Technical performance assessment and quality control of ultrasound device monitors

Anna Vuorenmaa[a,c,d,*], Eetu Siitama[a,c,d], Ullamari Hakulinen[b,c,d], Hannu Eskola[a,c]

[a] *The University Consortium of Seinäjoki, Finland*
[b] *Department of Radiology, Medical Imaging Center, Tampere University Hospital, Pirkanmaa Hospital District, Tampere, Finland*
[c] *Faculty of Medicine and Health Technology, Tampere University, Finland*
[d] *Department of Medical Physics, Medical Imaging Center, Tampere University Hospital, Pirkanmaa Hospital District, Tampere, Finland*

Abstract

The purpose of this study was to investigate and evaluate the current technical performance of ultrasound imaging device displays. Altogether 53 ultrasound device displays were evaluated in two hospital districts of Finland. The performance of the displays was evaluated with tests and test patterns developed by American Association of Physicists in Medicine (AAPM). Minimum, maximum and ambient luminances ($L_{min}, L_{max}, L_{amb}$) were measured. Ambient ratio (AR), Luminance ratio (LR), L'_{min} and L'_{max} were calculated and Luminance uniformity, defined as Deviation from the Median (MLD), was evaluated. The results show that none of the measured displays fulfils the AAPM Task Group (TG) 270 maximum luminance recommendation for diagnostic displays. Majority, 32/53 (60 %), of the displays fail the AAPM TG270 acceptable level for secondary displays as well. Only 3/53 (6 %) of the

*Corresponding Author: Anna Vuorenmaa, Elämänaukio 2, 33521 Tampere; Email, anna.vuorenmaa@tuni.fi; Phone, +358 44 472 9456

Email address: anna.vuorenmaa@tuni.fi (Anna Vuorenmaa)

displays were at the acceptable level for diagnostic displays. Also, for most of the displays 41/53 (77 %) L'_{min} was under the diagnostic acceptable level. Ambient ratios exceeded the acceptable limit in 31/53 (58 %) of the displays. Luminance ratios on the other hand, were within acceptable level for majority of displays 38/53 (72 %). All the devices passed the AAPM requirement of luminance uniformity (MLD). The results show that the maximum and minimum luminances of most displays are not sufficient. AAPM, Society for Imaging Informatics in Medicine (SIIM) and American College of Radiology (ACR) introduced the updated luminance L'_{min} and L'_{max} criteria already in year 2012. All the ultrasound displays should at least fulfill the AAPM TG18 secondary display minimum criteria. Even so, 6/53 (11 %) fail. Newest displays should be expected to fulfill the revised AAPM TG270 criteria as well. Display technology has developed and therefore the monitor testing needs to be updated.
Keywords: Ultrasound device display, Luminance, Luminance uniformity, Luminance Ratio, Ambient Luminance, Ambient Ratio

Introduction

Ultrasound (US) is one of the most applied imaging methods in clinical practice. It is preferred over x-ray imaging as it uses mechanical waves instead of ionizing radiation. The importance of quality assurance (QA) of medical ultrasound scanners is widely recognized and recommendations for performance testing have been published (Goodsitt et al., 1998; Spencer et al., 2014; Zagzebski et al., 2008). Ultrasound device monitors are used in diagnostics as the interpretation of the image is generally done simultaneously while the physicians perform the examination.

American Association of Physicists in Medicine (AAPM) Task Group (TG) 18, in 2005 (Samei et al., 2005) and AAPM Task Group 270 (Bevins et al., 2019) in 2019, have reported standard guidelines for quality control and acceptance testing of medical display devices. Between these recommendations AAPM, SIIM and ACR made their recommendations in 2012 (Norweck et al., 2013) and revised it in 2017.

According to AAPM the monitors are categorized in four categories. (Bevins et al., 2019) The first two categories diagnostic (primary) or modality (secondary) displays can concern ultrasound devices. Diagnostic displays are used to make medical diagnoses, modality displays instead refer to any display used during the acquisition and generation of medical images. (Samei et al., 2005; Bevins et al., 2019) Ultrasound monitors can be placed in both categories depending on usage. This research assumes that the ultrasound device displays belongs to the diagnostic (primary) displays category or at least into modality (secondary) display category set by AAPM.

In every imaging modality the display is an important piece of the whole imaging chain. Extensive studies about the display quality and its effects on diagnostics have been performed in different uses of x-ray imaging (Baltacıoglu et al., 2016; Butt et al., 2012; Countryman et al., 2018; Kallio-Pulkkinen et al., 2015) but ultrasound device displays have mostly been neglected. The display quality in different imaging modalities have been studied by Silosky et al. (2016) but only one study concentrating in ultrasound imaging was found reported by Moore et al. (2011).

Display technology has developed during the past few years. Cathode-ray tube (CRT) monitors have practically vanished, Liquid Crystal Displays (LCD's) are currently majority, and new technology Organic Light Emitting Diode Displays (OLED's) are entering the field.

Materials and Methods

Altogether 53 ultrasound device displays (21 General Electric (GE), (GE Healthcare, Chicago, Illinois, United States), 30 Philips (Philips healthcare, Amsterdam, Netherlands) and two Canon (Canon Medical Systems, California, USA) monitors were evaluated at the Hospital District of South Ostrobothnia and at Pirkanmaa Hospital District. GE scanner models were LOGIQ S7, LOGIQ E9 and LOGIQ S8. Philips scanners included models Affiniti 50/70G, iE33, iU22, HD15, EPIQ 7C and EPIQ ELITE. Canon scanners were A450 Series. All of the displays in this study represented LCD displays. The performance of the ultrasound device displays was evaluated with the tests and test patterns developed by AAPM (Bevins et al., 2019; Samei et al., 2005). The images for the ultrasound device display were either ready in the scanners patient list or were imported to the ultrasound device using a CD or memory stick. The measurements were performed by adjusting the best possible settings for the ultrasound device to find the absolut maximum luminance that can be obtained. We tested the effect of each setting on the maximum luminance and thus looked for the highest maximum luminance setting that was available by adjusting the color profile, gammacurve, tint, and black level to optimal. The adjustment was made for each monitor individually to find the maximum available luminance of that display. Monitor bighness was set to its maximum value of 100%.

The measurements were performed with RaySafe Xi light detector (Unfors RaySafe AB, Billdal Sweden) during the years 2018 - 2021. Three different devices were used, one in Seinäjoki and another two in Tampere. The older Tampere University Hospital's device was calibrated in 2014 and new calibration was made in 2019. The newest Tampere University Hospital's luminance meter was purchased and calibrated in year 2019. Seinäjoki Central Hospital's device was calibrated in 2018. The accuracy of luminance measurements is given in the calibration certificate. For the oldest device the accuracy of the luminance measurements is ±3 % and to the rest two of the devices ±1.8 %. The reference instruments are traceable to SP Technical Institute of Sweden providing traceability to international standards. The measurement range of luminance is same for both devices, 0.05 - 50 000 cd/m^2 and the resolution is 0.01 cd/m^2. Both devices also comply with the CIE standard photopic spectral response within 4%. This is one percentage point higher than the AAPM requirements (Samei et al., 2005). Otherwise the devices fulfil the AAPM requirements.

Performance parameters

AAPM has evaluated many parameters for acceptance testing and quality control of medical display devices. Only certain tests were chosen to be conducted.

A summary of the recommended performance parameters and their suggested criteria is summarized in Table 1.

Luminances, luminance ratio

Luminance, L, is the quantity of light emitted by the display. The SI unit for luminance is candela per square meter (cd/m^2). The displayed luminance L' includes both the luminance produced by the display, which varies between minimum luminance L_{min} and maximum luminance L_{max}, and the luminance reflected from the display surface when the power of the display device is switched off (ambient luminance, L_{amb}). Both L'_{min} and L'_{max} include the ambient luminance (Bevins et al., 2019). The maximum luminance, L_{max}, on an 8-bit system, is equal to the measured luminance at gray level 255 and the minimum luminance, L_{max}, to the measured luminance at gray level 0. Minimum and maximum luminances were measured from the brightest (TG18-LN12-18) and darkest (TG18-LN12-01) images in the TG18-LN DICOM calibrations series and calculated using equations (1) and (2). The luminance measurements were performed with the display settings at which the display luminance is at its maximum.

$$L'_{min} = L_{min} + L_{amb} \quad (1)$$

$$L'_{max} = L_{max} + L_{amb} \quad (2)$$

As luminance ratio, LR, depends on the ambient lighting, manufacturers can not report it. LR is defined as L'_{max}/L'_{min}. Instead they can provide the contrast ratio, (CR), of the display. CR excludes L_{amb} and is defined as L_{max}/L_{min}. As the luminance ratio affects how many different grayscales can be displayed, the ratios should fulfil the recommended values to ensure that enough grayscales are displayed. If same images are viewed from several different monitors the luminance ratios should be as close to each other as possible to ensure the consistency of the viewed images. An excessively large ratio exceeds the range of visual system and therefore does not have any clinical impact. If the maximum luminance of monitor is brighter, then the minimum luminance should also be larger so that the luminance ratio stays the same. Luminance ratio should be large for high image contrast (Norweck et al., 2013).

AAPM report recommended values for L'_{max}, L'_{min} and LR. For L'_{amb} there are no explicit recommended values but they are compared to minimum luminance (Table 1).

Ambient luminance and ambient ratio

In this study L_{amb} was approximated by measuring the luminance at approximately 15 cm distance from a turned-off display and lighting set to normal scanning conditions. As measured in this way, the value includes both specular and diffuse reflection of light. Although the method might not be very accurate, it is a way to approximate L_{amb}. During office use of the monitor, L_{amb} may be present more intensely, but when viewing radiological images, the light should be dimmed. Under normal scanning conditions, the ultrasound room lighting is well dimmed. A few monitors have been measured under operating room conditions. The L'_{amb} measured in operating rooms is clearly higher than in average ultrasound scanning rooms because the rooms are luminous. If there is no possibility of dimming in the room, the light coming from outside will also affect the magnitude of the L'_{amb}.

The ambient ratio (AR) is defined as the ratio of ambient and minimum luminance (equation (3)).

$$AR = \frac{L_{amb}}{L_{min}}. \tag{3}$$

AAPM gives the suggested AR limit to ensure that major (at least 80 %) of the contrast that is observed in total darkness will be visible. If the value of AR is beyond the recommendation, the contrast will degrade. (Bevins et al., 2019)

Luminance uniformity

In LCD's, the non-uniformity of luminance comes mostly from the non-uniformity of the backlight and differences in single pixels. Luminance non-uniformities are most common along the edges as at the corners (Bevins et al., 2019). Because many different grayscale values are shown it is important that the displayed luminance is uniform. Otherwise a contrast between different regions could be perceived, although an uniform image is displayed. Luminance uniformity was measured using TG18-UNL10 and TG18-UNL80 images. Luminances were measured at the center and corners of the display for each test pattern. Uniformities were calculated using TG18 5-point Maximum Luminance Deviation (MLD), equation (4).

$$MLD = 200\% \cdot \frac{L'_{max} - L'_{min}}{L'_{max} + L'_{min}} \tag{4}$$

AAPM TG270 uses 9-point method and luminance uniformity is calculated using Luminance Deviation from the Median ($LUDM$). The calculation method in MLD and $LUDM$ is different, so they cannot be directly compared. The MLD method has been used for the calculation in this study because most of the displays were measured before the publication of the TG270 recommendation. AAPM has set the acceptance value for MLD (Table 1).

Results

Maximum Luminance

Measured maximum luminance values are presented in Figure 1. As can be seen from the figure, none of the displays fulfil the TG270 maximum luminance recommendation (>350 cd/m^2) for primary displays. Three displays (6 %) fulfil the TG270 maximum luminance acceptable level for primary displays (300-350 cd/m^2). In total there are 15 (34 %) displays that fulfil the TG270 secondary display acceptable level (200-300 cd/m^2). Most of the displays 32 (60 %) fail the AAPM TG270 acceptable level for secondary displays requirement (>200 cd/m^2) If considering the old AAPM TG18 recommendations 31 (58 %) fulfil the recommendation for primary displays (>170 cd/m^2). 15 (28 %) displays maximum luminances are at the level of secondary displays (100-170 cd/m^2) and 6 (11 %) falls under the level of secondary display (<100 cd/m^2).

Minimum and ambient luminance, and ambient ratio

Ambient and minimum luminance values are compared in Figure 2. For the majority of the monitors the L_{min} is approximately the same. L_{amb},

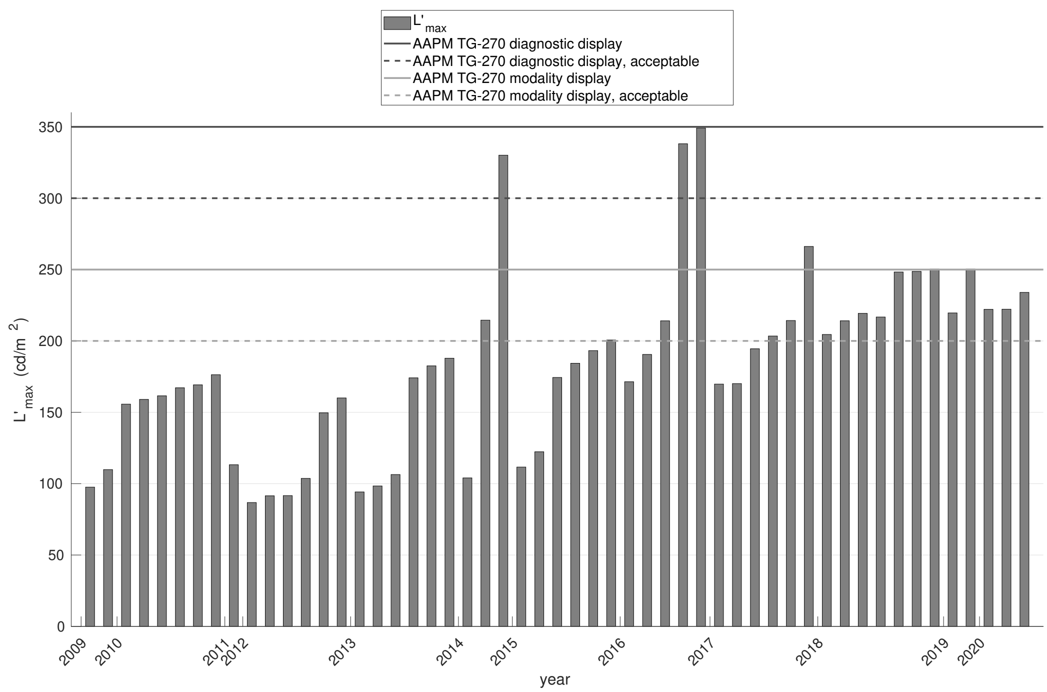

Figure 1: Measured maximum luminance (L'_{max}) values per device acquisition year. Measurements were performed between 2018 and 2021.

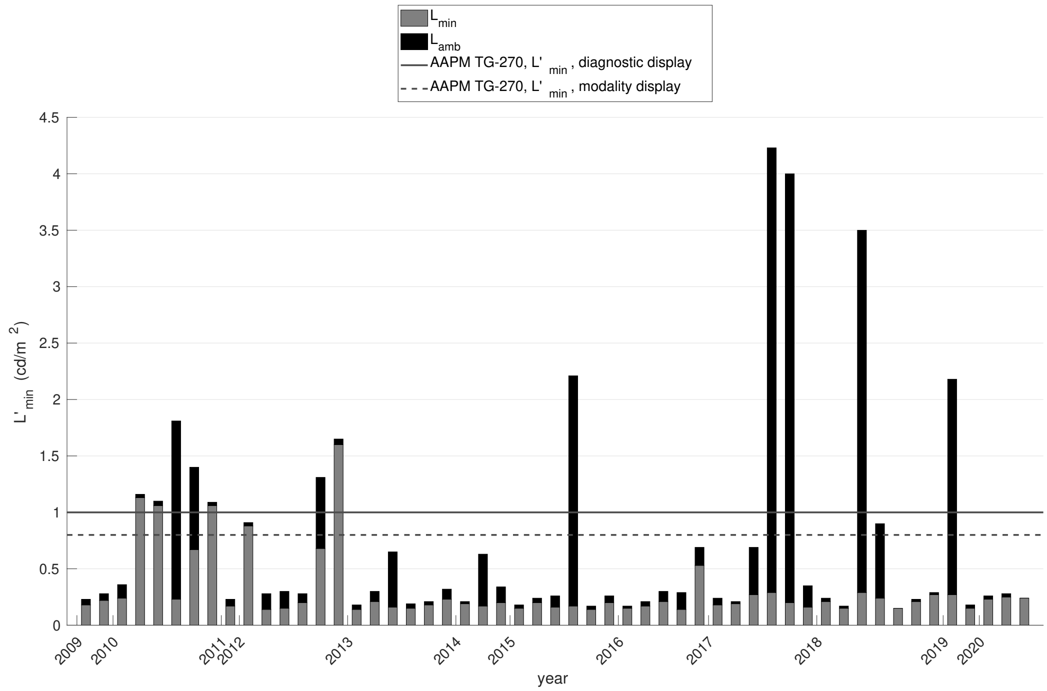

Figure 2: Measured minimum (L'_{min}) and ambient luminance (L_{amb}) values per device acquisition year. Measurements were performed between 2018 and 2021.

on the other hand, varies greatly depending on the lighting conditions and the measurement protocol. Ambient and minimum luminance values are compared in Figure 2.

For both display categories ambient ratio should be ≤0.25 (Bevins et al., 2019). 22 (42 %) of the displays fulfils the AR recommendation and 31 (58 %) of the displays fails it. Variation in L_{amb} is large, minimum 0, maximum 3.94. The majority 39 (74 %) of the monitors the L'_{min} is under 0.8 cd/m^2. 12 (23 %) of the monitors fulfil the AAPM TG270 L'_{min} limit (>1.0 cd/m^2) for primary displays. For two monitors (4 %) L'_{min} is between 0.8 - 1 cd/m^2.

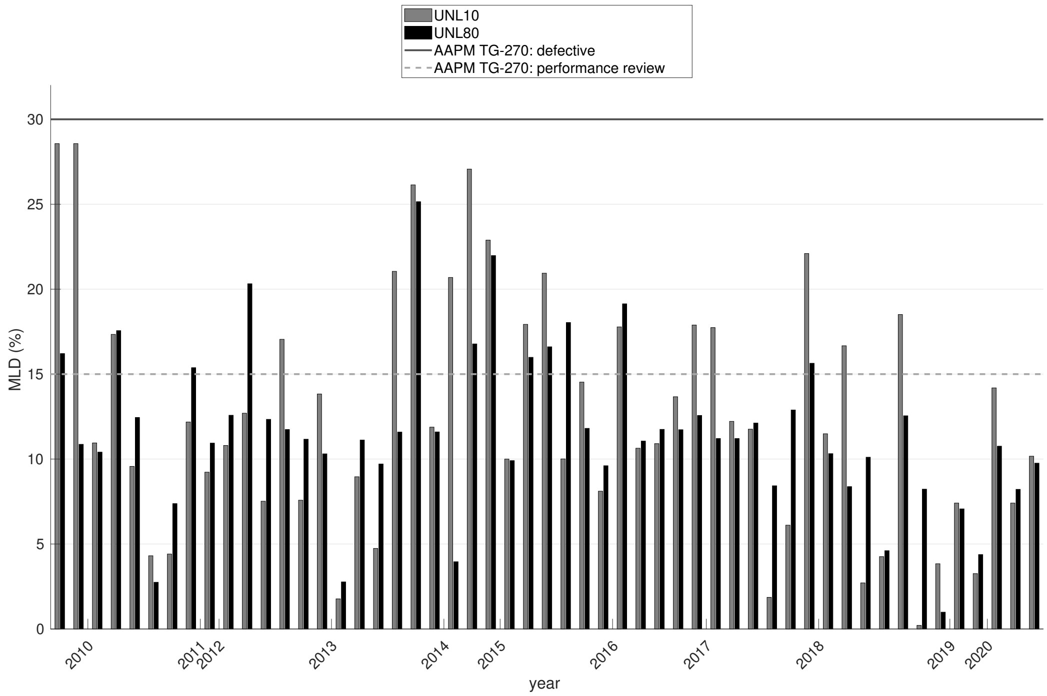

Figure 3: Measured and calculated luminance uniformity (MLD) values from UNL10 and UNL80 test patterns per device acquisition year. Measurements were performed between 2018 and 2021.

175 *Luminance uniformities*

176 AAPM TG18 uses MLD as the quantitative measure of luminance uniformity. Luminances were measured at the center and the corners (5-point method) using TG18-UNL10 and TG18-UNL10 images. The results for luminance uniformities, calculated with equation (4) are presented in Figure 3.

181 The uniformity measured from UNL10 test pattern were <15 % for 36 (68 %) of displays, between 15-30 % for 17 (33 %) of displays. For UNL80 test pattern the corresponding results were <15 % for 41 (77 %) of displays,

between 15-30 % for 12 (23 %) displays. All the devices pass the AAPM requirement of luminance uniformity.

Luminance ratio

Luminance ratio should be large for high image contrast, for acceptable contrast at least 250. If LR is very large, it exceeds the range of the human visual system. (Bevins et al., 2019; Norweck et al., 2013) AAPM TG270 criteria for optimal luminance ratio is 250< LR <450.

Luminance ratios L'_{max} / L'_{min} are represented in Figure 4. For 15 (28 %) of displays LR is under the AAPM TG270 recommendation (<250) and 29 (55 %) exceeds the recommended level (>450). Only 9 (17 %) of displays have the optimal LR level (250< LR <450).

Discussion

The most notable results are the maximum luminances of the displays (Figure 1). To evaluate how the age affects the maximum luminance, the displays were ordered by the year of purchase. The maximum luminance value for most of the measured ultrasound displays are <200 cd/m^2 although AAPM TG270 suggest maximum luminance values >350 cd/m^2 for primary use. The publication reported by Moore et al. (2011) showed that 39 % passed the AAPM TG18 recommendation for primary display maximum luminances >170 cd/m^2 after the adjustment. The corresponding value in our study was 58 %. Ambient ratios were in the AAPM TG270 suggested limit for 40% of the measured displays in this study. For comparison in Moore et al. (2011), 58 % of the displays passed the AAPM TG18 requirement for L_{min}/L_{amb} ratio. Luminance ratios were ≥250 for majority, 72%, of measured displays.

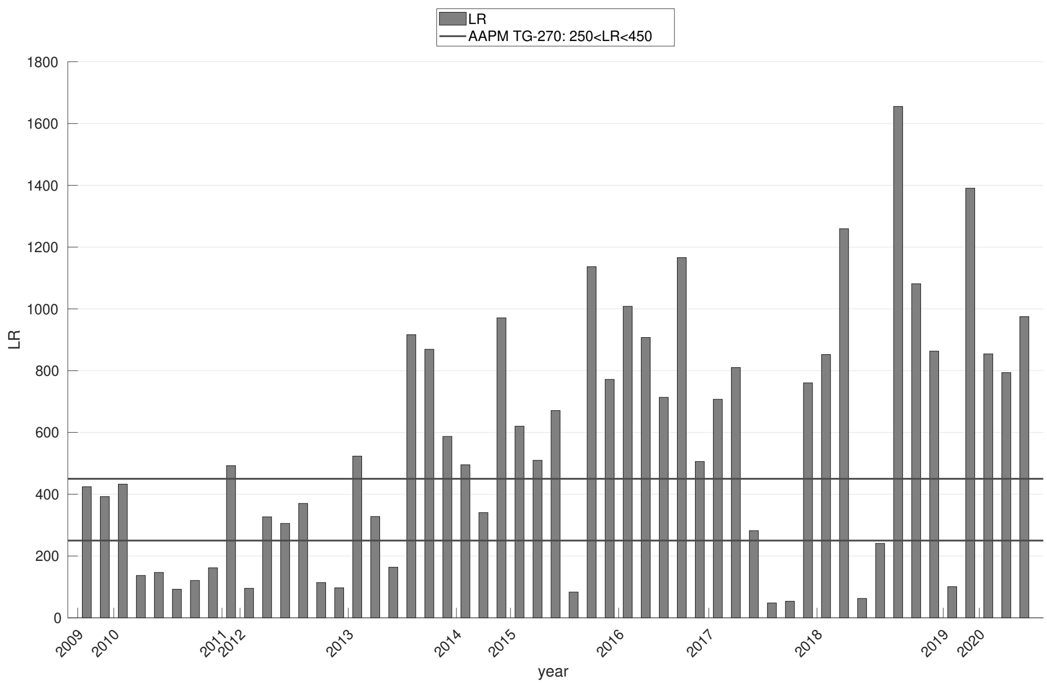

Figure 4: Calculated luminance ratio (LR) values per device acquisition year. Measurements were performed between 2018 and 2021.

In Moore et al. (2011) 81% systems passed the LR specification ≥250. It is notable that all the devices in both studies pass the AAPM requirement of luminance uniformity. Most of the displays in the Moore´s publication Moore et al. (2011) were CRT displays. All of the displays in this study represented LCD displays.

The AAPM TG270 recommendation is relatively new (published in Jan 2019). Major of the older displays cannot be assumed to exceed the AAPM TG270 maximum luminance levels. However, the AAPM/SIIM/ACR published the same levels for maximum luminances already in year 2012 so the progression in maximum luminances could be assumed to happen earlier. Average maximum luminances were in our study 183 cd/m^2. In Moore et al. (2011) corresponding value was 182 cd/m^2. The level of maximum luminances has not risen in ten years. It is also very common that the luminance settings during the use of the ultrasound device are even lower than the device monitor maximum luminances. This is be due to the different lighting conditions in the room (light / semi-dark / dark). One concern is also the grayscale standard display function (GSDF) compliance of the ultrasound displays, which depends significantly on the device settings.

Although maximum luminances are not affected very much of these, there are some limitations in this research. One limitation is the reflected ambient luminance L_{amb}, that was measured with free hand without any support, with the contact luminance meter. In addition, the lighting conditions used were average conditions used during examinations. All the measured L_{amb} values were not within the measurement range of the luminance meters (0.05 - 50 000 cd/m^2). The 23 L_{amb} values were below 0.05 cd/m^2. Three different Unfors

RaySafe Xi luminance meters were used in this study. 27 measurements during the year 2018 were performed with RaySafe Xi calibrated in 2014.

The interest in overall ultrasound quality control has risen but the development will be slow and it will always depend on the physicists and other staff unless national regulations are set. Many manufacturers are aware of the need for quality control of ultrasound but only few have included the display test patterns into their scanners. Another concern is that the quality of an display may fade in a few years.

The next logical step would be to study the effect of the display quality on the diagnostics. Ultrasound differs from the static imaging modalities in that the images are not static and even small changes caused by sensor or patient movement can be beneficial to the physician during the diagnostic examination. The data content of a moving ultrasound image is larger than a static image. The diagnosis is often made based on moving image during a patient examination. The operating hours affect the waning of the monitor and the life time could be increased if screen saver options would be brought into use. If the diagnosis is made directly from the display of the ultrasound device, the display should meet the requirements of the diagnostic displays. Also the experience of the professional who performs the ultrasound study has a high impact. The quality of the technology plays probably a more prominent role for young professionals than experienced specialists. Good quality displays might help them to make faster and more confident decisions. The poor quality of the displays should not prevent high-quality care.

Conclusions

The most commonly used test patterns show that the technical performance, especially maximum luminances of most of the ultrasound displays do not comply with AAPM recommendations. Fading of maximum luminance should be monitored regularly with a calibrated luminance meter. The replacement of the ultrasound display is necessary when the maximum luminance falls below the AAPM TG270 modality display minimum acceptable luminance limit ($<$200 cd/m^2). All the ultrasound displays should at least fulfill the AAPM TG18 criteria and newest displays can be expected to fulfill the revised AAPM TG270 criteria as well. When the hospitals are purchasing new equipment the absolute minimum requirements for technical performance of the device display should be the AAPM TG270 modality display criteria with maximum luminance of $>$250 cd/m^2. To ensure the best possible performance, the ultrasound monitors should be also DICOM calibrated with the used settings.

Conflicts of Interest

The authors have no conflicts of interest to disclose.

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Figure Captions

Figure 1: MEASURED MAXIMUM LUMINANCE (L'_{max}) VALUES PER DEVICE AQUISITION YEAR. MEASUREMENTS WERE PERFORMED BETWEEN 2018 AND 2021.

Figure 2: MEASURED MINIMUM (L'_{min}) AND AMBIENT LUMINANCE (L_{amb}) VALUES PER DEVICE ACQUISITION YEAR. MEASUREMENTS WERE PERFORMED BETWEEN 2018 AND 2021.

Figure 3: MEASURED AND CALCULATED LUMINANCE UNIFORMITY (MLD) VALUES FROM UNL10 AND UNL80 TEST PATTERNS PER DEVICE ACQUISITION YEAR. MEASUREMENTS WERE PERFORMED BETWEEN 2018 AND 2021.

Figure 4: CALCULATED LUMINANCE RATIO VALUES PER DEVICE ACQUISITION YEAR. MEASUREMENTS WERE PERFORMED BETWEEN 2018 AND 2021.

Tables

Table 1: SUMMARY OF RECOMMENDATIONS.

	L'_{max} [cd/m^2]	L'_{min} [cd/m^2]	AR	LR	Non-uniformity [%]
AAPM TG18 (2005)					
Primary display	≥ 170	-	$\frac{L_{min}}{L_{amb}} \geq 1.5$	≥ 250	$MLD \leq 30$
Secondary display	≥ 100	-		≥ 100	$MLD \leq 30$
AAPM/SIIM/ACR (2012/2017)					
Diagnostic display	≥ 350	≥ 1.0	$\frac{L_{amb}}{L_{min}} \leq 0.25$	250-350	-
Modality display	≥ 250	≥ 0.8		250-350	-
AAPM TG270 (2019)					
Diagnostic display	≥ 350	≥ 1.0	$\frac{L_{amb}}{L_{min}} \leq 0.25$	350	$LUDM \leq 30$
acceptable	≥ 300			250-450	(> 15 % evaluate performance)
Modality display	≥ 250	≥ 0.8	$\frac{L_{amb}}{L_{min}} \leq 0.25$	350	$LUDM \leq 30$
acceptable	≥ 200			250-450	(> 15 % evaluate performance)