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Aging and Quality Control of Color LCDs for Radiologic Imaging

A. Walz-Flannigan · S. Stekel · H. Weber · D. Lanners · R. Jonsgaard · T. Peterson · S. G. Langer

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Abstract Our practice has long been concerned with the effects of display quality, including color accuracy and matching among paired color displays. Three years of data have been collected on the historical behavior of color stability on our clinical displays. This has permitted an analysis of the color-aging behavior of those displays over that time. The results of that analysis show that all displays tend to yellow over time, but that they do so together. That is, neither the intra- nor inter-display color variances observed at initial deployment diverge over time as measured by a mean radial distance metric in color space (Commission Internationale d'Eclairage L', u', v' 1976). The consequence of this result is that color displays that are matched at deployment tend to remain matched over their lifetime even as they collectively yellow.

Keywords Digital display · Diagnostic image quality · Diagnostic display · Monitors

Background

Color liquid crystal displays (LCDs) have become more common place in reading rooms with the evolution of higher luminance backlights. However, quality control (QC) programs have largely been designed for grayscale displays [1]. The lack of published data on the color aging of displays hampers the development of evidence-based QC guidelines. Previous studies have quantified the threshold color difference that is detectable between displays, a quantity that can be used to color match pairs of displays at acceptance testing [2]. However, not enough is known about chromatic changes of aging color LCDs to guide if or how a QC program is needed to maintain color matching and uniformity.

Within our department, anecdotal evidence had suggested that non-uniform color aging of displays occurred. At that time, the displays in use were not easy to color calibrate and the displays were roughly color matched. Color problems were frequently cited. To prevent this, a quality control program was established which measured the mean radial distance between paired displays in CIE (Commission Internationale d'Eclairage) LUV 1976 color space [4]. After several years, new displays were introduced that could be color calibrated to match. With the new displays and the continued quality control program, color-related complaints were greatly reduced. After several more years of quality control data accumulation it was prudent (given the new fleet of displays and calibration practice) to see if the program was still fulfilling its purpose or if there were not more efficient ways to detect meaningful color drift.

Aspiring toward greater efficiency in maintaining our color displays, we analyzed the QC data to better understand LCD chromatic aging. In particular, we set out to answer the question, "Is attention to color calibration required at both display acceptance and routine QC?" And if the answer to the preceding question is "yes", we then wished to ascertain how deep an investigation is needed on each display; does one need to sample multiple points across the display, or is one repeatable position adequate?

A. Walz-Flannigan (✉) · S. Stekel · H. Weber · D. Lanners · R. Jonsgaard · T. Peterson · S. G. Langer
Mayo Clinic,
200 First St. SW,
Rochester, MN 55905, USA
e-mail: walzflannigan.alisa@mayo.edu

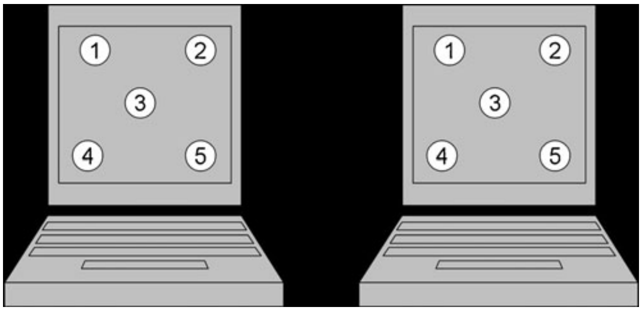

Fig. 1 Shows the measurement locations on paired displays and calculation for the MRD between displays

Methods

The displays included in this study are NEC 1990Sxi (NEC Display Solutions of America, Itasca IL) used with the color diagnostic workstations in our MRI practice. The displays are calibrated after an initial “burn-in” period of 2 days using NEC Spectraview II software with a GretagMacbeth Eye-One Display V1 colorimeter/photometer. The Spectraview II system makes color measurements and adjustments during calibration. The luminance of the display is calibrated to the DICOM part 14 grayscale standard display function (maximum=100 cd/m^2, minimum=0.2 cd/m^2 within the ACR accreditation guidelines for MRI). Displays are deployed as pairs and are initially color calibrated to have matching white points within 0.004 mean radial distance (see Eq. 6) in the CIE 1931 (x,y) color space.

The color measurements included in our analysis were accumulated quarterly over the course of many years from five locations on each display (see Fig. 1). The color measurements were made on a white screen which had been adjusted (using the ons-screen display brightness control) to read between 90 and 110 cd/m^2. Measurements were made using a Sencore ColorPro IV colorimeter (Sencore Inc, Sioux Falls, SD) with an x, y accuracy of ±0.004 (meaning absolute agreement with RGB color standard in the CIE 1931 color space). Repeated measurements have a precision of ±0.002 in x or y. For much of the data discussed in this paper, the color point measurements were converted to the 1976 CIELUV (u′, v′) color space which shows better correlation with the human visual system's interpretation of color [5]. The conversion is given below:

$$u' = \frac{4x}{-2x + 12y + 3} \tag{1}$$

$$v' = \frac{9y}{-2x + 12y + 3} \tag{2}$$

The uncertainty in CIELUV color space for a single measurement is given by

$$\Delta u' = \frac{4(12y + 3)}{(-2x + 12y + 3)^2}\Delta x + \frac{-48x}{(-2x + 12y + 3)^2}\Delta y, \tag{3}$$

$$\Delta v' = \frac{18y}{(-2x + 12y + 3)^2}\Delta x + \frac{-18x + 27}{(-2x + 12y + 3)^2}\Delta y, \tag{4}$$

where Δx and Δy is the measurement uncertainty which equals ±0.004. A typical measured color point for a display in this study is (x, y, Y)=(0.316, 0.331, 100 cd/m2) which yields $\Delta u'$=0.0013, $\Delta v'$=0.003.

The same colorimeter was used over the period of 3 years without recalibration. The displays had a staggered deployment such that during a single measurement time period, the ages of the tested displays could range from 0 to 24,000 operating hours; however, the displays measured at later dates were on average older than those measured at

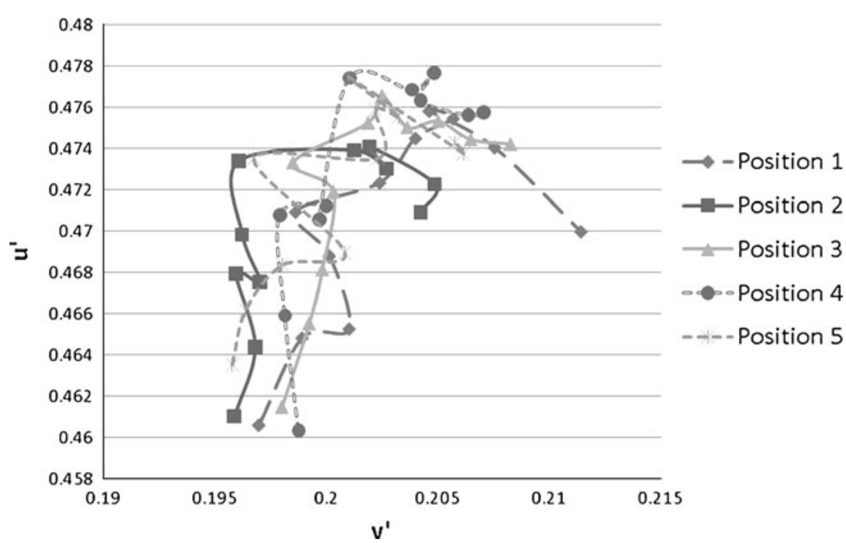

Fig. 2 Shows typical color point measurements (CIELUV 1976 color space) from a single display (with five measurement positions) over time. Each series represents a different position on the display and each point represents a different time. The points in this figure correspond to ages between 0 and 15,500 operating hours

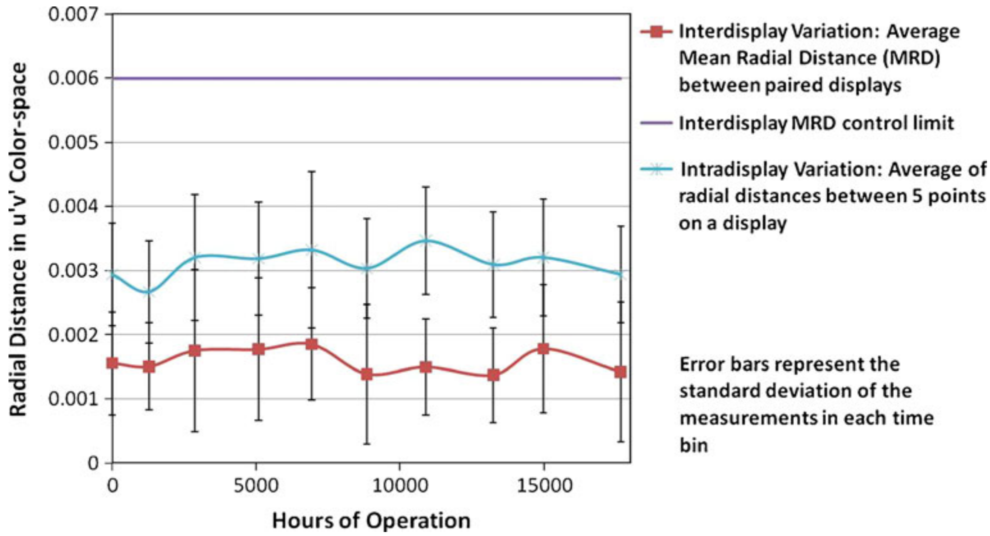

Fig. 3 Shows the average difference between color points on **a** the same (intra-) display or **b** different (inter-) displays as function of time. There is a small fluctuation consistent with the precision of the colorimeter, but for both cases the data do not indicate an overall drift between color points with time

earlier dates. Thus, it's anticipated that monotonic drifts in the colorimeter measurements would be dampened, but might not be totally eliminated.

The radial color "distance" between two points 1, 2 in CIELUV color space is defined by:

$$\text{Radial Distance }(1,2) = \left[\left(u_1' - u_2'\right)^2 + \left(v_1' - v_2'\right)^2\right]^{1/2} \tag{5}$$

The uncertainty in any radial distance measurement would be $\Delta_{\text{radial distance}}$=0.003. Similarly, the mean radial distance (MRD) between two displays (A and B) is calculated from radial distance between the average u′ and v′ values (CIELUV 1976) on each display.

$$\text{Mean Radial Distance }(A,B)$$
$$= \left[\left(u'_{A,\text{Avg}} - u'_{B,\text{Avg}}\right)^2 + \left(v'_{A,\text{Avg}} - v'_{B,\text{Avg}}\right)^2\right]^{1/2} \tag{6}$$

For quality control, if a visual color difference appeared between displays or the MRD measured greater than 0.006 in CIELUV 1976 color space, the displays were recalibrated to reduce the MRD. In addition, if the maximum luminance of the display fell below 90 cd/m^2 or artifacts appeared, the display was removed from service.

We retrospectively analyzed QC data taken over the last 3 years (the average display lifetime) for 38 displays. Typical data from an individual pair of displays is shown in the Results section (Fig. 2). For each time point and for each display, the average color point and the intra-display mean radial distance (between each combination of the five measurement points) was calculated. For each pair of displays at each time point, the mean radial distance was calculated between the average color points of each display and also for the central color points of each display. Individual display and display pair measurements were compared with quality control limits and averages to attain the rate of failure and measurement spread.

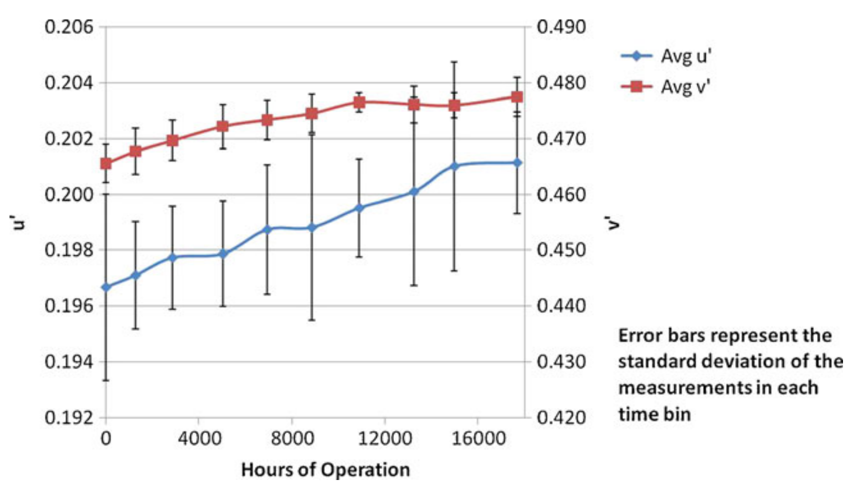

Fig. 4 Shows the temporal evolution of the average color points for 38 NEC 1990 SXi displays. Color points are given in CIELUV 1976 color coordinates (u',v'). Each display had a maximum luminance between 90 and 110 cd/m^2, for all measurements

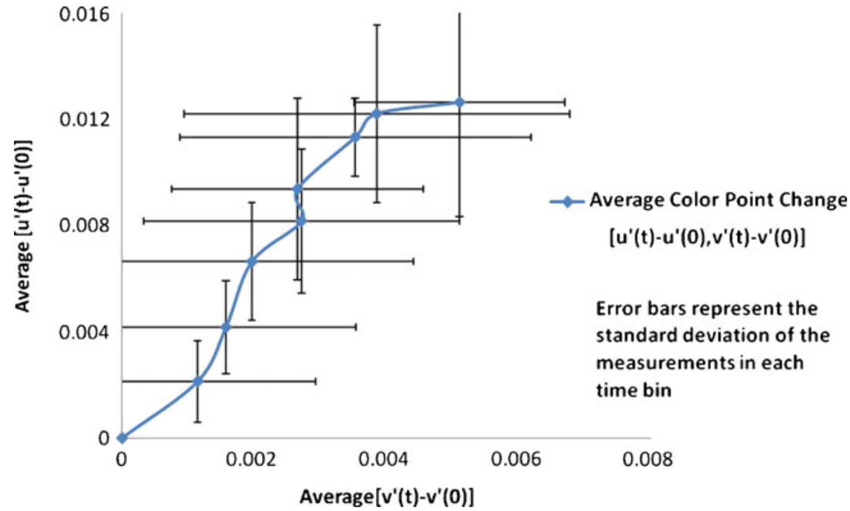

Fig. 5 Shows the change in color points from the data in Fig. 4, as plotted in CIELUV 1976 color space. The points in this figure correspond to ages between 0 and 15,500 operating hours

To ascertain the evolution of the average display color as well as the spread of display properties and trends, the data points from displays of the same age were averaged as follows. The average time between quality control tests was approximately 2,000 h. Data were binned with a granularity of 2,000 operating hours and include only one data point per display per bin. If two display data points happen to fall into one bin, only the most central time point was retained. For each time bin, the color points, radial distances, or net change in color point from $t=0$ (initial quality control test), were averaged. The uncertainty (standard error) in the average value was taken from the standard deviation of the mean over the time bin.

Results

Typical measurements from a single display, taken at different times, are shown in Fig. 2. These data are indicative of the variability and the overall trend in color points.

As shown in Fig. 3, the average color variation between positions 1 through 5 on the same display does not increase over time on average. Instead, there is a small variation accountable for by the uncertainty in our measuring device ($\Delta_{\text{radial distance}=}$ 0.003). Also in Fig. 3, we can see the difference between paired displays (of the same age) which were originally color calibrated to match. The difference between displays shows some oscillation but stays rather uniform on average. The quality control limit which requires display recalibration is 0.006 for inter-display MRD is displayed in Fig. 3 and all inter-display MRD values lie below this control limit (the threshold of visible color difference is between 0.004 and 0.006 [2]).

While in Fig. 3, we see that the color difference between displays does not grow, the color points of both displays do show change over time. This is shown in Fig. 4. Average values of u' and v' color points for the 38 displays increase over time which, in CIE 1976 LUV color space, is a tendency toward yellow.

Out of 404 display visits (2,020 measurements, five per display) over 3 years on the 38 display pairs[1]:

- Four pairs showed visible color differences between displays.
- Zero pairs MRD>0.006 (criteria for a failed match).
- Displays with identified visible color differences all had MRD<0.004.
- Two pairs had radial distances (at position 3)>0.006, both corresponded to displays that later were identified as having visibly different color.
- Eleven displays showed intra-display variation (maximum radial distance) >0.006 for the majority of their measurements over time. Only one of these corresponded to a pair with a visible color difference.
- Five showed intra-display non-uniformity>0.01.

Discussion

Individual color measurements did not appear to be good indicators of visible color mismatch. This is likely due to the limited precision of the colorimeter. An x,y precision of ±0.002 in CIE 1931 color space should correspond to precision in the measurement of color difference of about ±0.0015 in CIELUV 1976 color space. If the threshold for the visibility of color difference is between 0.004 and 0.006 (CIELUV 1976), a large number of false-positive color differences might be expected.

Despite the noise of the colorimeter measurements, it is still possible to see a net average color change for the fleet

[1] MRD values are given in the CIE 1976 LUV color space.

over time (Fig. 5). This average measurement indicates that displays will slightly “yellow” over time [6]. This appears to be a global trend across the face of the display and is most likely due to aging of the backlight (a trend that has been measured and verbally acknowledged by the display manufacturer) and not due to a change in the liquid crystal panel. As shown in Fig. 3, there do not appear to be significant trends toward increasing spatial color non-uniformity or divergent color trends between originally color-matched displays. It appears that if displays are originally color matched that they tend to stay color matched.

It has been shown that uniform yellowing of LCDs does not affect the diagnostic utility of a display [6]. However, to avoid the annoyance a visible color difference between displays could cause, we thought it would be appropriate to establish a quality control program to catch color mismatch before it becomes visible (this was the initial goal of our former QC program). What we have found, however, suggests that there is not a trend towards diverging color mismatch among initially matched displays (Fig. 3) and furthermore the QC measurements were not helpful for such quality assurance (see Results). Thus, in order to detect color mismatch during routine QC, tests beyond a visual assessment are not necessary.

Because radiologic images are presented in pseudo-color, there is no particular need for absolute color accuracy. However, lack of color uniformity has been described as distracting or annoying. This distraction may affect diagnostic performance but a direct link has not been studied. Regardless, we find that annoyance in itself is sufficient reason to prevent or remedy a color mismatch. To prevent mismatch, we color calibrate paired displays at installation and require a level of color uniformity across individual displays of less than 0.01 radial distance [3].

Conclusions

In the interest of achieving uniform presentation of diagnostic images, a quality control program for the color of our PACS displays was established. However, because of the time involved in quality control data collection and analysis and the likelihood that color recalibration would result in reduced display luminance or lifetime, we were strongly motivated to find control limits and testing frequencies that reflected meaningful changes in an aging LCD. To assess color change with LCD-aging we analyzed color measurements taken from a fleet of 38 paired color LCDs over the course of 3 years.

We have found that color LCDs appear to yellow over time, most likely due to the aging of their backlights. In our experience, visible color differences generally did *not* correlate with failed QC measurements (i.e. high inter-display MRD, Eq. 6). In addition, when the valued metric of the assessment is visibility of color difference, it seems unnecessary to measure color points when the human eye's interpretation is sufficient.

Our data showed minimal divergence in color points within and between displays. Displays which are originally color matched will age similarly and stay matched. The rare visible color difference that appears between matched and color-calibrated displays is mostly due to intra-display variability which is not reparable by color recalibration.

In summary, our analysis finds that color measurements should continue to be made at the time of acceptance testing for deployment in order to assure color-calibrated displays match. For ongoing routine quality control, however, visual assessment is sufficient.

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