Practical Considerations with the Clinical Implementation of TG-18 Guidelines

by

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Medical Physics Graduate Program
Duke University

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Thesis submitted in partial fulfillment of
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ABSTRACT

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Abstract

Purpose

Quality control of soft-copy displays is critical to ensure the proper contrast rendition of medical images. The American Association of Physicists in Medicine's (AAPM) Task Group 18 (TG-18) has developed a set of testing parameters for the acceptance testing and quality control of medical grade displays. This paper addresses practical challenges associated with the broad implementation of TG-18 in a clinical setting.

Methods

First, a computer model was developed to determine the effects of ambient light variations on the contrast response of a DICOM GSDF calibrated display. The model was based on an LCD displays with diffuse reflection coefficients of 0.0017 sr^{-1}, 0.0060 sr^{-1}, 0.0080 sr^{-1}, and 0.0200 sr^{-1}. Second, the influence on display assessment due to inter-device variability and measurement techniques was established. Finally, the utility of a commercially available quality control program for remote monitoring of soft-copy displays was examined by confirming the accuracy and precision of the program.

Results

In terms of ambient light effects, the results suggest that the maximum allowable increase in ambient lighting can be determined for primary and secondary class displays by the following equations.

$$E_{max}^{Primary} \leq \left(-521.62R_d^2 + 18.822R_d + 0.2511\right)E_{cal} + \left(0.2169R_d^{-1.002}\right) + E_{cal}$$

$$E_{max}^{Primary} \leq \left(-423.03R_d^2 + 22.306R_d + 0.5126\right)E_{cal} + \left(2.1328R_d^{-0.753}\right) + E_{cal}$$

Restricting ambient light increases to less than the ΔE_{max} value will ensure that GSDF calibration is maintained. Assessment of the displays can be performed with either telescopic or contact luminance meters provided the device behaves linearly and the diffuse reflected luminance (L_{amb}) is added to the contact measurements to generate L′, the luminance perceived by the human eye. Finally, some tests recommended by TG-18 can be implemented by the use of an automated QC system to perform many of the routine measurements.

Conclusion

A soft-copy display quality control program can be implemented effectively and efficiently. When performing the TG-18 recommended tests, any calibrated luminance meter can be used provided it captures L′. A commercial program can be used to facilitate these measurements. However, the contact luminance meters used by such systems should be characterized and calibrated against a stand-alone calibrated luminance meter with the required compensation for ambient lighting and reflections.

Dedication

I would like to dedicate this work to my loving wife, Jennifer. Without her constant motivation and hard work raising our two children this document would not be possible.

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Table of Nomenclature

Abbreviation	Mathematical derivation	Definition and explanation
${}^{E}L_{amb}$	${}^{E}L_{amb}=ER_d$	Luminance generated by a display when the device is off due to ambient light (E)
R_d		Diffuse reflection coefficient
E		Illuminance
L_{min}		Minimum luminance value generated by a display for the Digital Driving Level (DDL) =0. It is measured by contact meter or telescopic meter with the display shrouded
L_{max}		Maximum luminance value generated by a display for the DDL=maximum. It is measured by contact meter or telescopic meter with the display shrouded
${}^{E}L'_{min}$	$L_{min} + {}^{E}L_{amb}$	Luminance that will be perceived by the human eye for DDL=0. Measurement includes reflection of ambient light, ${}^{E}L_{amb}$, at illumination E
${}^{E}L'_{max}$	$L_{max} + {}^{E}L_{amb}$	Luminance that will be perceived by the human eye for DDL=max. Measurement includes reflection of ambient light, ${}^{E}L_{amb}$, at illumination E
J		Just Noticeable Difference (JND) as defined by the Barten Model
i		Digital Driving Level
J_{min}		JND value corresponding to the minimum luminance value ${}^{E}L'_{min}$
J_{max}		JND value corresponding to the maximum luminance value ${}^{E}L'_{max}$
J_{ave}	$(J_{max}-J_{min})/\Delta i$	The average number of JND's per integer change in Δi
${}^{E}L'^{d}_{i}$		GSDF calibration vector for all DDL's for a display calibrated for an ambient light value of E
${}^{E}\delta^{d}_{i}$	$\frac{2\left({}^{E}L'^{d}_{i} - {}^{E}L'^{d}_{i-1}\right)}{\left(L^{d}_{i} + L^{d}_{i-1}\right)\left(J_i - J_{i-1}\right)}$	The expected contrast response for display calibrated to the GSDF at an ambient light value of E

Table of Nomenclature continued.

Abbreviation	Mathematical derivation	Definition and explanation
${}^{E}_{\Delta E}L'^{d}_{i}$		GSDF calibration vector for all DDL's for a display calibrated with for an ambient light value of E with an additional ambient light change of ΔE
${}^{E}_{\Delta E}\delta_{i}$	$\frac{2\left({}^{E}_{\Delta E}L'_{i} - {}^{E}_{\Delta E}L'_{i-1}\right)}{\left({}^{E}_{\Delta E}L'_{i} + {}^{E}_{\Delta E}L'_{i-1}\right)(J_{i} - J_{i-1})}$	The expected contrast response for display calibrated to the GSDF at an ambient light value of E with an additional ambient light change of ΔE
${}^{E}_{\Delta E}\kappa_{\delta}$	$Max\left(\left\|\frac{{}^{E}\delta^{d}_{i}}{{}^{E}_{\Delta E}\delta_{i}} - 1\right\|\right)100$	Percent maximum deviation of a display calibrated to the GSDF at an ambient light value of E with an additional ambient light change of ΔE

Acknowledgements

I would like to thank my Advisor Dr. Ehsan Samei for his guidance, advice, knowledge, and encouragement during the completion of this document. I would also like to thank the Clinical Imaging Physics Group (CIPG) at Duke University for the use of the equipment used in several experiments. A special thank you is due to CIPG member Robert Ike for his assistance in obtaining experimental data and for assisting with the debugging of the ambient light simulation code.

1 Introduction

Digital technology has the potential to offer significant advantages over analog technology as it offers a disassociation of the image from the display medium [1]. This shift from hard-copy to soft-copy technology has placed the medical grade display as a key integral component in the digital imaging chain [1, 3]. Initially, most display devices were CRT's, but they have more recently been replaced by LCD displays. LCD displays offer significant advantages in that they have no geometric distortions, they are not vulnerable to magnetic fields, and they have less glare and reflection [4]. However, the performance of LCD displays can vary both with time and between displays, causing the appearance of displayed images to vary between displays. The performance of displays needs to be monitored to ensure that the appearance of an image is independent of the display.

The American Association of Physicists in Medicine's (AAPM) Task Group 18 (TG-18) has developed a set of testing parameters for the acceptance testing and quality control of medical grade displays [1]. Table 1 provides a summary of TG-18 guidelines. TG-18 specifically endorses the use of the Digital Imaging Communications in Medicine's (DICOM) Grayscale Standard Display Function (GSDF) to calibrate medical grade displays [1, 5]. The GSDF is based on the Barten model of the contrast response of the human visual system. The GSDF is often reflected in a table of luminance values required to detect a low contrast target. These subtle differences are known as Just

Noticeable Differences (JND) [5]. A plot of the GSDF is shown in Figure 1. The human visual system is less sensitive to contrast changes for dark luminance values than for higher luminance values. In other words, the lower JND values require a greater change in luminance to achieve the JND than the change in luminance required for the higher JND values [5]. The GSDF calibration process is designed to remove the inter-device variability of medical displays and allow for the correction of lost contrast in the dark regions of the image due to diffuse ambient light reflections [2, 3, 6].

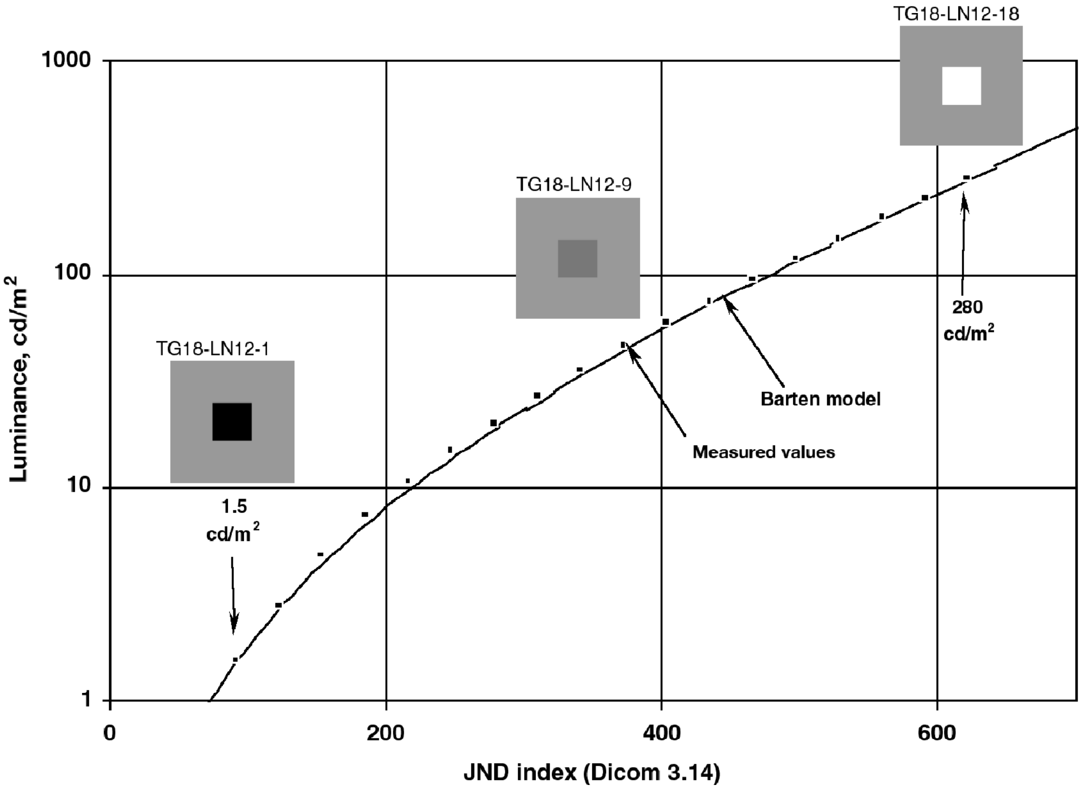

Figure 1: An example of the measured luminance for 18 display levels as plotted in relation to the GSDF, taken from TG-18.

The most common type of LCD display calibration is the gamma calibration. The gamma calibration follows the relationship, $L_i = p_i^{\gamma} + L_{min}$, where L_i is the luminance value produced by the pixel value, p, to the power of gamma. The L_{min} adjustment is due to the fact that LCD's allow some light to pass through at the zero pixel value. An illustration of how the contrast response of a display is dependent on the calibration is shown in Figure 2. As demonstrated by the graph, it is highly important to calibrate medical displays to the GSDF; for example, a gamma 1 calibrated display under-contrasts for the first 15 Digital Driving Levels (DDL), over-contrasts for the darker gray DDL's, and under-contrasts for the highest DDL's.

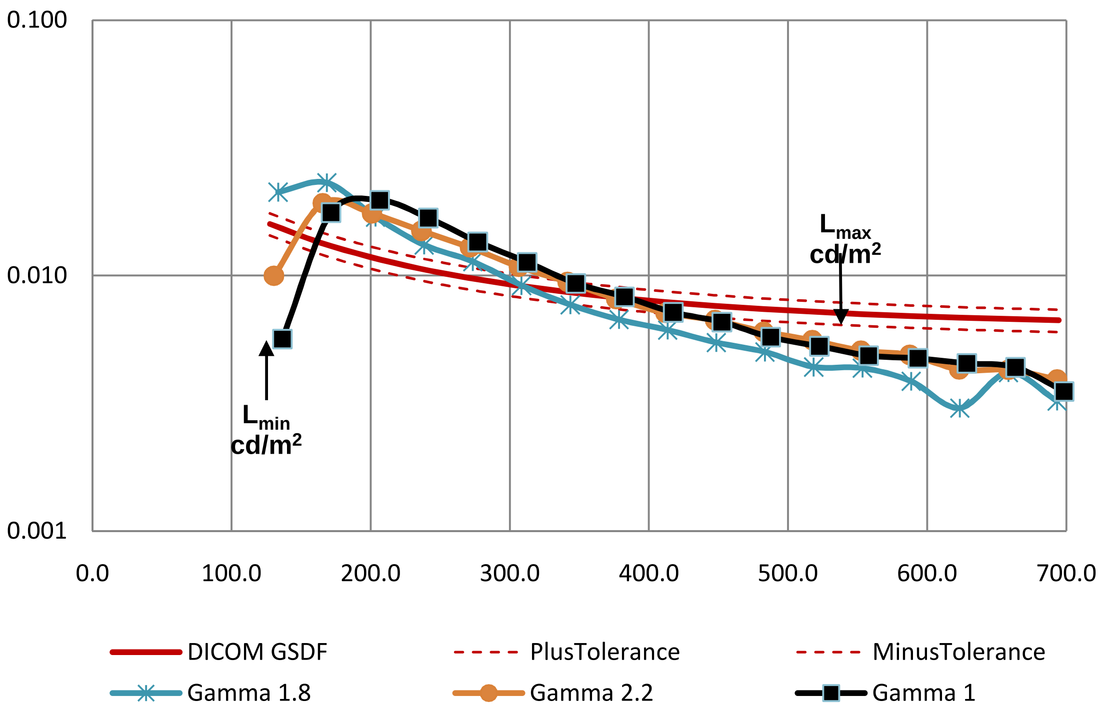

Figure 2: The contrast response of a medical grade display for gamma 1, gamma 1.8 and gamma 2.2 as compared to the GSDF

The purpose of this study was to address some practical challenges associated with broad implementation of TG-18 in a clinical setting. Specifically, the effect of ambient light changes on a GSDF calibrated display was established. Furthermore, the influence on display assessment due to the inter and intra device variability of luminance meters and the use of telescopic versus contact measurement techniques was determined. Finally, the utility of commercial quality control software for remote monitoring of display devices according to the standards recommended by TG-18 was assessed.

Table 1: TG-18 recommended QC program for primary displays.

Test	Requirement	Testing Frequency
Ambient Light	$E \leq (0.25\ L_{min})/R_d$	Monthly/Quarterly
Diffuse Reflection	The threshold of visibility for low-contrast patterns in the TG18-AD test pattern should not be different when viewed in total darkness and when viewed in ambient lighting conditions.	Monthly/Quarterly
Specular Reflection	No specularly reflected high contrast objects should be seen under normal viewing conditions	Monthly/Quarterly
Geometric Distortion	Spatial deviations < 2%	Monthly/Quarterly
Uniformity	The maximum deviation of luminance values across a display should not exceed 30%	Monthly/Quarterly
Resolution	The visual assessment of the TG18-CX test pattern should result in a score ≤ 4	Monthly/Quarterly
Contrast Response	Deviation from GSDF not to exceed ± 10%	Monthly/Quarterly
Noise	Visual inspection of the TG18-NS test pattern should yield all but the smallest quadrants visible.	Annually

2 Materials and Methods

2.1 Simulation of ambient light changes

A computer program using a commercial package (MATLAB r2009b, Mathworks Inc.) was created to simulate the luminance response of displays calibrated with ambient light levels (E) ranging from 0 to 300 lux in steps of 10 lux. This luminance range was chosen because it encompasses the ambient light levels typical in the variety of reading rooms found in today's medical centers [7]. The ambient light in a room corresponds to a given amount of reflected luminance from the display face (${}^{E}L_{amb}$) equivalent to the ambient light (E) in lux multiplied by the diffuse reflection coefficient (R_d) in sr^{-1} or ${}^{E}L_{amb} = ER_d$ [6,7,8]. For the purposes of this experiment, the diffuse reflection coefficients were assumed to be 0.0017 sr^{-1}, 0.0060 sr^{-1}, 0.0080 sr^{-1}, and 0.0200 sr^{-1}, typical values for medical grade LCD [7].

The ambient light levels were added to the display's native minimum and maximum values to create 31 sets of apparent L'_{min} and L'_{max} values, where $L'_{min} = L_{min} + L_{amb}$. A perfect set of calibration luminance values was obtained for each ambient light condition using the following method.

The minimum and maximum Just Noticeable Differences (J_{min} and J_{max}) values corresponding to L'_{min} and L'_{max} were determined using Equation 1, where the parameters A-I that define the polynomial are defined in Table 2 [1].

$$J = A + BLog_{10}(L') + C\left(Log_{10}(L')\right)^2 + D\left(Log_{10}(L')\right)^3 + E\left(Log_{10}(L')\right)^4$$
$$+F\left(Log_{10}(L')\right)^5 + G\left(Log_{10}(L')\right)^6 + H\left(Log_{10}(L')\right)^7 + I\left(Log_{10}(L')\right)^8 \qquad \text{(eq. 1) [1]}$$

Table 2: Coefficients that define the GSDF polynomial in terms of JND.

A=71.498068	B=94.593053	C=41.912053
D=9.8247004	E=.28175407	F=-1.1878455
G=-0.18014349	H=0.14710899	I=-0.017046845

These J_{min} and J_{max} values were then used to find the average number of JND's per Digital Driving Level (DDL, i). Since most medical displays currently in use are 8-bit displays, the number of available DDL's is 2^8 or i = 0 - 255. The total number of i changes (Δi) is 255 and $J_{ave} = (J_{max}-J_{min})/ \Delta i$ [3]. A calibration vector, ${}^{E}L_i'^{d}$, containing the correct JND values for all DDL's was then obtained by using $J_i = J_{min} + i * J_{ave}$ [3]. The calibration luminance values were then obtained by using Equation 2, where the parameters a-m that define the polynomial are listed in Table 3 [1].

$$Log_{10}\left({}^{E}L_i'^{d}\right) = \frac{a + c(\ln J_i) + e(\ln J_i)^2 + g(\ln J_i)^3 + m(\ln J_i)^4}{1 + b(\ln J_i) + d(\ln J_i)^2 + f(\ln J_i)^3 + h(\ln J_i)^4 + k(\ln J_i)^5} \qquad \text{(eq. 2) [1]}$$

Table 3: Coefficients that define the GSDF polynomial in terms of luminance.

a=-1.3011877	b=-2.584019x10^{-2}	c=8.0242636x10^{-2}
d=-1.0320229x10^{-1}	e=1.3646699x10^{-1}	f=2.8745620x10^{-2}
g=-2.5468404x10^{-2}	h=-3.1978977x10^{-3}	k=1.2992634x10^{-4}
m=1.3635334x10^{-3}		

The calibration luminance values were then used to compute the expected contrast response of the display as ${}^{E}\delta_i^d = \frac{2({}^{E}L_i'^d - {}^{E}L_{i-1}'^d)}{({}^{E}L_i'^d + {}^{E}L_{i-1}'^d)(J_i - J_{i-1})}$ [7].

With the display calibrated to the assumed ambient light level (E) additional ambient lighting (ΔE) was simulated by adding ambient light from -200 to 200 lux in steps of 10 lux to each of the 31 calibration vectors, ${}^{E}L_i'^d$. The new ${}_{\Delta E}^{E}L_i'^d = {}^{E}L_i'^d + {}_{\Delta E}^{E}L_{amb}$ vector was then placed through the same algorithm above, to generate the simulated contrast response, ${}_{\Delta E}^{E}\delta_i = \frac{2({}_{\Delta E}^{E}L_i' - {}_{\Delta E}^{E}L_{i-1}')}{({}_{\Delta E}^{E}L_i' + {}_{\Delta E}^{E}L_{i-1}')(J_i - J_{i-1})}$ [7]. The maximum percent deviation of the contrast response from the GSDF was then obtained for each calibrated display at E for all ambient light variations ΔE by ${}_{\Delta E}^{E}\kappa_\delta = Max\left(\left|\frac{{}^{E}\delta_i^d}{{}_{\Delta E}^{E}\delta_i} - 1\right|\right)100$. It should be noted that the adaptation response of the human visual system was not included in this study. This study focused on how ambient lighting effects the measurement of the contrast response of the display independent of adaptation processes.

2.2 Luminance measurement dependencies

Almost all of the tests recommended by TG-18 require the measurement of luminance values produced by several display test patterns. Several different luminance meters were used to measure the TG18-LN test patterns on a DICOM calibrated display (MDCG-3120-CB, Barco, Duluth GA) in order to determine the effect of measurement device on the outcome of the luminance and contrast response tests. Additionally, the average luminance measurements of the tested luminance meters was determined to serve as a gold standard for device comparison. The display device used for this component of the study was a high quality medical grade display (RadiForce G31, Eizo, Cypress, CA). The device was located in a display laboratory where the ambient lighting in the room was below 5 lux. Two identical telescopic luminance meters (LS-110, Konica Minolta, Ramsey, NJ) calibrated by the manufacturer's calibration laboratory (Konica Minolta, Ramsey, NJ) were used. An alternate luminance meter capable of both contact and telescopic measurements (LX-Plus, Scanditronix Welhofer, Germany) calibrated by a NIST traceable calibration laboratory (Davis Calibration, Timonium, MD) and one displays' built-in luminance meter (I-Guard, Barco, Duluth, GA) were also used.

In accordance with the TG-18 guidelines, each device was mounted to a tripod with a fixed distance of 40 cm from the display face plate to the first lens of the luminance meter. The meters were positioned such that the sensitive area of the device was centered within the TG18-LN test pattern and perpendicular to the display face. The ambient light in the room was reduced as low as possible and strictly controlled throughout the testing and verified to be constant by measuring the illuminance in the room before and after each test. The measured contrast response was then calculated and plotted for analysis.

The LX-Plus luminance meter can function as a distance luminance meter or as a contact luminance meter. When assessing the performance of displays it is necessary to measure $L' = L + L_{amb}$. Telescopic luminance meters can measure L′ directly while contact luminance meters can only measure L. L_{amb} must be measured directly with a telescopic meter or obtained by $L_{amb} = ER_d$ where E is the illuminance falling on the display face and R_d is the diffuse reflection coefficient.

The effect of the measurement technique on the outcome of display assessment was determined by measuring the TG18-LN test patterns with the same experimental setup as above. However, for this experiment the display was calibrated for an ambient light level of 0 lux, while the ambient light in the reading room was 40 lux. The disagreement between the ambient light compensated for at calibration, and the ambient light during testing will cause a deviation between the measured contrast response and the GSDF for telescopic luminance measurements due to ambient light reflections. The test patterns were measured by the Barco I-Guard (Contact), the LS-110 meter (Telescopic), and the LX-Plus in both contact and distance mode. The contrast response for each display was calculated and plotted. The contact measurements were plotted with both contact meter data, L, and with L_{amb} added to the contact meter data. These measurements demonstrate the effect of assessing display performance incorrectly with L, verses correctly with $L' = L + L_{amb}$.

2.3 Automated quality control software assessment

Implementing an effective display quality control program for major medical centers can be a daunting task. The contrast response of the display, the luminance ratio, and the ambient light conditions in the room all need to be monitored frequently to maintain high quality image presentation. Fortunately, commercial software exists that can dramatically reduce the effort required to monitor display systems. However, the accuracy and precision of these systems need to be tested before they are entrusted to be integrated into a quality control program.

Most of the medical grade displays used for reading diagnostic images at our institution are from a single manufacturer (Barco, Duluth, GA). Because of this logistical limitation, our study was limited to the software provided by the manufacturer (MediCal QA Web, v1.06, Barco, Duluth, GA). However, the same testing procedure can be implemented to evaluate other such software packages. The Barco displays conveniently have a luminance meter and illumance meter built into the display requiring no further equipment to implement the automated QC program.

Prior to full scale implementation, a small test system was set up that ran the quality control tasks for eight representative dual head Picture Archiving and Communication System (PACS) workstations equipped with primary class medical grade displays (MDCG-3120-CB, MFGD-3220-D, MFGD-3420, Barco, Duluth, GA) for a total of 16 displays included in the study. The system was programmed to monitor ambient light conditions daily, monitor display luminance ratio daily, monitor display contrast response monthly, and calibrate the displays semi-annually.

The accuracy and precision of the software was monitored by measuring the luminance ratio, contrast response, and ambient light, and comparing the physical results with the results obtained by QA Web on all 16 tested displays. When measuring the luminance ratio and contrast response, the test patterns used were the TG18-LN test patterns provided by the QA Web software. This was done to remove any potential differences between the patterns used by the system and other such patterns available on PACS. The luminance device used to assess the performance of the QA Web system was the LX-Plus, as the performance of this device best matched the performance of the built-in Barco I-Guard sensor. The LX-Plus was used as a contact meter to remove ambient light effects. The accuracy of the Barco I-Guard sensor was assessed by comparing average percent difference between the Barco measurements with those from the LX-Plus meter. The luminance measurements of all 18 TG18-LN test patterns were followed over a six month period to assess the intra-device variability of the I-Guard sensors.

3 Results

3.1 Ambient light effects

The deviations from the GSDF (${}_{\Delta E}^{E}\kappa_{\delta}$) due to changes in ambient light expressed as a maximum percentage are shown in Figures 3, 5, 7, and 9 for ambient light increases, and Figures 4, 6, 8, and 10 for ambient light decreases. The ambient light compensated for at the time of calibration (E) is along the horizontal-axis while the ambient light change (ΔE) is along the vertical-axis.

As expected, at no additional added illuminance (ΔE=0), the top horizontal portion of the charts, all displays are perfectly calibrated, that is the error between the measured and expected contrast response is zero, or ${}_{\Delta E}^{E}\kappa_{\delta} = 0$. However, with ambient light values other than the calibration value (ΔE≠0), the calibration of the display is impacted. The green color bands on both charts represent allowable ambient light levels for a primary class GSDF calibrated display ${}_{\Delta E}^{E}\kappa_{\delta} < 10\%$. For example, a display with an average diffuse reflection coefficient of 0.0060 sr^{-1}, calibrated in a diagnostic x-ray reading room with an ambient light level of 20 lux at the time, of calibration can withstand an increase in ambient lighting of about 40 lux (Figure 5) and a decrease in ambient light of 20 lux (Figure 6).

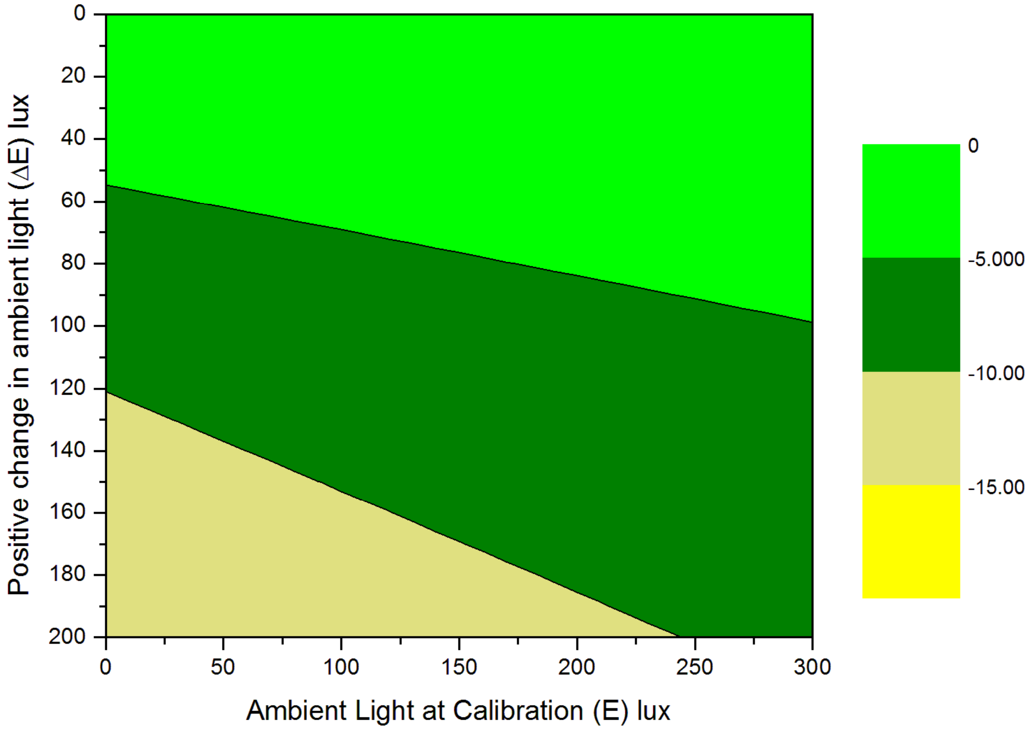

Figure 3: Percent maximum deviation of calibrated displays from the GSDF due to ambient light increases on a simulated display with a diffuse reflection coefficient of 0.0017 sr^{-1}. Per TG-18, green shaded areas represent allowable configurations for primary class displays $\left({}_{\Delta E}^{E}\kappa_{\delta} < 10\%\right)$. Yellow shaded area represents allowable conditions for secondary class displays $\left({}_{\Delta E}^{E}\kappa_{\delta} < 20\%\right)$. Red shaded area represents failing conditions for all GSDF calibrated displays $\left({}_{\Delta E}^{E}\kappa_{\delta} > 20\%\right)$.

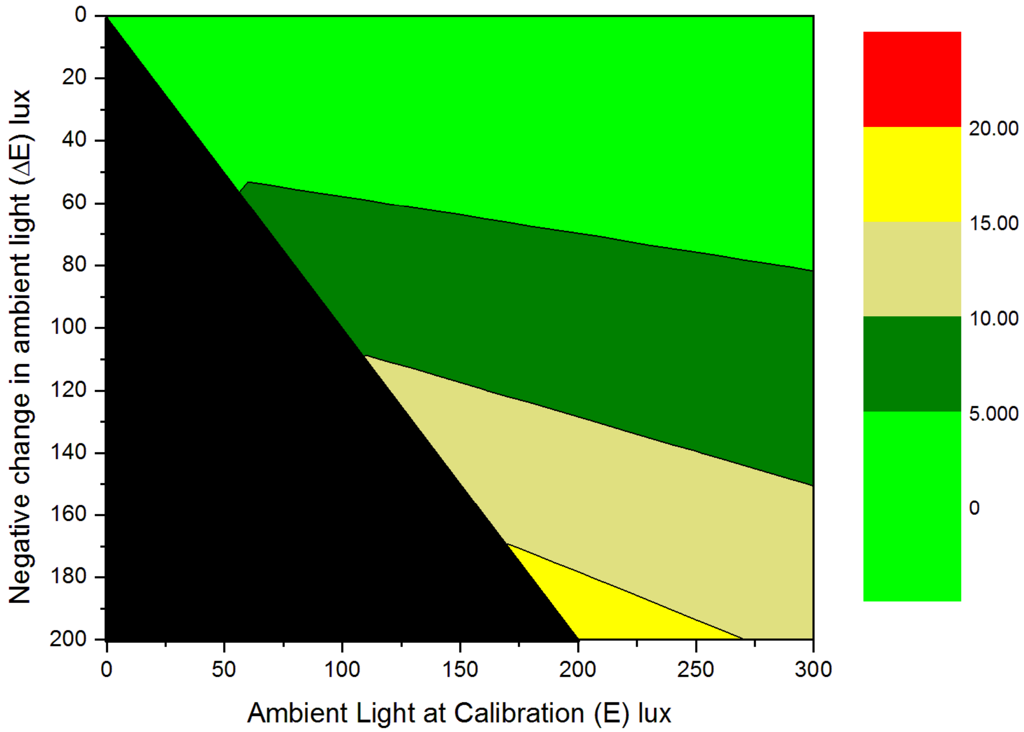

Figure 4: Percent maximum deviation of calibrated displays from the GSDF due to ambient light decreases on a simulated display with a diffuse reflection coefficient of 0.0017 sr^{-1}. Per TG-18, green shaded areas represent allowable configurations for primary class displays $\left({}_{\Delta E}^{E}\kappa_\delta < 10\%\right)$. Yellow shaded area represents allowable conditions for secondary class displays $\left({}_{\Delta E}^{E}\kappa_\delta < 20\%\right)$. Red shaded area represents failing conditions for all GSDF calibrated displays $\left({}_{\Delta E}^{E}\kappa_\delta > 20\%\right)$. Note: The black region represents generally non-physical display room configurations.

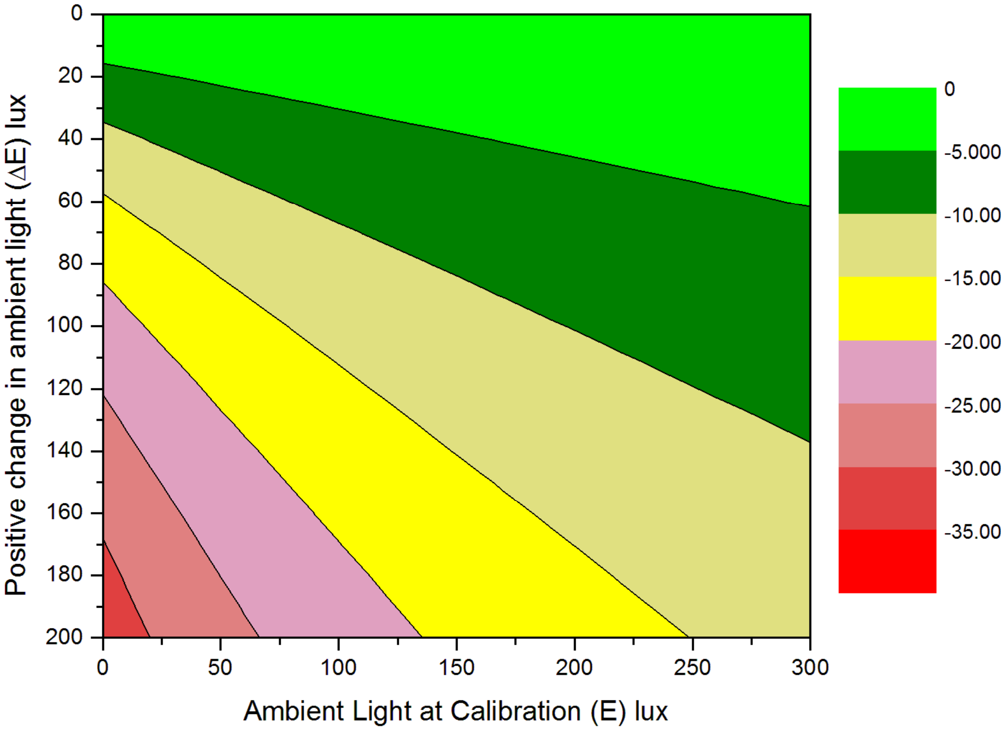

Figure 5: Percent maximum deviation of calibrated displays from the GSDF due to ambient light increases on a simulated display with a diffuse reflection coefficient of 0.0060 sr^{-1}. Per TG-18, green shaded areas represent allowable configurations for primary class displays $\left({}_{\Delta E}^{E}\kappa_{\delta} < 10\%\right)$. Yellow shaded area represents allowable conditions for secondary class displays $\left({}_{\Delta E}^{E}\kappa_{\delta} < 20\%\right)$. Red shaded area represents failing conditions for all GSDF calibrated displays $\left({}_{\Delta E}^{E}\kappa_{\delta} > 20\%\right)$.

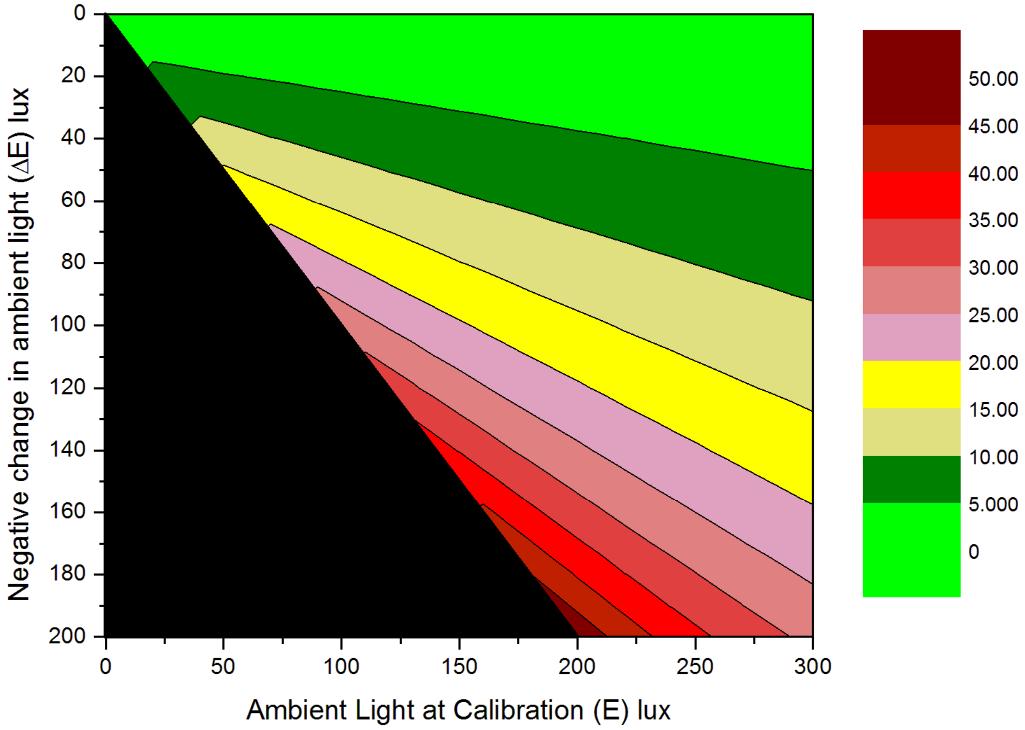

Figure 6: Percent maximum deviation of calibrated displays from the GSDF due to ambient light decreases on a simulated display with a diffuse reflection coefficient of 0.0060 sr^{-1}. Per TG-18, green shaded areas represent allowable configurations for primary class displays $\left({}^{E}_{\Delta E}\boldsymbol{\kappa}_{\delta} < 10\%\right)$. Yellow shaded area represents allowable conditions for secondary class displays $\left({}^{E}_{\Delta E}\boldsymbol{\kappa}_{\delta} < 20\%\right)$. Red shaded area represents failing conditions for all GSDF calibrated displays $\left({}^{E}_{\Delta E}\boldsymbol{\kappa}_{\delta} > 20\%\right)$. Note: The black region represents generally non-physical display room configurations.

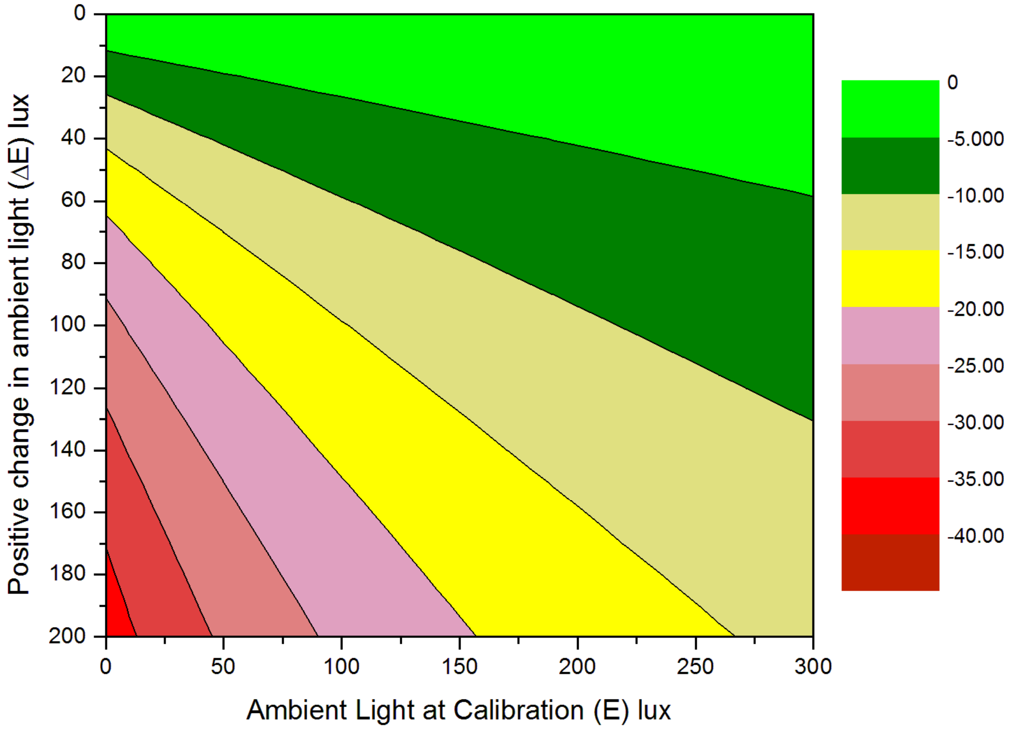

Figure 7: Percent maximum deviation of calibrated displays from the GSDF due to ambient light increases on a simulated display with a diffuse reflection coefficient of 0.0080 sr^{-1}. Per TG-18, green shaded areas represent allowable configurations for primary class displays $\left({}_{\Delta E}^{E}\boldsymbol{\kappa}_{\delta} < 10\%\right)$. Yellow shaded area represents allowable conditions for secondary class displays $\left({}_{\Delta E}^{E}\boldsymbol{\kappa}_{\delta} < 20\%\right)$. Red shaded area represents failing conditions for all GSDF calibrated displays $\left({}_{\Delta E}^{E}\boldsymbol{\kappa}_{\delta} > 20\%\right)$.

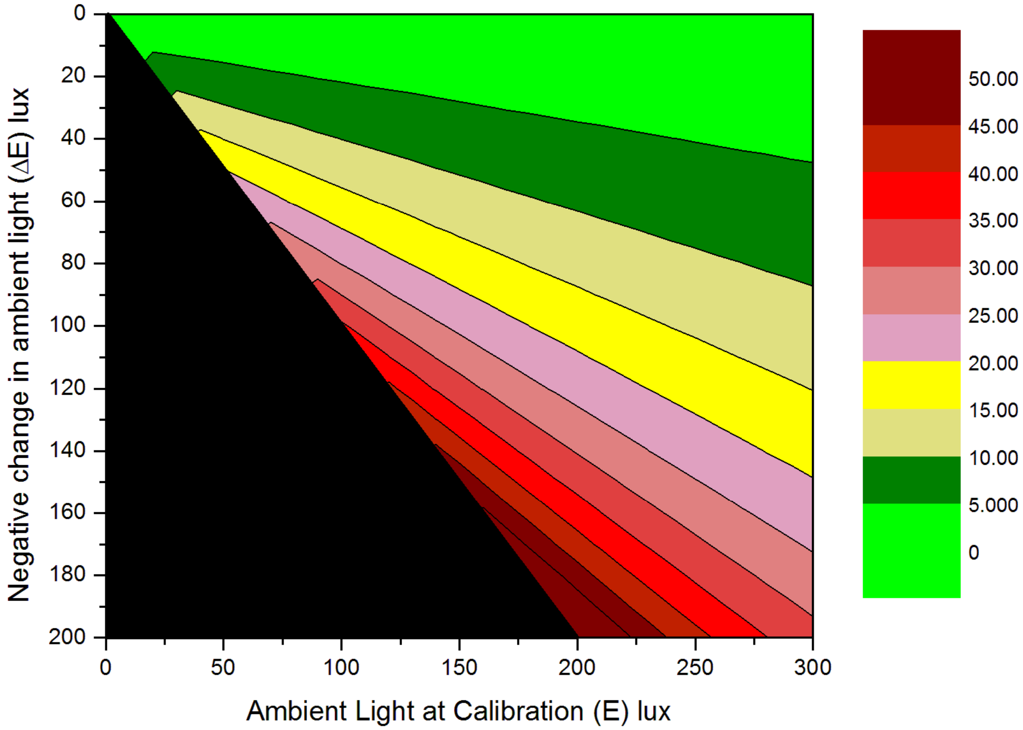

Figure 8: Percent maximum deviation of calibrated displays from the GSDF due to ambient light decreases on a simulated display with a diffuse reflection coefficient of 0.0080 sr^{-1}. Per TG-18, green shaded areas represent allowable configurations for primary class displays $\left({}_{\Delta E}^{E}\boldsymbol{\kappa}_{\delta} < 10\%\right)$. Yellow shaded area represents allowable conditions for secondary class displays $\left({}_{\Delta E}^{E}\boldsymbol{\kappa}_{\delta} < 20\%\right)$. Red shaded area represents failing conditions for all GSDF calibrated displays $\left({}_{\Delta E}^{E}\boldsymbol{\kappa}_{\delta} > 20\%\right)$. Note: The black region represents generally non-physical display room configurations.

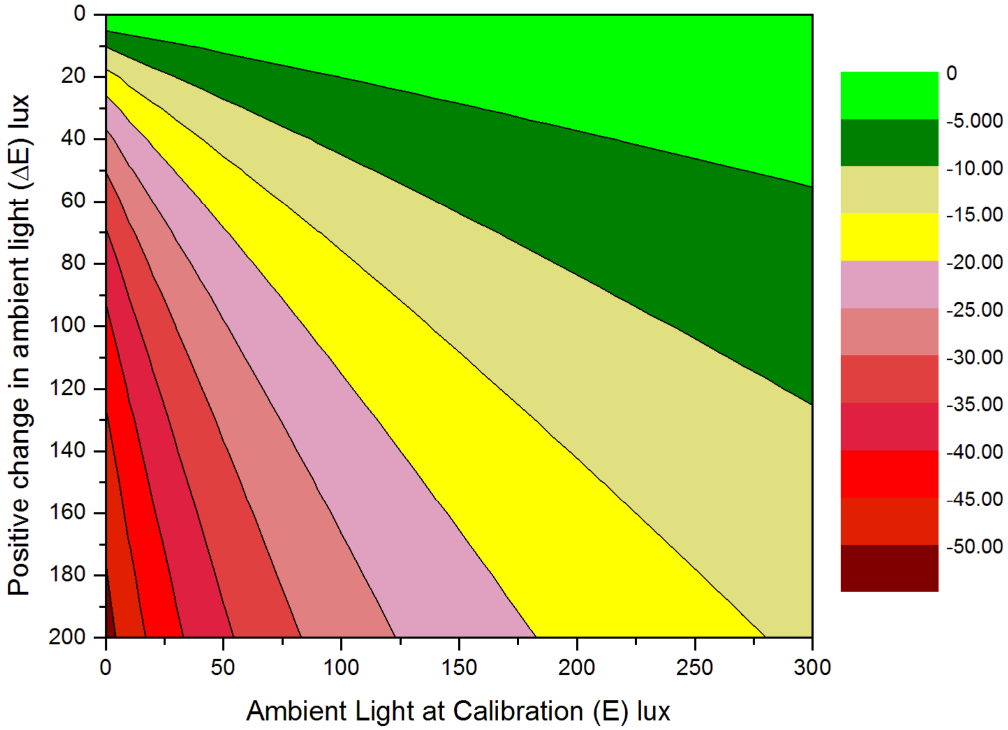

Figure 9: Percent maximum deviation of calibrated displays from the GSDF due to ambient light increases on a simulated display with a diffuse reflection coefficient of 0.0200 sr^{-1}. Per TG-18, green shaded areas represent allowable configurations for primary class displays $\left({}_{\Delta E}^{E}\boldsymbol{\kappa}_{\delta} < 10\%\right)$. Yellow shaded area represents allowable conditions for secondary class displays $\left({}_{\Delta E}^{E}\boldsymbol{\kappa}_{\delta} < 20\%\right)$. Red shaded area represents failing conditions for all GSDF calibrated displays $\left({}_{\Delta E}^{E}\boldsymbol{\kappa}_{\delta} > 20\%\right)$.

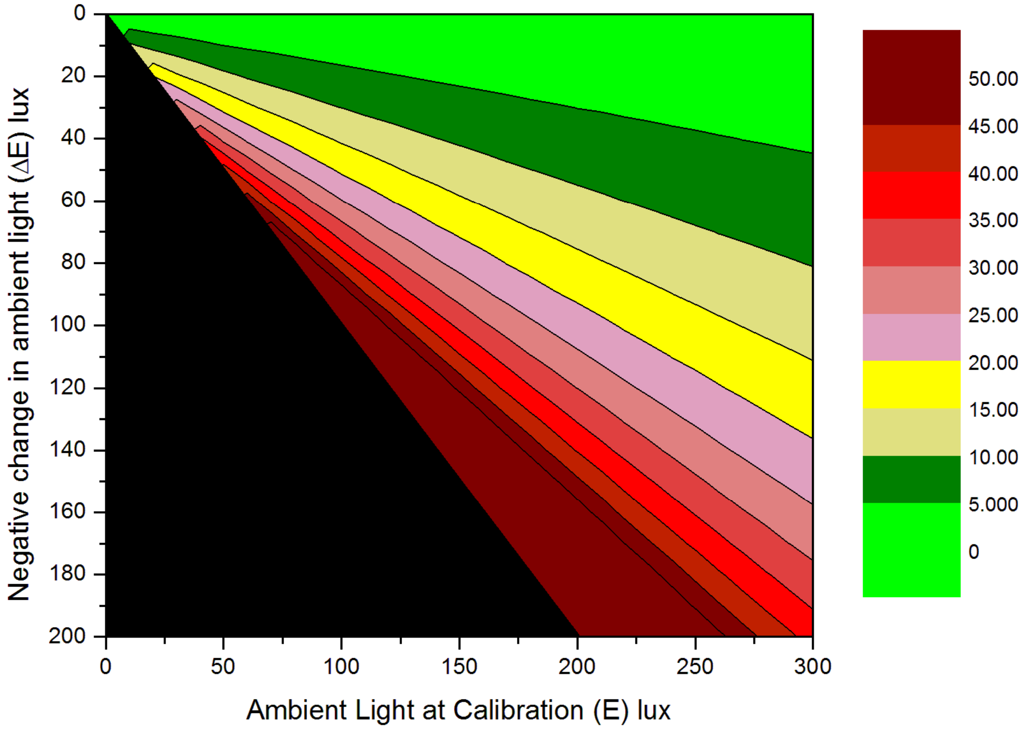

Figure 10: Percent maximum deviation of calibrated displays from the GSDF due to ambient light decreases on a simulated display with a diffuse reflection coefficient of 0.0200 sr^{-1}. Per TG-18, green shaded areas represent allowable configurations for primary class displays $\left({}_{\Delta E}^{E}\kappa_{\delta} < 10\%\right)$. Yellow shaded area represents allowable conditions for secondary class displays $\left({}_{\Delta E}^{E}\kappa_{\delta} < 20\%\right)$. Red shaded area represents failing conditions for all GSDF calibrated displays $\left({}_{\Delta E}^{E}\kappa_{\delta} > 20\%\right)$. Note: The black region represents generally non-physical display room configurations.

The ambient light at calibration and the increased ambient light values along the 10% deviation line are of important consequence because they impose a limit on the range of ambient light variability a room with DICOM GSDF calibrated display can tolerate before the displays contrast response no longer follows the GSDF. The ambient light ranges for typical reading rooms for a diffuse reflection coefficient of 0.0060 sr^{-1} have been listed in Table 4. It is important to note that these ranges will vary depending on the diffuse reflection coefficient of the display.

Table 4: Maximum allowable ambient illumination ranges for primary class displays calibrated at typical diagnostic reading room illuminance values for a display with a R_d of 0.0060 sr^{-1}.

Ambient Illuminance at Calibration (E)	Maximum E range for Primary Displays		Maximum E range for Secondary Displays	
10 lux	0 lux	40 lux	0 lux	70 lux
20 lux	0 lux	60 lux	0 lux	80 lux
50 lux	20 lux	100 lux	10 lux	130 lux
80 lux	40 lux	140 lux	30 lux	180 lux

In order to fully ascertain the restrictions on ambient light variations, a function was designed to indicate the maximum allowable increase in ambient light as a function of the diffuse reflection coefficient of the display, R_d, and the ambient light compensated for during calibration, E. An equation for the slope and intercept of the 10% deviation line dependent on R_d was found. The equations for the 10% deviation lines for the displays simulated in Figures 3, 5, 7, and 9 are shown in Figure 11 for primary class displays and Figure 12 for secondary class displays. The equations for the slope were fitted in Figure 13, and the intercepts were fitted in Figure 14. Using the data from

Figures 13 and 14, new equations for limits on ambient lighting based on deviation from the GSDF have been formed for primary and secondary class displays.

$$E_{max}^{Primary} \leq \left(-521.62R_d^2 + 18.822R_d + 0.2511\right)E_{cal} + \left(0.2169R_d^{-1.002}\right) + E_{cal} \qquad \text{(eq. 3)}$$

$$E_{max}^{Primary} \leq \left(-423.03R_d^2 + 22.306R_d + 0.5126\right)E_{cal} + \left(2.1328R_d^{-0.753}\right) + E_{cal} \qquad \text{(eq. 4)}$$

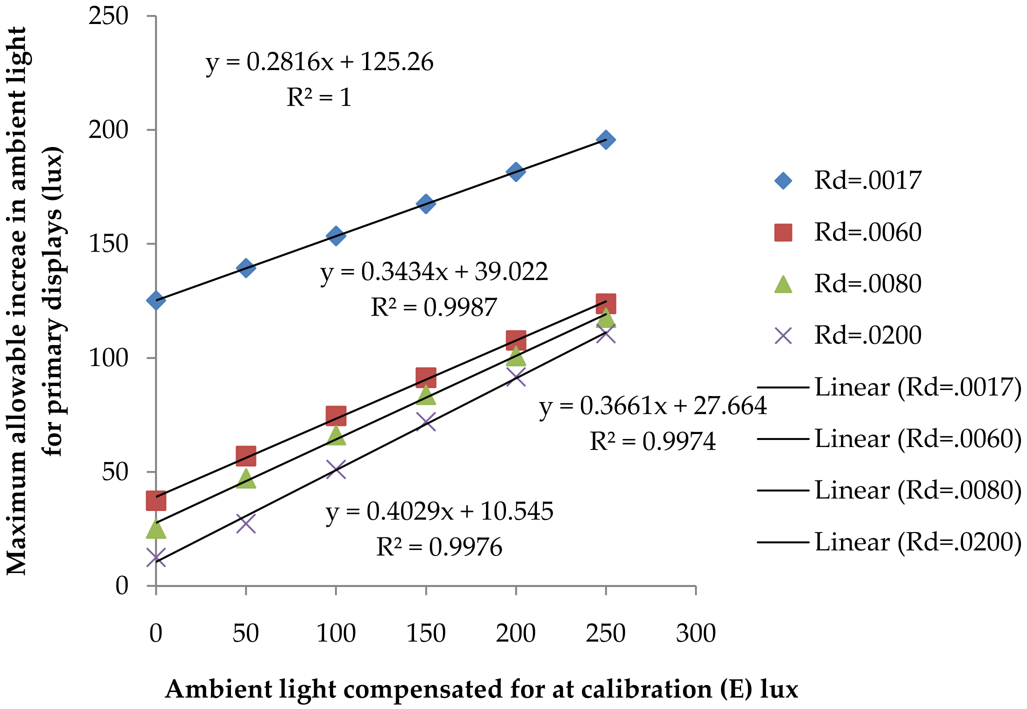

Figure 11: Shown here are the equations for the maximum allowable increase in ambient light for primary class displays with diffuse reflection coefficients of 0.0017 sr^{-1}, 0.0060 sr^{-1}, 0.0080 sr^{-1}, and 0.0200 sr^{-1} as a function of the ambient light compensated for at calibration.

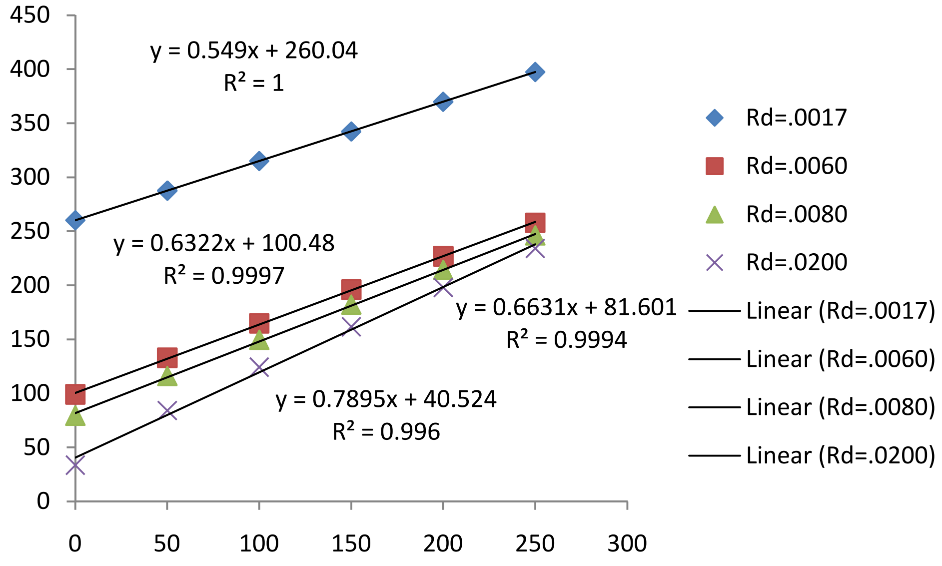

Figure 12: Shown here are the equations for the maximum allowable increase in ambient light for secondary class displays with diffuse reflection coefficients of 0.0017 $^{sr-1}$, 0.0060 sr^{-1}, 0.0080 sr^{-1}, and 0.0200 sr^{-1} as a function of the ambient light compensated for at calibration.

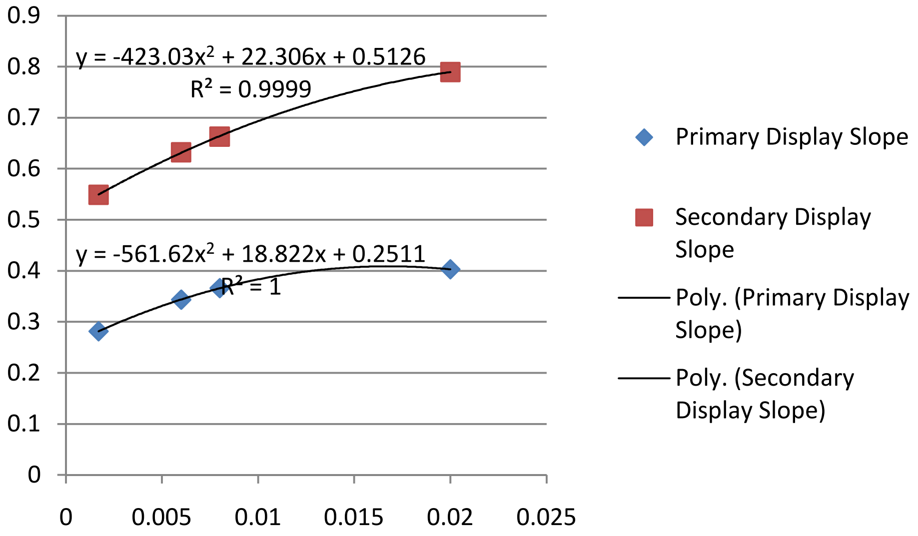

Figure 13: Shown here are the equations used to fit the slopes of the 10% and 20% deviation lines of GSDF calibrated displays as a function of the diffuse reflection coefficient.

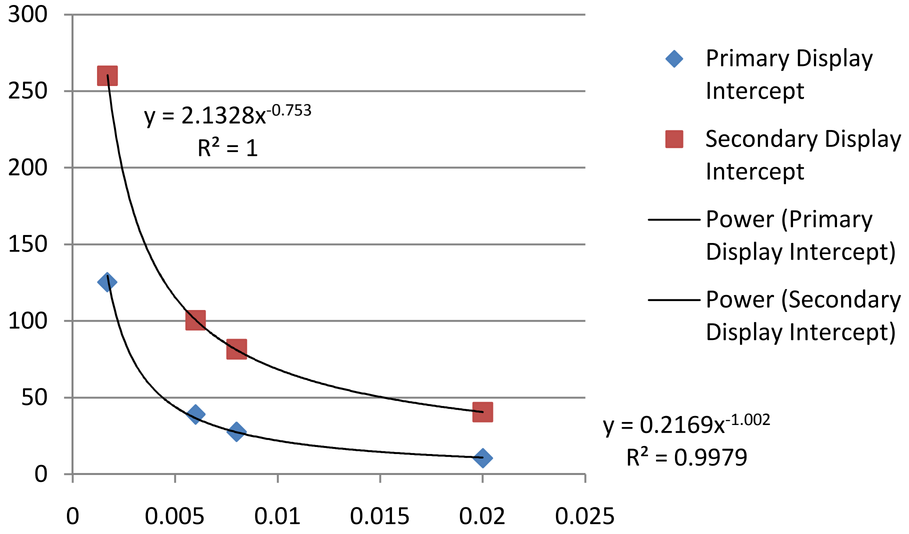

Figure 14: Shown here are the equations used to fit the intercept of the 10% and 20% deviation lines of GSDF calibrated displays as a function of the diffuse reflection coefficient.

3.2 Luminance measurement dependencies

3.2.1 Inter-device variability

The measured luminance values and contrast values from each luminance meter for all 18 of the TG18-LN test patterns are plotted in Figure 15. Each luminance meter gave dramatically different measurements for each of the test patterns. However, the contrast differences between each test pattern remained constant. This stability of contrast measurements lead to an equivalent outcome of the display's contrast response test, as shown if Figure 16. The dashed lines above and below the data points represents a 10% deviation from the GSDF shown here by the solid line.

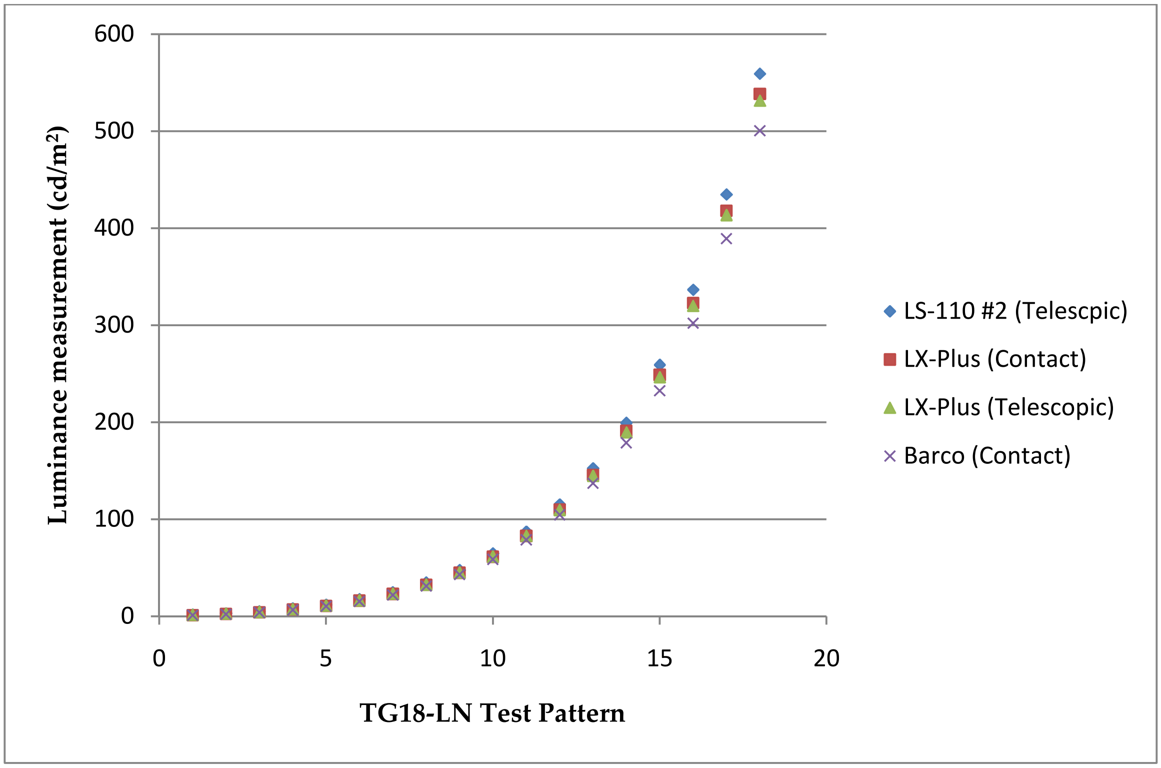

Figure 15: Measured luminance values of the TG18-LN Test patterns for a GSDF calibrated display using four calibrated luminance meters. Luminance meter setup was in accordance with TG18 directives and the user manuals of the devices.

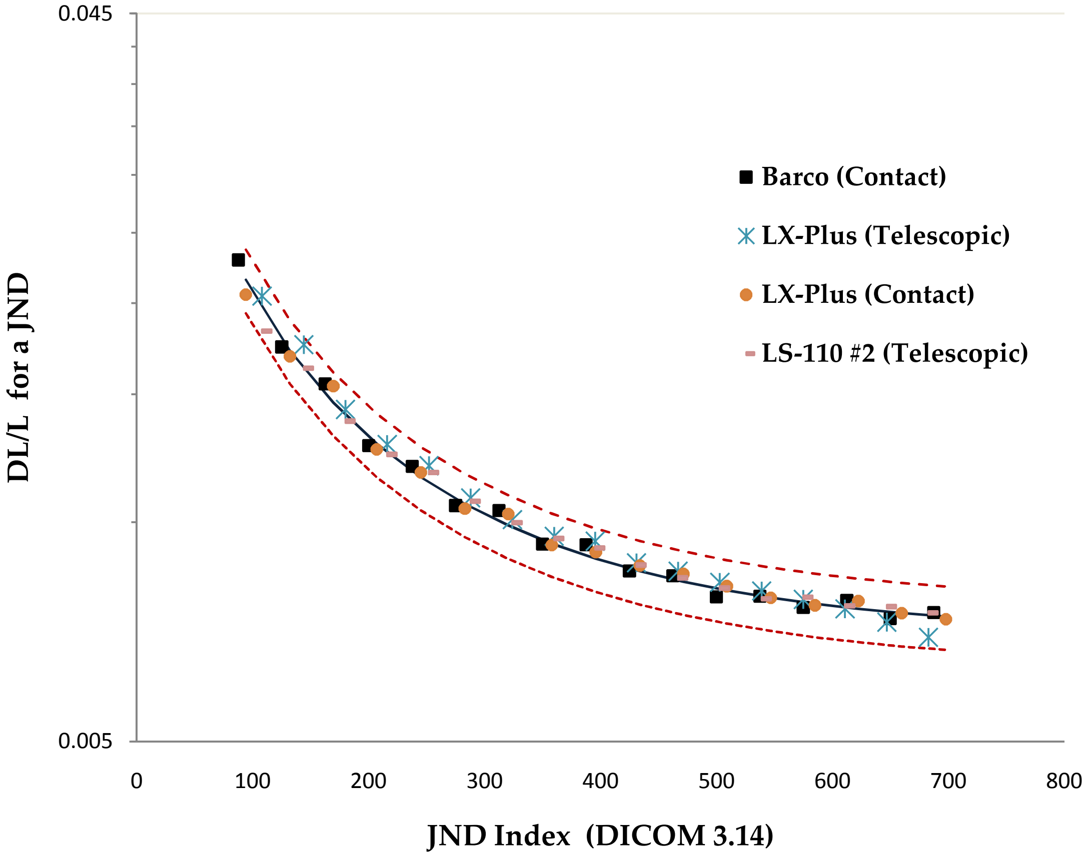

Figure 16: Measured contrast response of a GSDF calibrated display using four calibrated luminance meters. Luminance meter setup was in accordance with TG18 directives and the user manuals of the devices.

Due to the inter-device variability of the calibrated luminance meters, no one meter could be chosen as a gold standard. Instead, their mean measurement was used. Figure 17 shows that on average, a group of luminance meters will deviate from their mean by approximately 10%. That value is increased to 12%-15% for the lower luminance DDL's.

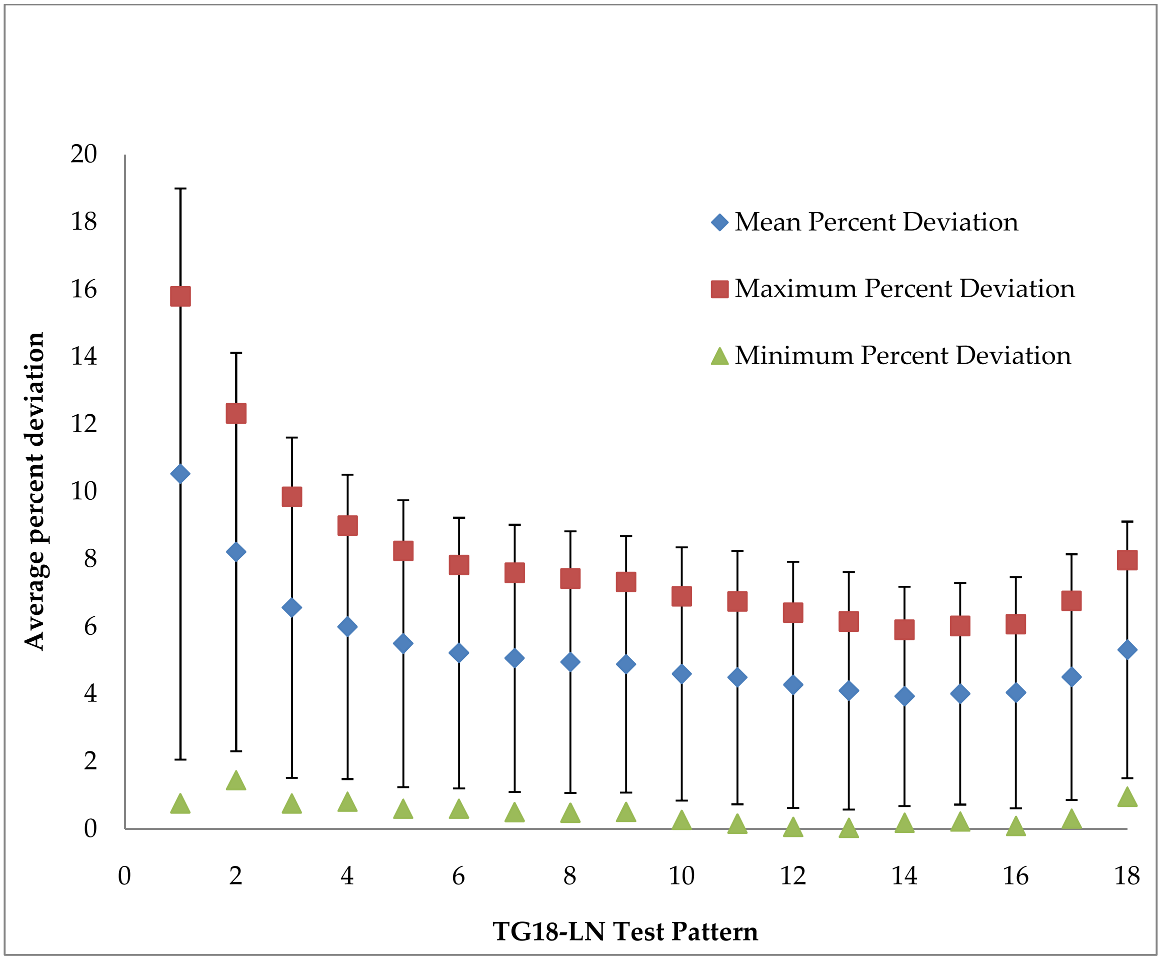

Figure 17: Average percent difference between calibrated luminance meters compared to their mean. The LX-Plus and two LS-110's were used to measure the TG18-LN test patterns in order to determine a nominal percent difference between luminance meter devices.

3.2.2 Luminance measurement, technique dependencies

The contrast response of displays measured by telescopic and contact meter with ambient light (E) of 40 lux is shown in Figure 18. The Barco (Contact, L) and LX-Plus (Contact, L) data sets show the measured contrast response if only L is obtained. The

Barco (Contact, L′) and LX-Plus(Contact, L′) data sets show the measured contrast response if the display is assessed correctly using L′=L+L_{amb}. Notice that the display artificially passes the contrast response test if L is improperly used to assess display performance. The display is actually providing inadequate contrast for the first 15 digital driving levels.

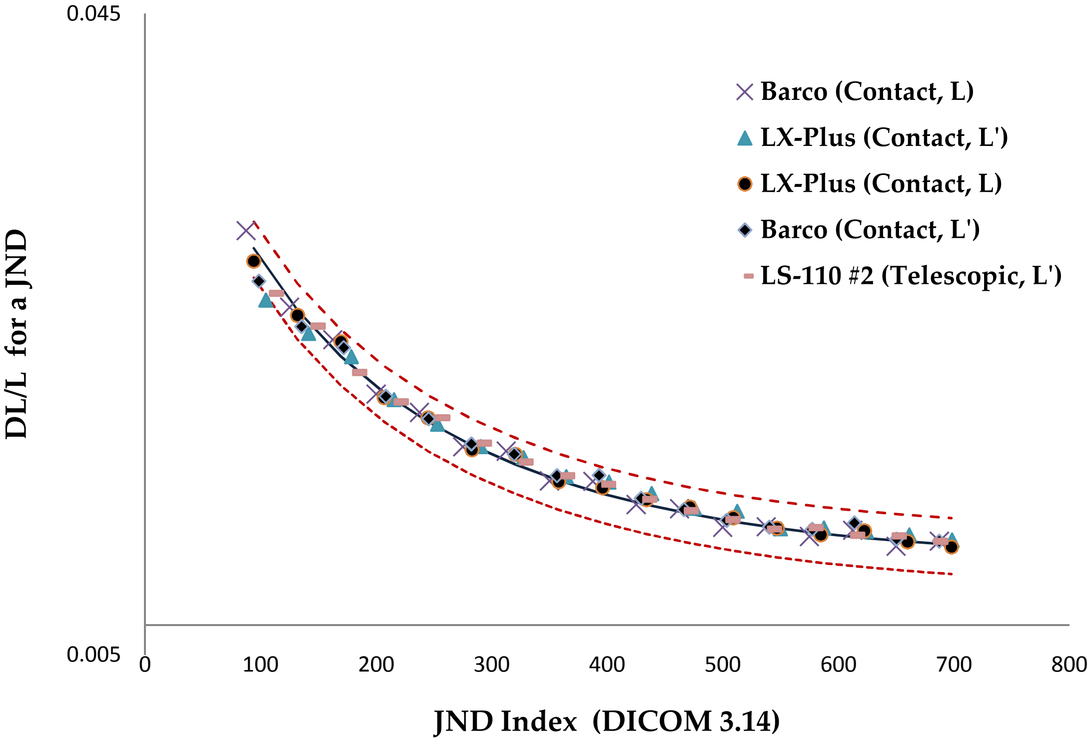

Figure 18: Measured contrast response of a display using contact luminance meters. The LX-Plus (Contact, L′) and Barco (Contact, L′) measurements have L_{amb} added for E=40 lux.

3.3 Automated quality control software assessment

The Barco MediCal QA Web system has performed quite well with monitoring the display devices inside the installed test system. Upon assessment, almost all of the displays under the test system passed the Contrast Response test as outlined by TG-18 with both the QA Web measurements and the LX-Plus measurements. The few devices that failed were due to luminance measurement inconsistencies between the two luminance devices. The average percent difference between the Barco I-Guard and LX-Plus meters along with the standard deviation and minimum and maximum values is shown in Figure 19.

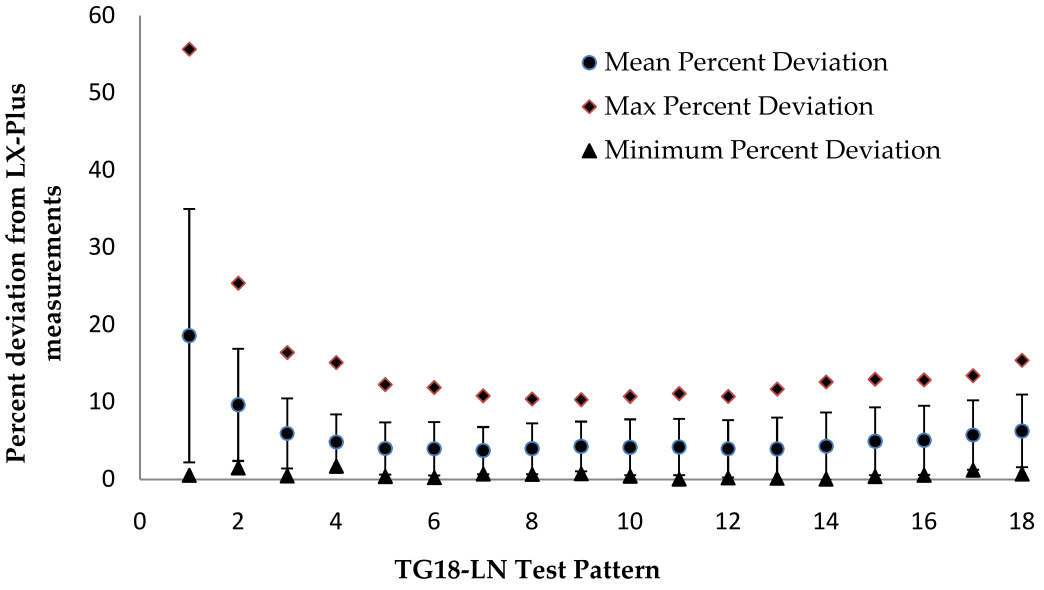

Figure 19: Accuracy of the QA Web system benchmarked against the LX-Plus luminance meter. The TG18-LN test pattern measurements from the Barco I-Guard sensor and the LX-Plus luminance meter were compared for accuracy on 16 displays.

On average, the measurements obtained by the QA Web system deviate from the LX-Plus measurements by as much as 10% for most contrast levels. At the lowest contrast step, that value is raised to 10%-20%. The maximum deviation, however, can be as much as 17% for the majority of contrast steps and 25%-55% at the lowest two contrast levels. The Barco I-Guard sensor, on the average, is just as good as any other commercial luminance meter. However, any particular sensor can exhibit at least two times more deviation than the three tested devices represented in Figure 17. In other words, Barco I-Guard meters show an increased level of inter-device variability.

Beyond luminance and contrast absolute values, the precision of the QA Web system was very good. The maximum standard deviation measured was 0.48 cd/m^2. The deviation of luminance measurements over the six month time period is plotted in Figure 20. This implies a low level of intra-device variability.

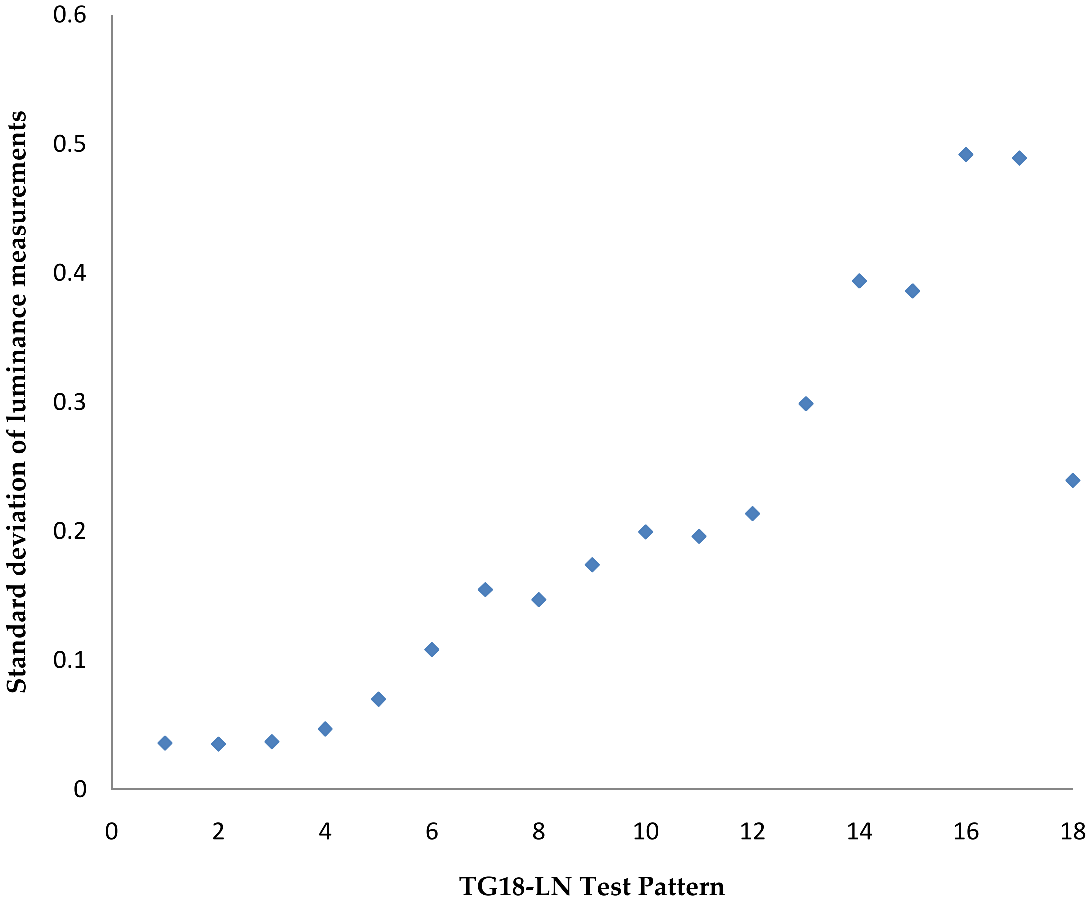

Figure 20: Precision of QA Web system followed over six month period. The luminance measurements of the TG-18 LN test patterns were followed for six months. Shown here are the luminance deviations.

4. Discussion

Many factors need to be considered when implementing a soft-copy display quality control program. Of these, equipment availability, budget, and time significantly impact the design and implementation of the program. The ambient lighting in a room needs to be controlled to ensure displays remain calibrated. The assessment of TG-18 compliance requires the measurement of luminance values from the display. The type of luminance meter available will determine what type of technique is employed, either telescopic or contact, with added strategy to account for ambient light reflections. Additionally, a commercial program may be used to implement a remote quality control program and dramatically reduce the manpower required to maintain the QC program. In our study, we found TG-18 can reasonably be implemented clinically with certain practical adjustments in terms of allowable ambient light levels. The variability across luminance meters was found to be a notable challenge for implementing a QC Program. However, that challenge was solved with proper methodology. Finally, we found automated display QC solutions highly convenient, provided their performance is benchmarked against a standard technique and a calibrated luminance meter.

The ambient illumination in medical reading rooms is currently kept at a level such that reflecting light does not exceed the minimum luminance values of the display. However, GSDF calibration has the ability to shift L_{min} up from the native minimum luminance of the display to a higher level, thus compensating for ambient light. The results from Figures 3-10 imply that there is more tolerance for ambient light variations for displays calibrated to compensate for higher luminance calibrated displays. While this statement is true, it neglects the fact that increasing the ambient lighting in a reading room reduces the contrast ratio of the display [1, 2, 6]. The TG-18 committee has recommended an ambient light setting such that $E \leq (0.25\ L_{min})/R_d$ to ensure that ambient lighting does not reduce the contrast ratio below 250 [1]. However this limit does not take into account the fact that increasing the ambient lighting in a reading room causes a deviation in the contrast response of the display away from the GSDF.

Equation 3, will provide the maximum allowable ambient light value for any GSDF calibrated display if the diffuse reflection coefficient, R_d, and the ambient light compensated for at calibration, E_{cal}, are known. It should be further noted that the additional luminance, L_{amb}, that corresponds to the maximum allowed ambient light should not reduce the perceived contrast ratio, $CR' = L'_{max} / L'_{min}$ to a value below 250.

The inter-device variability between the luminance meters assessing the same display had a dramatic outcome on the result of the assessment. All but three of the luminance meters tested caused a failing result for the tested displays. The most dramatic difference in the luminance response results occurred between the two LS-110's. These two identical devices yielded very different results when measuring the first three TG18-LN test patterns. It is extremely important to know the behavior of the luminance meter when testing displays as a failing result may be due to a poorly functioning luminance meter and not a poorly functioning display. Additional studies are warranted for the accuracy of calibration procedure for luminance meters.

When assessing displays, two techniques can be employed. Using a telescopic luminance meter and measuring L′ directly or using a contact meter to measure L, and then adding L_{amb} to the measurements. The results from Figure 18 show that the two assessment techniques are equivalent. However, each has its advantages and drawbacks. The telescopic technique is advantageous in that it only requires one device to fully assess the display performance. But telescopic devices are cumbersome to use when measuring the first three TG18-LN test patterns due to the flare of the device. Much care must be taken to minimize this effect in order to obtain proper data. The contact luminance meter is superior in that it does not succumb to non-uniformities of the reflected light from the display in relation to ambient light effects when obtaining data, but it fails to obtain the proper data. All assessments must be done with L′ to get accurate results. In order to obtain this with a contact luminance meter, L_{amb} must be known. This can be done by turning off the display and measuring L_{amb} directly. However, that measurement is also subject to reflection non-uniformity. The preferred method is to use the diffuse reflection coefficient (R_d), if known, with added illuminance measurement. Alternatively, R_d may be measured using the TG-18 methodology [1].

In terms of the choice for a luminance meter, the best choice would be to use a meter that is capable of both contact and telescopic measurements. The meter can be used in telescopic mode to measure L_{amb} directly and then switched to contact mode to obtain the L measurements. When added together, they efficiently produce highly accurate results using the proper metric.

Implementation of remote quality control software such as MediCal QA Web can dramatically reduce the effort required for an effective display quality control program. While the inter-device variability was respectable, the intra-device precision was excellent. This high precision allows the use of a lookup table to convert the software luminance measurements to the luminance measurements form a calibrated luminance meter for proper assessment of the display using TG-18 guidelines. However, such a secondary calibration would be necessary to ensure proper implementation of this QC tool.

A common feature of the remote quality control software and calibration software is ambient light compensation. When used properly, it allows for a display to remain GSDF calibrated for a variety of reading room conditions. However, when used improperly, it can result in a deviation from the GSDF equivalent to a change in ambient light levels as simulated in Figures 3-10.

5. Conclusion

Proper assessment of soft copy devices is necessary to ensure that the quality of the image, from receptor to radiologist, is not lost in the final component of the imaging system. The tests described in TG-18, Table 1, provide an effective approach to assess the performance for all soft copy displays, and their implementation can be optimized. Before testing is performed, it is critical that all medical grade displays be calibrated to the DICOM GSDF. Viewing medical images on a non-GSDF calibrated display can impair a radiologist's ability to properly diagnose a patient due to image detail that is lost because the display is not providing adequate contrast. GSDF calibration ensures that the reduced contrast due to ambient light can be removed. Under these conditions, the results from section 3.1 are valid. The maximum allowable ambient light for primary class displays is predicted by Equation 3 and secondary class displays by Equation 4. Adhering to these limits will ensure GSDF compliance. Before measurements are made, the performance and linearity of luminance meters must be maintained to minimize the test outcome variability due to luminance device variability. Furthermore, it is extremely important to include the ambient lighting when obtaining tests measurement with either telescopic or contact luminance meters to ensure that the contrast response test is not biased due to improper measurement technique.

Appendix A

The following code was used to obtain the data simulated in section 3.1 as described in section 2.1. The first part of the code computes the expected contrast response for all 31 simulated display calibrations. The second part of the code was used to generate the measured contrast response for the ambient light variations from -200 lux to 200 lux.

```
Part 1.
clc;close all;clear all;
%% Define physical parameters of display
L_min=.7;  % minimum luminance value of display (cd/m^2)
L_max=500;  % maximum luminance value of display (cd/m^2)
Rd=.0060;  % Diffuse reflection coefficient (sr^-1)
DDL=(0:255); % DDL vector for 8-bit display

%% GSDF JND table Generation
%Coefficients used to generate the luminance values of the DICOM GSDF
for
%JND values ranging from 0 to 1024.
a=-1.3011877;b=-2.584019*10^-2;c=8.0242636*10^-2;d=-1.0320229*10^-1;
e=1.3646699*10^-1;f=2.8745620*10^-2;g=-2.5468404*10^-2;
h=-3.1978977*10^-3;k=1.2992634*10^-4;m=1.3635334*10^-3;
% Coefficients used to generate JND values for given luminance values.
A=71.498068;B=94.593053;C=41.912053;D=9.8247004;E=.28175407;
F=-1.1878455;G=-.18014349;H=.14710899;I=-.017046845;

%% Ambient Light values
% The following code computes the ambient light to be added to the
above
% GSDF values.  The initial ambient light increase is in lux.  The
% increased illuminance values are then multiplied by the diffuse
% reflection coefficient to get a reflected light value in cd/m^2.
Ambient_light=(0:10:300);  % Ambient light values in lux
Lamb=Ambient_light*Rd;
% Adds ambient light to the minimum luminance value
Lprime_min=L_min+Lamb;
Lprime_max=L_max+Lamb;
%% Preallocation of memory for vectors
calibration_values=zeros(length(Ambient_light),256);
calibration_JND=zeros(length(Ambient_light),256);
%% Calculates Expected Response for perfectly calibrated display.

for x=1:length(Lprime_min)
```

```
% Calculates the minimum JND values corresponding to Lmin
JND_min=A+B*log10(Lprime_min(x))+C*(log10(Lprime_min(x)))^2+...
    D*(log10(Lprime_min(x)))^3+E*(log10(Lprime_min(x)))^4+...
    F*(log10(Lprime_min(x)))^5+G*(log10(Lprime_min(x)))^6+...
    H*(log10(Lprime_min(x)))^7+I*(log10(Lprime_min(x)))^8;
% Calculates the maximum JND value corresponding to Lmax
JND_max=A+B*log10(Lprime_max(x))+C*(log10(Lprime_max(x)))^2+...
    D*(log10(Lprime_max(x)))^3+E*(log10(Lprime_max(x)))^4+...
    F*(log10(Lprime_max(x)))^5+G*(log10(Lprime_max(x)))^6+...
    H*(log10(Lprime_max(x)))^7+I*(log10(Lprime_max(x)))^8;

JND_ave=(JND_max-JND_min)/255;
% Creates a calibration lookup table in JND format.
JND_DDL=JND_min+DDL*JND_ave;
calibration_JND(x,:)=JND_DDL;
% Converts JND lookup table to luminance lookup table.
for j=1:length(JND_DDL)
    Log10_Ljnd(j)=(a+c*log(JND_DDL(j))+e*(log(JND_DDL(j)))^2+...
        g*(log(JND_DDL(j)))^3+m*(log(JND_DDL(j)))^4)/...

(1+b*log(JND_DDL(j))+d*(log(JND_DDL(j)))^2+f*(log(JND_DDL(j)))^3+...
    h*(log(JND_DDL(j)))^4+k*(log(JND_DDL(j)))^5);
end
L_cal=10.^Log10_Ljnd;
calibration_values(x,:)=L_cal;
end
% Computes delta value for later assessment.
delta_d=zeros(31,255);
for row=1:31
    for col=2:256
        delta_d(row,col-1)=(2*(calibration_values(row,col)-...
            calibration_values(row,col-
1)))/(calibration_values(row,col)+...
            calibration_values(row,col-1)* (calibration_JND(row,col)-
...
            calibration_JND(row,col-1)));
    end
end




%% Calculates contrast response for ambient light variations
% z is mannual changed from 1 to 21 to simulate the ambient light
changes.
for z=21
Lprime_min2=(calibration_values(:,1)-Lamb(z))';
Lprime_max2=(calibration_values(:,256)-Lamb(z))';
if Lprime_min2<.7
    Lprime_min2=L_min
end
```

```
Part 2.
    for x=1:length(Lprime_min2)
% Calculates the minimum JND values corresponding to Lmin
if Lprime_min2(x)<.7
    Lprime_min2(x)=L_min;
end
    JND_min2=A+B*log10(Lprime_min2(x))+C*(log10(Lprime_min2(x)))^2+...
    D*(log10(Lprime_min2(x)))^3+E*(log10(Lprime_min2(x)))^4+...
    F*(log10(Lprime_min2(x)))^5+G*(log10(Lprime_min2(x)))^6+...
    H*(log10(Lprime_min2(x)))^7+I*(log10(Lprime_min2(x)))^8;
% Calculates the maximum JND value corresponding to Lmax
    JND_max2=A+B*log10(Lprime_max2(x))+C*(log10(Lprime_max2(x)))^2+...
    D*(log10(Lprime_max2(x)))^3+E*(log10(Lprime_max2(x)))^4+...
    F*(log10(Lprime_max2(x)))^5+G*(log10(Lprime_max2(x)))^6+...
    H*(log10(Lprime_max2(x)))^7+I*(log10(Lprime_max2(x)))^8;

    JND_ave2=(JND_max2-JND_min2)/255;
    JND_DDL2=JND_min2+DDL*JND_ave2;
    calibration_JND2(x,:)=JND_DDL2;

        for j=1:length(JND_DDL2)
        Log10_Ljnd2(j)=(a+c*log(JND_DDL2(j))+e*(log(JND_DDL2(j)))^2+...
        g*(log(JND_DDL2(j)))^3+m*(log(JND_DDL2(j)))^4)/...

(1+b*log(JND_DDL2(j))+d*(log(JND_DDL2(j)))^2+f*(log(JND_DDL2(j)))^3+...
        h*(log(JND_DDL2(j)))^4+k*(log(JND_DDL2(j)))^5);
        end
    L_cal2=10.^Log10_Ljnd2;
    calibration_values2(x,:)=L_cal2;
    end
delta=zeros(31,255);
for m=1:31
    for n=2:256
        delta(m,n-1)=(2*(calibration_values2(m,n)-
calibration_values2(m,n-1)))/...
            (calibration_values2(m,n)+calibration_values2(m,n-1)*...
            (calibration_JND2(m,n)-calibration_JND2(m,n-1)));
    end
end
% Creates output kappa delta matrix.
kappa_d=((delta./delta_d)-1)*100;
max_deviation=(max((delta'./delta_d')-1))'*100;
min_deviation=(min((delta'./delta_d')-1))'*100;
max_kappa=max(abs((delta'./delta_d')-1))'*100;

end
```

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