Characterization of Luminance and Color Properties of 6-MP Wide-Screen Displays

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Abstract Luminance and color performance are routinely evaluated as part of acceptance testing of displays used in diagnostic radiology. Previous work has indicated that as some diagnostic liquid crystal displays (LCDs) increase in backlight hours (BLH), the luminance measured with an external luminance meter exceeds the luminance reported by the manufacturer's built-in meter. The purposes of this work were as follows: first, to characterize several luminance and color performance characteristics for 23 Barco Coronis Fusion 6-MP MDCC 6230 color displays and, second, to provide initial data for a longitudinal study evaluating changes in luminance and color performance as BLH increase. Grayscale display conformance and maximum luminance were evaluated using a calibrated luminance meter and AAPM Task Group 18 test patterns, and agreement between target and measured luminance was calculated. Luminance uniformity was evaluated by calculating maximum luminance deviation. Color point and color uniformity were evaluated using a spectrophotometer, and the radial color distances between the corners and center of the display were calculated. Above 3 cd/m², there was good agreement between the target and measured luminance. At the maximum luminance, the mean difference was less than 1 %. The mean maximum luminance deviation for these displays was 10.40±2.38 %. Color point was observed to be very consistent between displays with mean values of u' and v' of 0.187±0.002 and 0.474±0.004, respectively. Among all displays, maximum radial color distance had a mean value of 0.003±0.001. These data provide a baseline for the

acceptance of future displays as well as for longitudinal studies of luminance and color performance.

Keywords Image display · Acceptance testing · Clinical image viewing · Luminance · Chromaticity

Introduction

During acceptance testing of displays used for diagnostic interpretation of medical images, several luminance performance characteristics are typically evaluated including digital imaging and communication in medicine (DICOM) grayscale display function (GSDF) conformance, maximum luminance, and luminance uniformity. However, these properties have not yet been well characterized for wide-screen liquid crystal displays (LCDs). It has become common practice for routine quality assurance (QA) to test display luminance and GSDF conformance using a built-in luminance meter and vendor-specific software. Examples of this technology include Barco's i-Guard (Duluth, Georgia) and Dome's RightLight (NDS Surgical Imaging, LLC, San Jose, CA). Understanding when and how these systems are likely to fail is an essential component of a QA program.

The effective age of a display can be characterized by the cumulative on time of the display backlight or backlight hours (BLH). Previous work performed on 3-MP grayscale displays has indicated that as BLH increase, the maximum luminance measured with an external meter tends to exceed the value reported by the manufacturer's built-in meter, though the cause of the disagreement remains undetermined [1]. One possible cause is a color dependency of the built-in luminance meter.

Chromaticity, or color point, describes the color qualities of a display [2] and is affected by the spectral properties of the

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display backlight [3]. Although the color point of a display is independent of luminance [3], it has been demonstrated that color point may affect perceived luminance [4]. Further, it has been demonstrated that the color point of some LCDs changes as the BLH increase [5]. This suggests that previously observed disagreement between externally measured luminance and those reported by a built-in meter may be caused by a luminance meter's sensitivity to changes in color point.

Because previous work had been limited to grayscale displays, the first goal of the current study is to evaluate luminance and color characteristics of color displays as part of acceptance testing and to set performance baselines for future QA tests.

The second goal of this work is to collect the initial data for a longitudinal study that will track agreement between external and built-in luminance meter measurements and determine if they are subject to the same behaviors as previously studied grayscale models. If the luminance behaviors are similar to those seen in grayscale displays and changes in color point are observed, a correlation between these properties will be considered.

Methods

Measurements were performed on Corionis Fusion 6-MP MDCC 6230 displays ($n=23$) as part of acceptance testing prior to use in a clinical radiology department (Barco, Duluth, Georgia). This department had recently acquired a large number of these displays, providing the sample size needed to effectively study longitudinal changes in display performance. The make and model of the displays used in this study were chosen solely because of availability; the authors had no role in the purchasing decision. A single workstation was used throughout testing, with each display connected to the designated workstation, tested, and then moved to a new workstation and put into clinical use.

The MDCC 6230 displays are 6-MP color LCDs with 30.4-in. diagonal length for the active display. This corresponds to a similar pixel density as other diagnostic displays (pixel pitch = 199.5 μm) but with twice the standard width (active display width = 654 mm). These displays ranged from 19 to 152 BLH with a mean value of 49 BLH. Data were not included for displays rejected for reasons unrelated to luminance characteristics (i.e., bad pixels, visible damage, etc.) All luminance measurements were made using a calibrated RaySafe Unfors Xi luminance meter (Billdal, Sweden), which has a 10-mm diameter circular measurement field of view. The reproducibility of luminance measurements performed with this device was evaluated in a previous study, showing a coefficient of variation of less than 1 % across a wide range of luminance values (0.67 to 524.0 cd/m^2) [1]. Consequently, no additional evaluation was performed here. Color measurements were

performed using a calibrated Konica-Minolta CS-100a Color Meter (Tokyo, Japan) and included an evaluation of measurement reproducibility.

Validation of GSDF Conformance and Maximum Luminance

MDCC 6230 displays have a built-in luminance meter, positioned in the center of the upper edge of the active display. It is used in conjunction with Barco's MediCal QAWeb software to perform routine luminance calibration and GSDF conformance checks. The conformance test displays a series of luminance steps in the location of the built-in luminance meter and records the measured value, comparing it to a predetermined target. These steps correspond to the luminance test patterns, LN-1 through LN-18, from the American Association of Physicists Medicine (AAPM) Online Report No. 3, commonly referred to as TG-18 [3].

Before testing, the calibration and built-in conformance test were run on each display. To validate the results of the conformance test, luminance was measured for each TG-18 luminance test pattern using the previously mentioned external luminance meter. All measurements were made in a dark, temperature-controlled room identified for this purpose, with each display connected to the same workstation in the same location. Because each of these displays was put into clinical use following acceptance, the front glass was kept intact. The difference between both the reported and measured luminance and the target luminance for each driving level was calculated as a percentage of the target. The mean percent difference and standard deviation of the differences were determined for each luminance step and plotted as a function of target luminance. To determine if the differences observed between reported and measured luminance were statistically significant, paired t tests were performed for each driving level, comparing the reported values from each display to the measured values. Additionally, performance criteria for future evaluation of maximum luminance were identified by calculating the mean value ± 2 standard deviations, as recommended in previous work [1].

Evaluation of Luminance Uniformity

Previous work demonstrated an increase in luminance nonuniformity for grayscale displays as BLH exceeded the expected lifetime [1], but this increase was not found to be statistically significant. However, this earlier study was limited in that longitudinal measurements for individual displays were not made. To set a baseline for luminance uniformity evaluation over the lifetime of MDCC 6230 displays, the maximum luminance was measured at five locations on the display—the center and approximately 2.5 cm from each of the four corners. The maximum luminance deviation (MLD) was

calculated as $(L_{\max} - L_{\min}) / (L_{\max} + L_{\min}) \times 200$ for each display where $L_{\max}$ and $L_{\min}$ are the maximum and minimum measured luminance, respectively [3]. Additionally, the mean value across all displays was calculated and a performance criterion for future evaluation was identified by calculating the mean value plus 2 standard deviations as an upper limit for MLD. No attempt was made to correlate MLD with BLH for these displays. Assuming that they perform similarly to previously evaluated models, any correlation would be too small to observe due to the very low BLH at the time of acceptance.

Measurement of Color Point and Uncertainty

To evaluate color point, a TG-18 LN-18 test pattern was displayed and five independent measurements were made in the center of the display using the CS-100A Chroma Meter. This test pattern was chosen because it drives the display to its maximum luminance, enabling a comparison between changes in maximum luminance with changes in color as these displays age. Measurements were made in the CIE 1931 (x , y) color space [2] and converted to the 1976 CIELUV (u' , v') color space [6] using the following equations from the five measurements of x and y :

$$u' = \frac{4x}{-2x + 12y + 3}; \quad (1)$$

$$v' = \frac{9y}{-2x + 12y + 3}. \quad (2)$$

The uncertainties in u' and v' were calculated using the following equations [2]:

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

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

where $\Delta u'$ and $\Delta v'$ are the uncertainties in each calculated value of u' and v' , respectively, and Δx and Δy are the standard deviations of the five measurements of x and y made in the CIE 1931 (x , y) color space. The mean values of u' and v' , as well as their associated error, were calculated for each display. Based on these calculations, the minimum, maximum, and mean values of u' and v' and their standard deviations were calculated for the entire cohort of displays measured.

Evaluation of Color Point Uniformity

To evaluate color point uniformity, measurements were made at five locations on a white display—the center and approximately 2.5 cm from each of the four corners using the CS-100A Chroma Meter. As in “Measurement of Color Point and Uncertainty” section, measurements were made in the CIE

1931 (x , y) color space and converted to the 1976 CIELUV (u' , v') color space using Eqs. 1 and 2. After the conversion, the radial color distance (RCD) between the center measurement and each of the corner measurements was calculated as follows:

$$RCD(C, 1) = \left[(u'_c - u'_1)^2 + (v'_c - v'_1)^2 \right], \quad (5)$$

where u'_c and v'_c are the values of u' and v' at the center of the display, and u'_1 and v'_1 are the values of u' and v' measured at the corner of the display. Based on the RCD calculated for each display, the minimum, maximum, and mean values and their standard deviations were calculated for the entire cohort of displays measured.

Results

Validation of GSDF Conformance and Maximum Luminance

Figure 1 shows a plot of the mean difference between measured and target luminance, calculated as a percentage of the target, for both the external and built-in luminance meters. For the built-in meter, the measured luminance was within 5 % of the target luminance at all driving levels. It should be noted that the calibration algorithm used by the manufacturer bases the luminance for steps LN2 through LN18 on the values from LN1. As a result, the difference between the value reported by the built-in meter and the target luminance for test pattern LN1 is always 0 %. At the lower luminance levels provided by test patterns LN1 and LN2, the difference between the external meter and target value becomes substantial, with percent differences of −35.6 and −10.5 %, respectively. For test patterns LN3 through LN18, corresponding to mean target luminance between 3.18 and 450.4 cd/m², the difference falls to less than 4 %. For the maximum luminance, the mean difference between external and target levels was 0.29 ± 1.22 % corresponding to a measured luminance of 451.7 ± 5.5 cd/m². Based on this result, lower and upper action limits were identified at 440.7 and 462.7 cd/m², respectively. The t tests performed to compare measured and reported luminance showed a statistically significant difference ($p < 0.05$) for all but three driving levels. At levels 6, 16, and 18 (corresponding to target luminance of 13.6, 272.0, and 450.4 cd/m²), there was no statistically significant difference between measured and reported luminance values, with $p = 0.77$, $p = 0.12$, and $p = 0.24$, respectively.

Evaluation of Luminance Uniformity

Table 1 provides the measured luminance values from the center and four corners of all 23 displays tested along with

Fig. 1 The mean differences between luminance values measured with external and built-in meters and the target luminance, as a percentage of that target (ordinate), are plotted vs. the mean target luminance (abscissa) for 23 MDCC 6230 displays. The difference between built-in meter values and target luminance is within 5 % at all luminance levels. At

lower luminance values, the external meter measured substantially lower luminance (−35.58 % for the LN1 test pattern). Above $\sim 3 \text{ cd/m}^2$, this difference fell to less than 4 %. The plot is rescaled as an inset to help visualize the difference between external and built-in meter measurements at low luminance values

Table 1 Target and measured luminance values

Serial number	BLH	Target luminance (cd/m^2)	Measured luminance (cd/m^2)					MLD
			Center	Upper left	Upper right	Lower left	Lower right	
1890342057	19	450.5	450.4	416.3	396.4	421.2	404.9	12.8
1890342061	21	450.4	456.8	427.9	406.9	431.5	413.2	11.6
1890321892	23	450.5	450.5	401.4	399.7	407.3	415.0	12.0
1890321760	25	450.3	441.3	409.4	407.6	408.1	409.5	7.9
1890321890	25	450.2	455.6	411.0	421.5	422.1	428.0	10.3
1890321891	25	450.6	461.0	412.5	434.4	414.4	441.8	11.1
1890343148	25	450.5	460.1	408.0	434.6	405.2	449.6	12.7
1890321584	26	450.4	447.0	420.1	428.7	424.1	430.5	6.2
1890341670	26	450.3	458.2	425.6	424.5	438.8	436.1	7.6
1890321619	28	450.5	451.4	427.6	444.1	421.5	439.0	6.9
1890320720	32	450.5	445.7	398.0	417.2	405.0	427.3	11.3
1890339394	41	450.3	463.2	402.0	420.7	404.7	435.4	14.1
1890341669	43	450.5	445.8	420.8	404.9	430.3	412.5	9.6
1890322007	48	450.4	449.2	410.9	417.2	418.8	426.9	8.9
1890321893	58	450.5	451.0	426.5	427.2	408.7	430.1	9.8
1890342053	60	450.4	453.2	419.4	402.7	417.1	416.0	11.8
1890321766	63	450.4	451.1	427.7	432.8	426.1	435.7	5.7
1890330529	66	450.4	459.3	440.4	414.4	434.8	418.0	10.3
1890339775	72	453.2	453.2	436.8	390.3	440.2	404.7	14.9
1890321759	86	450.4	456.6	411.1	420.0	412.5	416.8	10.5
1890321582	88	450.5	445.5	408.8	404.1	403.5	403.7	9.9
1890321560	119	450.4	451.0	403.6	405.6	399.2	418.6	12.2
1890321610	152	450.4	449.6	414.4	438.0	425.2	439.4	8.1

Target and measured luminance values from the center and four corners using a RaySafe Xi luminance meter are listed for 23 MDCC 6230 displays ranging from 19 to 152 BLH. Among the displays, the mean MLD was 10.40 ± 2.38 %

the target luminance, BLH, and MLD calculated for each display. The mean MLD for these displays was 10.4 ± 2.4 %. An upper action limit for the MLD of these displays was identified at 15.2 %, corresponding to the mean value plus 2 standard deviations.

Measurement of Color Point and Uncertainty

Figure 2 shows the mean values of u' and v' for the five measurements made on each of the 23 displays evaluated. The minimum and maximum values of u' and v' were 0.182, 0.190, 0.468, and 0.480, respectively. Additionally, color space measurements performed on individual displays were shown to be very reproducible. The mean values of u' and v' across the entire cohort of displays were 0.187 ± 0.002 and 0.474 ± 0.004 .

Evaluation of Color Point Uniformity

Table 2 displays the RCD calculated between measurements made in each of the corners and measurements made in the center of the displays using Eq. 5. Also, the minimum, maximum, and mean RCDs are listed for each display. Additionally, the mean RCD and standard deviation across the entire cohort of displays have been calculated for each corner as well as for the minimum, maximum, and mean values listed. There was no difference in the mean RCD measurements at the corners of the displays.

Discussion

Rejected Displays

While performing acceptance testing on the displays included in this study, several displays were rejected and required replacement. As stated in “Evaluation of Luminance Uniformity” section, data collected during testing of the rejected displays

Fig. 2 Mean values of u' and v' from five repeated measurements performed on 23 MDCC 6230 are shown. The mean values of u' and v' across the entire cohort of displays were 0.187 ± 0.002 and 0.474 ± 0.004 . Due to the small magnitude of the error, error bars have been omitted because they are too difficult to visualize

were not used in this work. It should be noted that each of these displays ($n=4$) was rejected because of visible particulate matter behind the front glass and that no display was rejected due to luminance or color performance. While it was difficult to ascertain exactly what this substance was, it manifested itself as small objects or flakes. In minor cases, portions of individual pixels were obscured while in more substantial cases, these objects would limit visibility of all or portions of five or six adjacent pixels at a time. Additionally, the substance was visible even when the displays were turned off or unplugged and could be observed without any backlight. It should be reiterated that whatever the material was, it was behind the front glass and not on the outer surface and no manner of cleaning led to any improvement. This event provides a reminder of the importance of a thorough visual inspection when accepting new displays.

Luminance Characteristics

When performing acceptance testing of a new device, it is necessary to have criteria that determine whether the equipment is performing as expected. Additionally, a robust QA program requires action limits, or a defined range of expected performance values, to alert the user to any significant changes in equipment performance. The first part of this study established action limits for this particular display model, but the methodology could be applied to any group of displays, given that they are compared within groups of the same model.

As shown in Fig. 1, at low driving levels (below ~ 3 cd/m^2), there is a substantial disagreement between the values measured using the external luminance meter and both the target luminance as well as the values reported by the built-in meter. Previous work has shown that measurements made with the RaySafe Unfors Xi are reproducible and agree well with measurements made using another meter at low luminance levels [1].

One explanation for the discrepancy between measured and reported luminance at low driving levels is whether or not the meters mask ambient light during measurement. The external meter used in this study and the one used for comparison in the above-referenced work are contact luminance meters. The RaySafe Unfors Xi luminance meter is used with a flange, extending several centimeters around the measurement field of view, excluding ambient light from luminance measurements. The internal meter, on the other hand, is flangeless and likely includes some ambient light as part of the measured luminance. Furthermore, the vendor reports an ambient light value as part of the GSDF conformance test which was consistently reported as 0.21 cd/m^2 for each display. This is similar to the discrepancy seen at low luminance between the external and internal meters. Because the measured ambient light is so small, this discrepancy is only substantial at very low driving levels. It is worth noting that the

Table 2 Radial color distance measurements

Serial number	Radial color distance relative to display center						
	Upper left	Upper right	Lower left	Lower right	Min	Max	Mean
1890342057	0.000	0.000	0.001	0.001	0.000	0.001	0.001
1890342061	0.002	0.001	0.004	0.002	0.001	0.004	0.002
1890321892	0.001	0.001	0.001	0.001	0.001	0.002	0.001
1890321760	0.002	0.001	0.001	0.001	0.001	0.002	0.001
1890321890	0.002	0.002	0.002	0.002	0.002	0.003	0.002
1890321891	0.001	0.002	0.003	0.002	0.001	0.003	0.002
1890343148	0.001	0.001	0.002	0.002	0.001	0.002	0.001
1890321584	0.001	0.003	0.004	0.002	0.001	0.004	0.002
1890341670	0.003	0.002	0.003	0.002	0.002	0.003	0.002
1890321619	0.003	0.003	0.003	0.004	0.003	0.004	0.003
1890320720	0.002	0.001	0.002	0.001	0.001	0.002	0.001
1890339394	0.001	0.000	0.003	0.001	0.000	0.003	0.001
1890341669	0.001	0.001	0.001	0.002	0.001	0.002	0.001
1890322007	0.003	0.002	0.004	0.002	0.002	0.004	0.003
1890342053	0.004	0.003	0.003	0.002	0.002	0.004	0.003
1890321566	0.001	0.002	0.001	0.001	0.001	0.002	0.001
1890321766	0.002	0.003	0.002	0.002	0.002	0.003	0.002
1890330529	0.004	0.002	0.003	0.002	0.002	0.004	0.003
1890339775	0.003	0.002	0.003	0.002	0.002	0.003	0.003
1890321759	0.004	0.002	0.003	0.001	0.001	0.004	0.002
1890321582	0.002	0.001	0.002	0.001	0.001	0.002	0.002
1890321560	0.004	0.000	0.002	0.002	0.000	0.004	0.002
1890321610	0.003	0.003	0.002	0.001	0.001	0.003	0.002
Mean	0.002	0.002	0.002	0.002	0.001	0.003	0.002
Std. dev.	0.001	0.001	0.001	0.001	0.001	0.001	0.001

Radial color distance between the corners and the center of 23 MDCC 6230 displays is shown along with the minimum, maximum, and mean value for each display. Additionally, the mean value and standard deviation calculated across all displays are shown for each of these metrics

externally measured luminance results fall outside of the GSDF compliance limits of 15 % provided by the vendor. While it is known that variation in display luminance can affect the perception of displayed images [7], the clinical significance of deviation from the GSDF curve at low luminance levels is unclear.

Good agreement was observed between the target luminance and measured values above 3 cd/m² with the mean difference between measured maximum luminance and target maximum luminance less than 1 %. Based on these results, action limits have been identified at 440.7 and 462.7 cd/m² corresponding to the mean value for maximum luminance $\pm$ standard deviations. Because these values are quite a bit tighter than the limits provided by the manufacturer, they are not intended to act as rejection criteria. However, as newer displays are accepted, those that fall outside these limits should come under greater scrutiny, including a repeat of the calibration procedure and GSDF conformance test. As previously stated, these values are specific to the model of displays

included in this study, and a similar analysis would be required to establish action limits for other display models.

As stated in “[Evaluation of Luminance Uniformity](#)” section, the mean MLD for the color displays tested in this study was 10.40 $\pm$ 2.38 %. This demonstrates similar luminance uniformity to grayscale displays with less than 800 BLH which were observed to have a mean MLD of 9.5 $\pm$ 4.3 %, evaluated as part of previous work [1].

Evaluation of Changes in Luminance and Color over Time

One of the goals of this work is to collect the initial data for a longitudinal study that will track agreement between external and built-in luminance meter measurements for MDCC 6230 color displays to determine if they behave similarly to grayscale models. Previous work demonstrated a difference between the measured and reported white level luminance of 5.84 $\pm$ 3.49 % for displays with less than 25,000 BLH and

38.92 ± 22.01 % for displays with greater than 25,000 BLH [1]. Although the displays evaluated in the current study showed excellent agreement between measured and target maximum luminance, with a mean difference of 0.29 ± 1.22 %, it is unknown whether this agreement will persist as the units increase in BLH. To this end, the displays will be routinely retested to characterize their behavior over time.

Previous work seemed to suggest that a change in luminance uniformity across the face of the displays was not the cause of the observed disagreement between externally and internally measured luminance [1]. As mentioned, one possible cause might be sensitivity of the built-in luminance meter to changes in display color point. A shift in u' and v' of approximately 2.0 and 2.5 %, respectively, has been observed over 18,000 BLH in other LCD displays [5], although these displays were not radiologist review workstations and therefore had a substantially lower maximum luminance (maximum luminance ~ 100 cd/m²) than the ones used in this study. At acceptance, the color point of MDCC 6230 displays was observed to be very consistent between units with the standard deviations of u' and v' both less than 1 % of their mean values. If disagreement between measured and target maximum luminance becomes significant as these displays increase in BLH and these changes can be correlated with changes in either color point or color uniformity, it may indicate that the built-in luminance meter used to calibrate the display has a color point dependency.

Conclusions

This work evaluated GSDF conformance, maximum luminance, luminance uniformity, color point, and color uniformity as part of acceptance testing for 23 Corion Fusion 6-MP MDCC 6230 color displays. These data will provide a

baseline of performance for both the acceptance of future displays of the same model and longitudinal studies of luminance and color performance. While excellent agreement was demonstrated between target and measured luminance for the majority of tested driving levels, some substantial disagreement was observed at low luminance (less than 3 cd/m²). The color point was observed to be very consistent between displays, as indicated by the small variation in u' and v' . However, it remains to be determined whether or not these displays will behave similarly to previous models as they age, resulting in growing disagreement between measured and target luminance as the displays increase in BLH. While this study only considered a single display model, the methodology could be used to characterize performance of other displays.

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