull of the set is a well-defined notion (resembling the gamut); however, it may over-estimate the gamut substantially (see Figure 1). The use of the convex hull might be satisfactory for device comparison, but is certainly not sufficient for print fading monitoring. In spite of the rather vague gamut definition, we shall propose a method for estimating the volume of the gamut by identifying its "vertices", approximating it by a (generally non-convex) polyhedron and calculating the volume of the polyhedron. This very procedure may serve as a definition of the gamut; however, its result depends not only on the number and position of the measured points but also on a parameter gamma (see below). By a "vertex" of the gamut we shall understand any data point that is also a vertex of the approximating polyhedron. All remaining data points will be called "interior" points of the gamut.

Several methods for the determination of gamut vertices have been reported. Bakke and co-workers summarized most of them into a neat review.[15] Of these, the combination of a non-linear preprocessing step in conjunction with one of the standard convex hull algorithms introduced by Balasubramanian and Dalal[16] is of great interest if raw Lab data are the preferred input. We found this approach to be the most useful and adopted it for our fading studies. The algorithm works as follows.

Let us start with a set of *Lab* coordinates of N measured color patches. Denote by x_i the *Lab* coordinates of the i-th data point, i.e.,

$$x_i = (L_i, a_i, b_i). \tag{1}$$

First, the center of gravity of the set is calculated,

$$CG = (L_{CG}, a_{CG}, b_{CG}) = \frac{1}{N}\sum_{i=1}^{N} x_i. \tag{2}$$

It is reasonable to assume that this point lies inside the gamut and its coordinates are usually close to (50, 0, 0). Then, the distance d_i of each of the points x_i from the center of gravity is calculated as follows:

$$\begin{aligned} d_i &= \|CG - x_i\| \\ &= \sqrt{(L_i - L_{CG})^2 + (a_i - a_{CG})^2 + (b_i - b_{CG})^2}. \end{aligned} \tag{3}$$

The distance is normalized so that all the values are between 0 and 1, i.e.,

$$nd_i = \frac{d_i}{\max\{d_i\}}. \tag{4}$$

Now, a non-linear "convexing" transformation is performed by means of the function $x \to x^{\gamma}$ for some parameter $\gamma \in (0, 1)$. We thus obtain

$$cnd_i = (nd_i)^{\gamma}. \tag{5}$$

It is important to understand the role of the parameter γ. The convexing transformation moves points with small nd_i (close to CG) towards the gamut boundary while leaving points close to the boundary (nd_i close to 1) almost unchanged (see Figure 2). The original body is thus

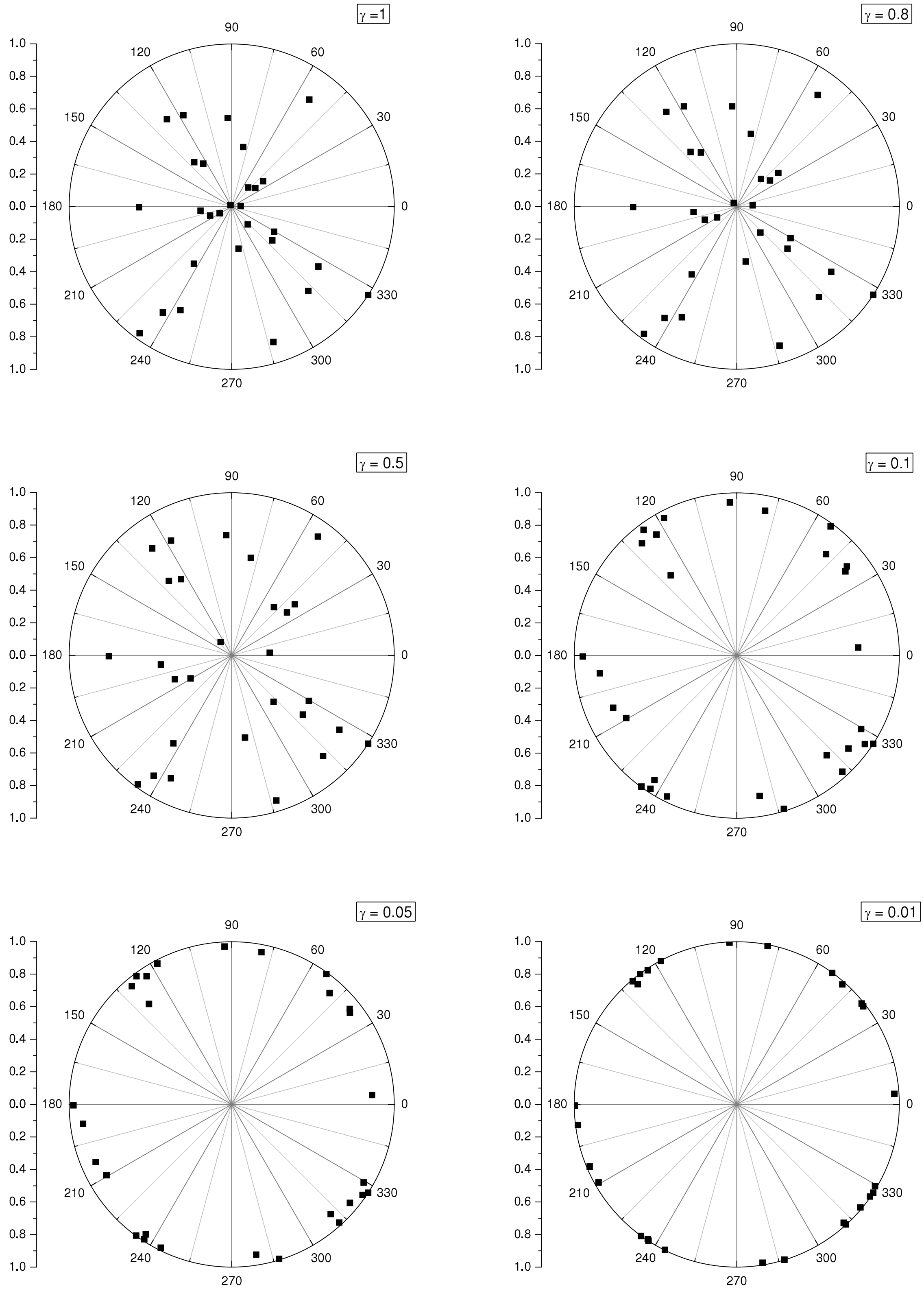

Figure 2. The influence of the parameter γ on the performance of the convexing algorithm. The procedure is illustrated on a random two-dimensional data set. The original data are shown for $\gamma = 1$. As γ approaches 0, more and more points move towards the boundary and become identified as gamut vertices.

"blown up" to become similar to a convex body. After this transformation, the convex hull of the blown-up set is found by means of the quick-hull algorithm[17] and its vertices are identified. These vertices (in their original positions, before the transformation!) are then used to define the polyhedron approximation of the gamut. The polyhedron

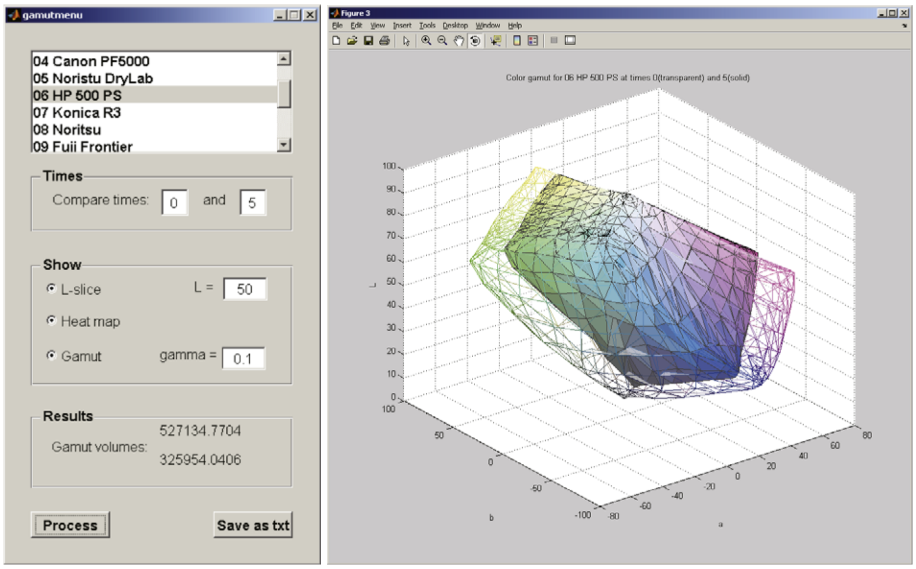

Figure 3. Screenshot from the VolGa utility.

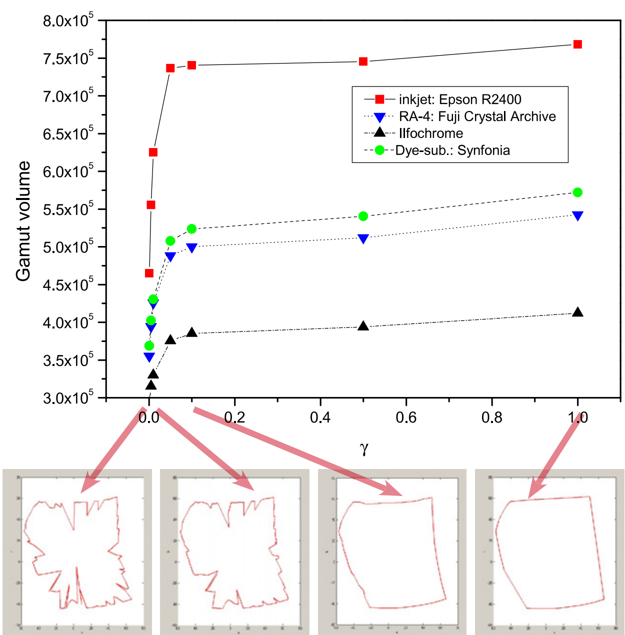

Figure 4. The influence of γ on the polyhedron approximation of the gamut volume on real samples. The images at the bottom represent the section of the polyhedron approximation shown for $L^* = 50$.

volume is then found by segmenting the polyhedron into a disjoint union of many tetrahedra, the volumes of which are easily calculated. By altering the value of γ, we can control the degree of the convexing transformation. High γ values ($\gamma \to 1$) result in minor blow-up only, so that too few vertices are identified and the resulting polyhedron over-estimates the true gamut volume. On the other hand, too small γ values ($\gamma \to 0$) result in major blow-up, too many vertices are identified and the resulting polyhedron is too rough and dented, under-estimating the volume of the true gamut (see Figure 4).

This approach was implemented in a proprietary piece of software utilizing MatLab libraries and compiled into a stand-alone application called VolGa, which is now routinely used by the authors for print permanence evaluation.[18]

METHOD OPTIMIZATION

Selection of the optimal γ is the crucial point of the described method. Too small a value of γ increases the probability of including some of the interior datapoints into the set of vertices. On the other hand, too large a γ value results in "over-convexing," i.e., omitting local departures from convexity of the true gamut.

In order to find the appropriate value of γ, an extended study on 19 testcharts produced by different printers was conducted. The testchart set included all common photo-printing techniques (inkjet dye and pigment prints, dye sublimation, xerography, Kodak, Fuji and Konika chromogenic papers, Ilfochrome dye-bleach print, Pictrography and a dye imbibition print). The standard X-rite calibration target TC RGB 9.18 was printed without color management, as all printing systems used were RGB-driven. In the case of the dye imbibition print, a positive intermediate was recorded onto an E-6 reversal film stock and this was used for the production of CMY separations by optical copying. An automated GretagMacbeth Spectrolino reflection spectrophotometer was used with a polarizing filter in absolute calibration mode to measure reflectance spectra. While ICC does not recommend the use of polarizing filters for profiling,[19] we found it useful for color change monitoring because the removal of specular reflections enabled us to better resolve subtle color changes in dark test patches. Recorded spectra were converted into $L^*a^*b^*$ coordinate values (D50 illuminant, 2° observer).

Gamut volumes were calculated by the VolGa application for all the samples and various γ values ($\gamma = 0.001$, 0.005, 0.01, 0.05, 0.1, 0.5, 1) (see Figure 3). The gamut

Table I. Sample selection.

Sample No.	Target user group	Machine	Colorant technology	Paper
2	Consumer inkjet	Epson R220	Dyebase inkjet, MIS Associates aftermarket refill dye ink set	Ilford smooth gloss
3	Professional inkjet	Epson 9600	Pigment inkjet, OEM Ultrachrome K2	Epson premium semigloss paper
6		HP 500PS	Dyebase inkjet, OEM dye ink set	HP glossy photopaper
8	Consumer minilab	Noritsu QSS		Kodak royal digital paper
10		Fuji frontier	Chromogenic, RA-4 process	Fuji crystal archive
11	Professional photofinishing	OCE Lightjet		Kodak endura glossy

volume was plotted as a function of γ. The resulting dependences clearly depict the influence of γ on the gamut volume of real samples (see Fig. 4; for the sake of readability only selected samples are presented). Low γ values cause the inclusion of interior datapoints in the set of vertices and the resulting polyhedron is too dented, which causes the gamut volume to be underestimated. Large γ values result in ignoring the subtle departures from convexity and thus over-estimating the gamut volume. The value of $\gamma \cong 0.1$ seems to be the correct choice, yielding a sufficiently smooth boundary while respecting the departures from convexity. This behavior applies generally for all the samples, regardless of the printing technology used for their production.

METHOD IMPLEMENTATION EXAMPLE

The 19 samples used for the evaluation of γ (see section Method Optimization for test chart data) were also used for a comparative print permanence study utilizing the discussed gamut volume shrinkage method. Since the purpose of this article is to present the method itself rather then to compare the permanence of different photoprinting techniques, only a limited selection of results will presented in order to illustrate the method properties. Full image permanence data for this comparative sample set will be published separately. The papers, inks and printers selected for method presentation are summarized in Table I. For the test target design and sample production details, see chapter 4.

Accelerated aging tests of prints were performed in a xenon light test chamber. The machine (Q-Sun-Xe-1B by Q-lab Corporation) was set according to ASTM F 2366-05.[20] The irradiation intensity was 0.9 $\mathrm{Wm^{-2}\ nm^{-1}}$ at 420 nm and the black panel temperature was maintained at 63°C by air circulation. This irradiation intensity corresponds to an illumination intensity of 64 klx, as measured by a Gigahertz-Optik X-11 optometer with an XD-950 probe. Each sample was given a series of five exposure doses, each lasting 10 h. Thus, each sample received a total exposure dose of 3200 klx h, consisting of five 640 klx h steps.

The samples were measured at the beginning of the experiment and after each exposure step. An automated GretagMacbeth Spectrolino reflection spectrophotometer was used with a polarizing filter and in absolute calibration mode. The measured reflectance spectra were converted into $L^*a^*b^*$ values (D50 illuminant, 2° observer). The converted $L^*a^*b^*$ values were then used in the VolGa utility to calculate the corresponding gamut volume for each incremental exposure dose. In principle, it is possible that the appropriate value of γ may change in the course of time, i.e., the faded samples may suggest a different value of γ from the original samples. Clearly, we need an unbiased (fair) measure of the gamut volume evolution and so we cannot adjust the value of γ in time. The question of optimum γ changing during fading was not addressed in this study and a value of 0.1 was used for the calculation of gamut volume of all samples. These values were normalized by the gamut volume of an initial unexposed sample. Normalized data (as a fraction of the unexposed sample) were plotted as a function of the exposure dose. Also, the equivalent sample age A expressed in days was calculated according to Eq. (6) as the total exposure dose H to average daily dose ratio and co-plotted as an alternative horizontal scale. The average daily dose was accepted to be 450 lx for 12 h, as the de-facto standard in the industry.[21]

$$A[\text{eqv. days}] = \frac{H[\text{lux hours}]}{450 \times 12}. \tag{6}$$

Quite surprisingly, the relative gamut volume followed a reasonably linear trend within the observed range of exposure doses, i.e., during the first ca 40% of gamut volume drop. Therefore, a simple linear fitting model was adopted to find the slope of the plot (Eq. (7)),

$$y = 1 - ax. \tag{7}$$

The parameter a corresponds to the rate of the gamut shrinkage process. It can be found by the least-square method (Eq. (8)). Strictly speaking, from the kinetic point of view this parameter deserves to be called a *rate constant* only if it is calculated from the *equivalent age* increments. If the *exposure dose* is used for its calculation, it no longer has the meaning of rate constant and should be formally distinguished. The authors suggest the term *fading coefficient* to be used in this case.

Table II. Gamut volume shrinkage evaluation.

Sample No.	Relative fitting deviation	Fading coefficient [ΔE^3 Mlux^{-1} h^{-1}]	Relative fading coefficient [equivalent days^{-1}]	Time for 30% gamut volume loss [years] * = extrapolated
2	1.24E−02	3.30E+04	2.76E−04	3.0*
3	7.46E−04	3.31E+03	3.88E−05	21.2*
6	5.27E−02	7.05E+04	7.22E−04	1.1
8	1.46E−03	9.32E+03	1.51E−04	5.5*
10	4.48E−03	8.74E+03	1.04E−04	7.9*
11	3.35E−03	5.92E+03	6.32E−05	13.0*

Also, the parameter S can be calculated according to Eq. (9) as the relative quadratic deviation of measured points from the regression line. The S parameter is thus a quality measure of the linear fit to the experimental data, with a low S value indicating a good linear fit,

$$a = \frac{\sum_{i=1}^{N} x_i - \sum_{i=1}^{N} x_i y_i}{\sum_{i=1}^{N} x_i^2}, \quad (8)$$

$$S = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\frac{(1 - a x_i - y_i)^2}{y_i^2}}. \quad (9)$$

Figure 5 depicts the gamut volume data for all discussed samples. All fading coefficients are summarized in Table II. The table gives both the fading coefficients and a lifetime estimate based on the extrapolation of the linear fit. The end-point criterion for this extrapolation was adopted to be 30% gamut loss, by analogy to the visual density end-point criteria used in the ISO standard 18909. Obviously, the authors are well aware of the fact that these two qualities are totally different in their nature and the selection of this particular value is arbitrary. Since all samples in our laboratory are measured by spectrophotometers, we can convert the measured spectra to both colorimetric data for gamut analysis and densitometric data for conventional evaluation. Preliminary comparison of the two approaches has been reported recently.[14] However, the question of acceptable gamut loss and corresponding end-point criteria certainly requires further discussion and surely represents a challenge for further psychophysical study.

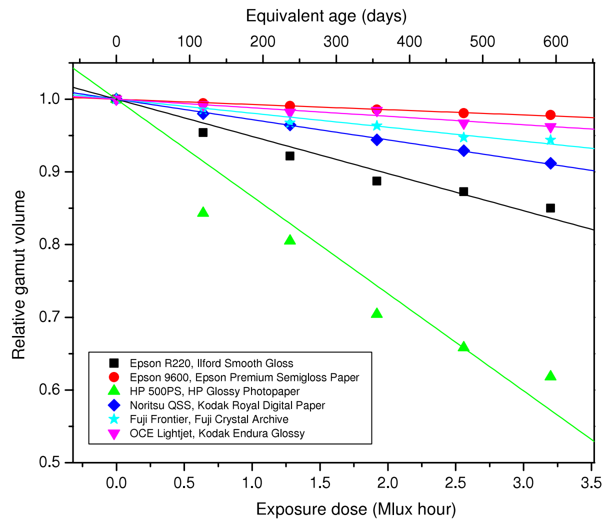

Figure 5. Gamut volume shrinkage rate expressed as a function of exposure dose and equivalent age for the selected samples.

DISCUSSION

The presented relationships simply and clearly describe the archival properties of the studied materials. However, we need to bear in mind that the observed phenomena arise from particular samples and, in order to draw sound general conclusions, the averaging of much larger sample sets is necessary. Nevertheless, several interesting facts concerning the actual permanence performance, as determined by the gamut volume method, are worth discussing with respect to the general reputation of the studied samples' properties. First of all, samples 8, 10 and 11, i.e. those produced by the RA-4 process, show essentially quite similar values of the gamut fading coefficient. It seems that the image permanence on this type of medium is not significantly influenced by the manufacturer and/or processing, but is rather determined by the common chemical nature of chromogenic dyes which are shared by all the manufacturers in order to ensure their materials' compatibility within the RA-4 process. Despite this common principle, the professional user targeted Kodak Endura and Fuji Crystal Archive seem to have manifestly better permanence than the consumer-grade Kodak Royal paper.

On the other hand, samples 2, 3 and 6 show a great variability of measured fading coefficient. This well illustrates the wide range of dyes and pigments used in inkjet formulations. Therefore, no general conclusion can be drawn with respect to the image permanence of inkjet prints—all cases have to be treated individually according to experimental data. Moreover, the inkjet samples selected for this article clearly illustrate the improvements in inkjet technology during its development in the past 20 years. Of these, sample 6 is the worst one in terms of print permanence. This printer (HP 500 PS) dates back to the 1990s and utilizes an early-generation dye-based ink set that has a very poor lightfastness. Sample 2, printed by an MIS Associates Dyebase aftermarket inkset, shows marginally better lightfastness. However, sample 3 printed by an Epson Ultrachrome pigment inkset exhibits the best lightfastness of all the tested materials and outperforms silver-halide papers as well.

From the general methodological point of view, our approach introduces an elegant and universal tool for monitoring and evaluation of print fading kinetics, regardless of the technology of their production. It addresses all the problems inherently associated with modern digital printing techniques, as mentioned in section Present Practices and Challenges of Print Permanence Testing: color changes are monitored by colorimetry rather than densitometry, extended test targets provide sufficient data so that the effects of catalytic fading and direct process color fading are not omitted, and the method is equally suited for gas fading studies as well.

Gamut volume is easy to imagine and interpret, which makes the method accessible even for the non-professional audience. On the other hand, gamut volume captures only information about changes at the boundary of the gamut body, all summarized into a single figure. This reduction could result in neglecting the following three phenomena which are not accompanied by gamut volume change:

(1) shifts of neutral colors located close to the middle lightness axis,
(2) shifting of the whole gamut body in the $L^*a^*b^*$ color space without deforming it or
(3) expansion of one part of the gamut accompanied by a matching retraction of another part.

If changes of interior datapoints are to be monitored as well, a different measure would have to be adopted, such as the total sum of color differences, average color difference or other global measures of color variance. These issues were addressed at the very beginning of the experiment described in section Method Optimization and it became evident that all such global measures of color variance correlate well with gamut volumes. In other words, of the 19 samples included in the gamma optimization study, not a single one exhibited changes in the interior datapoints without simultaneous changes at the boundary. The second and third points are purely theoretical and have never been observed on real samples in our laboratory. The authors therefore believe that the use of gamut volume does not result in the omission of any significant information, and gamut volume can be accepted as the preferred measure, due to its easy interpretation and visualization.

The acceptance of *relative* gamut volume as a measure of print permanence has been accompanied by much controversy. Reporting absolute gamut volume in $(\Delta E)^3$ would also enable one to assess the quality of printing and compare the colorfulness of prints. However, due to the adaptive nature of human vision the authors feel that the use of relative values is more appropriate.

The use of extended test charts makes this method less efficient from the labor and time point of view. The TC 9.18 RGB discussed in this article is nearly A4 size. If size really matters, the smaller TC 2.73 will work as a space-saving alternative, still producing reasonably detailed sampling of color fading data and correct gamut volumes. The use of special dedicated charts containing only boundary colors and omitting the interior ones would decrease the target size without any negative impact on gamut volume calculation accuracy and reliability.

However, the use of the standard profiling targets for fading studies makes another useful feature possible—fading softproofing, as originally proposed by Tastl et al[22]. Once we have measured the test charts during the accelerated fading, we can calculate the corresponding ICC profiles for every measured incremental exposure step. While the profiles calculated from these measurements are essentially useless for the traditional color management workflow, they can be conveniently used for softproofing and simulating the appearance of a faded print. If such profiles are available, every user will be able to take the advantage of this process and display the faded print appearance simulation on their computer screen and decide on their own whether the observed changes are acceptable or not. This brings a totally new dimension into the permanence testing practice! Rather than reporting estimated life expectancy of certain material the manufacturers could provide users with ICC profiles of aged prints for individual assessment. Moreover, the ICC profile of faded media could be used for the duplication and restoration of faded prints if the original digital image source files were lost.[23]

CONCLUSION

Photography, as a part of cultural heritage, is an ever-lasting subject of various stability experiments and analyses. This testing has become more important in recent years as new digital printing techniques have been penetrating the market and receiving acceptance from graphic arts professionals and artists alike. However, it seems that the application of traditional fading tests and standards developed for silver-halide photography is not straightforward and brings many controversies. The shift from densitometric monitoring of print fading towards colorimetric monitoring is obvious and generally accepted. On the other hand, methods for print life estimation from colorimetric data are still being debated.

The presented article deals with one such method. Gamut volume, i.e., the volume of a 3D body encompassing all the colors a device is capable of reproducing, seems to be a suitable global measure of color changes of a studied sample. Relative gamut volume changes plotted as a function of exposure dose can then used to determine fading rate parameters, which can be further used to compare the lightfastness of different media or predict their lifetime, if the end-point criteria are known.

Calculation of the gamut volume is not a simple task as gamuts are not necessarily convex bodies. The previously reported non-linear data conditioning combined with the standard quick-hull algorithm proved to be well suited for gamut volume calculations based on CIE $L^*a^*b^*$ datasets. The question of an appropriate γ value has been empirically addressed in this article and we recommend using $\gamma \cong 0.1$. The proprietary MatLab-based utility developed for this study enables batch processing of multiple testchart measurement files and convenient visualization of results. It has been compiled into a stand-alone application recently and is offered to other users for free non-commercial use.[18]

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