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SCIENTIFIC PAPER

Performance evaluation of soft copy display systems according to AAPM TG18 protocol

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Abstract The purpose of this study was to evaluate the display performance of the liquid crystal display monitors according to the American association of physicists in medicine task group 18 (AAPM TG18) protocol at prior and after new calibration. We measured minimum and maximum luminance, luminance ratio, luminance and contrast response, luminance angular and spatial dependency, resolution, veiling glare and chromaticity quantitatively for 33 medical displays. Display noise was evaluated only visually. The mean maximum luminance and luminance ratio were 386 and 273 cd m^{-2}, respectively. The mean deviation of measured luminance and contrast response from expected response associated with the digital imaging and communications in medicine (DICOM) grayscale standard display function (GSDF) were 9.76 and 2.35 % at prior calibration and 1.23 and 0.26 % after recalibration, respectively. In luminance uniformity test the mean maximum luminance deviation was 16 %. Luminance method was used in the spatial resolution test and the mean percent luminance difference was 12 % at the center. The mean glare ratio was 1 154. The average color uniformity parameter across the display area of each display device was 0.0093. Majority of the test results were in good agreement with the criteria recommended by AAPM TG18 report. Considerable improvement was observed in display luminance and contrast response with respect to expected response of DICOM GSDF after new calibration for some displays.

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Introduction

Introduction of digital detector technology and picture archiving and communication systems have enabled radiology departments to electronically archive and retrieve radiological images. There has been an increase in the transition from conventional hardcopy films to soft copy display systems for presentation and medical interpretation of radiological images over the last decade. Nearly all workstation displays now use liquid crystal display (LCD) panels for displaying medical images, with advances in thin-film transistor and liquid crystal technologies [1, 2]. According to the American association of physicists in medicine (AAPM) professional guidelines, the performance testing of the soft copy displays falls within the professional responsibilities of medical physicists. Performance tests of medical monitors should be carried out to assure that images are viewed at an appropriate quality for accurate diagnosis. AAPM task group 18 (TG18) has described standard guidelines and provided a set of test patterns for the implementation of subjective and objective assessments of medical display systems [3]. The guidelines also provide tolerance levels for both subjective and objective evaluations for primary and secondary displays as classified in protocol. Primary display systems are used for interpretation of medical images produced by various imaging modalities such as computed radiography (CR), digital radiography (DR), mammography and computed tomography (CT). Secondary displays are used for viewing medical images by medical staff and medical specialists other than radiologist for purposes other than medical interpretation.

The American college of radiology and the national electrical manufacturers association formed a committee to develop a standard for digital imaging and communications in medicine (DICOM). The committee developed a document which specifies a standardized display function known as the grayscale standard display function (GSDF) for grayscale images [4]. The main objective of the standard is to define mathematically an appropriate GSDF for all image presentation systems. In the absence of any standard, a digital image may have different visual appearance and gives different diagnostic information on different display devices.

The purpose of this study was to assess the display performance of the LCD monitors according to the American association of physicists in medicine task group 18 (AAPM TG18) protocol at prior and after new calibration. In this context, performance tests of 33 flat panel LCDs were carried out according to AAPM TG18 protocol. All the evaluated display devices in this study are used for clinical diagnostic interpretation and selected randomly from different medical imaging areas and hospitals.

Materials and methods

The medical display systems used in this study are given in Table 1. A nuclear associates (New York, NY) photometer, model 07-621 was used to measure ambient light in the unit of lux. Photometer can be also used for luminance measurement in cd m^{-2}. Photometer provides a illuminance measurements range 0.1-999 lux. VeriLUM 5.2. (VeriLUM by Image-Smiths Inc., Germantown, MD,USA) was used to measure the luminance via a photometer and to calibrate the monitors to a luminance response model. In this study monitors were calibrated according to DICOM 3.14 grayscale standard display function. VeriLUM provide a luminance measurements range 0.05–1 000 cd m^{-2}, luminance accuracy and repeatability of less than ± 2 and ± 1 %, respectively. PTW Candelameter 2 (PTW, Freiburg, Germany) with light blocking devices in the form of baffled cone was used for angular dependency of luminance, veiling glare and luminance measurements for display resolution test by luminance method. Candela meter provide a luminance measurements range between 0.05 and 5 000 cd m^{-2}. Each monitor was warmed up approximately 30 min for electronic stabilization before the measurement. Faceplate of each display device was cleaned with specialized display cleaning solution and lint-free cloth. The geometric distortion test was not carried out. Luminance ratio was calculated from the measurements of maximum (L_{max}), minimum (L_{min}) and ambient (L_{amb}) luminance levels using the following expression.

Table 1 Details of display devices evaluated in this study

	Monitor ID	Model	Pixel matrix	Chromaticity	Using area
Hospital A	1–2/3–4/5–6	3 Dual-head Barco Coronis	(1,536 × 2,048) (3MP)	Monochromatic	General purpose radiology
Hospital B	7–8	Dual-head Barco Coronis	(2,048 × 2,560) (5MP)	Monochromatic	Mammography
	9–10	Dual-head Dome e5	(2,048 × 2,560) (5MP)	Monochromatic	Mammography
	11–12	Dual-head Eizo FlexScanL768	(1,280 × 1,024) (1.3 MP)	Colour	Computed tomography (CT)
	13	1 HP2009v	(1,600 × 900) (1.44 MP)	Colour	Direct radiography (DR)
	14	1 HP LP1965	(1,280 × 1,024) (1.3 MP)	Colour	Emergency radiology
Hospital C	15–16	Dual-head Totoku ME551i2	(2,048 × 2,560) (5MP)	Monochromatic	Mammography
	17–18	Dual-head Barco Coronis	(2,048 × 2,560) (5MP)	Monochromatic	Mammography
Hospital D	19–20	Dual-head Dell 2007FP	(1,600 × 1,200) (2MP)	Colour	Magnetic resonance imaging (MRI)
	21–22	Dual-head Philips 190S	(1,280 × 1,024) (1.3MP)	Colour	Magnetic resonance imaging (MRI)
Hospital E	23–24/25–26	2 Dual-head Barco Nio	(1,600 × 1,200) (2MP)	Monochromatic	General purpose radiology
	27–28	Dual-head Barco Coronis	(2,048 × 2,560) (5MP)	Monochromatic	Mammography
	29–30	Dual-head Barco Coronis	(1,600 × 1,200) (2MP)	Monochromatic	Computed tomography (CT)
	31–32	Dual-head Barco Coronis	(2,048 × 2,560) (5MP)	Monochromatic	Computed tomography (CT)
Private mammography center	33	HP Touchsmart IQ530	(1,680 × 1,050) (1.7MP)	Colour	Mammography

MP Mega Pixel, *ID* Identification

$$LR = \frac{L'_{\max}}{L'_{\min}} = \left(\frac{L_{\max} + L_{amb}}{L_{\min} + L_{amb}}\right)$$

Quantitative evaluation of luminance response was accomplished using VeriLUM test patterns (similar to TG18-LN test patterns) included in VeriLUM software following on-screen instructions. When the measurements are completed a gamma correction table is created as a file in the folder in which VeriLUM was installed. The gamma correction conforms to the model specified. With gamma correction on-board the effect of perceptual linearization (DICOM 3.14) can be seen immediately by displaying Society of motion picture and television engineers (SMPTE) pattern [5]. One should be able to see clearly the 5 % square in the 0 % surround and the 95 % square in the 100 % surround. Measurements of luminance response for conformance tracking were also carried out following of on-screen instructions. When the measurements are completed the VeriLUM software gives the current characteristic curve of the medical display found prior to testing and after calibration (called conformance tracking in software). The characteristic curve describes luminance versus digital driving level (DDL). In order to relate measured luminance values to the DICOM 3.14 standard luminance response, the DDLs used in a set of luminance measurements should be transformed to just noticeable difference (JND) indices. The performance of the display monitor against DICOM GSDF can be determined by plotting the luminance levels against JNDs. After completing luminance measurements for conformance tracking, the VeriLUM software gives VeriLUM display index and a graph of the JNDs per luminance interval calculated from the tracking luminance measurements. A determination is made as to how well the individual values of the JNDs per luminance interval correlate with the expected JNDs per luminance interval. A rating of excellent, good, fair or poor assigned. The display index is a number between 01 and 10. The closer the display index is to 01 the closer the video display system is to matching the luminance model specified. The expected response of quantitative measurements evaluated in terms of the contrast response rather than the luminance response as suggested by AAPM TG18. Thus, the measured data was expressed as the observed contrast at each luminance step as a function of mean JND index value associated with that step [3].

Luminance uniformity across the display area was measured using a related test pattern in VeriLUM software. Luminance was measured in the center and four corners of the display and the maximum luminance deviation (defined as non-uniformity) across the display face was calculated as the percent difference between the recorded maximum and the minimum luminance values relative to their average value,

$$Non - uniformity = 200 \times \frac{(L_{\max} - L_{\min})}{(L_{\max} + L_{\min})}(\%)$$

The angular responses of the display were evaluated in terms of variation in the luminance ratio as a function of polar and azimuthal viewing angles. The luminance ratio in LCDs drops rapidly with increasing viewing angle from the on-axis because of non-Lambertian light distribution [6]. Viewing angle is the maximum angle at which the display can be viewed with acceptable image quality. TG18-LN01 and TG18-LN18 test patterns were used for this measurement [3]. The PTW Candela meter 2 was placed on a tripod and the monitor rotated manually in order to reach the desired viewing angle. AAPM TG18 suggests that the angular response of a display should not reduce the luminance ratio by more than 30 %. Thus, the acceptable viewing angle for primary displays is where luminance ratio reaches the limit of 175 (250 × 0.7).

The spatial resolution is the measure of the ability of a display device to produce distinguishable images of different points with high accuracy. Display resolution was measured quantitatively using luminance method as described by AAPM TG18 [3]. The method consists of measuring the average luminance of two line-pair patterns with maximum modulation at Nyquist frequency placed vertically and the other horizontally. These two patterns are located at the centre and four corners of the multipurpose TG18-QC pattern. The percent luminance difference ΔL at each location was calculated as,

$$\Delta L = 200 \times \frac{(L_{ver.} - L_{hori.})}{(L_{ver.} + L_{hori.})}(\%)$$

where L_{ver} and L_{hori} indicate the luminance measured on the vertical and horizontal line patches at each location, respectively.

The detectability of small and low contrast objects in a medical image depends not only on their size and contrast but also on the noise in the immediate surroundings. Display noise was only evaluated visually by using the TG18-AFC test pattern. This pattern contains four quadrants and each quadrant contains a large number of regions with varying target position. In each quadrant, the contrast and size of the target are constant [3].

Light scattering in display devices induces a diffuse luminance and causes contrast reduction, which is most significant in low luminance regions surrounded by bright areas. The quantitative evaluation of veiling glare was realized using TG18-GQ, TG18-GQB and TG18-GQN test patterns. The luminance at the center of the central dark region of the TG18-GQ pattern, L, the white luminance at the center of the white region of the TG18-GQB pattern, L_{B}, and the background luminance value at the center of the TG18-GQN pattern, L_{N}, were recorded [3]. The glare ratio (GR) for the display is then computed as,

$$GR = \left(\frac{L_B - L_N}{L - L_N}\right)$$

Measurement of display color tint is important as it relate to matching the color of multiple grayscale displays used in a single workstation. VeriLUM 5.2 can also used as a colorimeter. Its specifications for chromaticity accuracy and repeatability were less than ± 0.004 and ± 0.002 % respectively [7]. Chromaticity measurement according to method explained by AAPM TG18 was carried out only for color displays because of software limitation of the VeriLUM. To quantify color uniformity, VeriLUM pod was used to measure the color coordinates u′ and v′ for all display devices associated to a workstation using TG18-UNL80 test pattern at the center and four corners of the display area of each display device. The color uniformity index was calculated as the maximum distance,$\Delta(u', v')$, in $u' - v'$ space between any possible pair of (u', v') points using,

$$\Delta(u', v') = \sqrt{\left(u'_1 - u'_2\right)^2 + \left(v'_1 - v'_2\right)^2}$$

The color coordinates measured at the center and four corners of the display area of each display device were averaged to produce a mean (u', v') chromaticity measurement for the display device [3]. The color uniformity parameter between multiple display devices connected to a workstation was calculated as the maximum distance $\Delta(u', v')$, in u'–v' space between any possible pair of average (u', v') points using the same formula given above.

Results

The measured mean illuminance value was 7.2 (ranged from 1 to 28) lux during ambient light measurements. Ambient light level was 16.7 lux in room containing displays for general purpose radiology in hospital E and 28 lux in room containing display for mammography in private mammography center. These values were higher than recommended value by AAPM TG18 protocol for diagnostic room stations (X-rays). The AAPM recommendation for ambient light value is 2–10 lux for diagnostic reading stations (X-rays) and 15–60 lux for diagnostic reading stations with CT/magnetic resonance imaging (MRI)/nuclear medicine (NM). The ambient light value was 10 lux in room that contained displays for mammography in hospital B and this value is equal to the upper limit of recommended value for diagnostic reading stations (X-rays). The measured mean maximum luminance value was 386 (ranged from 98 to 578) cd m^{-2}. Figure 1 shows the measured maximum luminance value for each tested monitor. Maximum luminance value of diagnostic monitors used for interpretation should be at least 350 and 420 cd m^{-2} for the interpretation of mammograms according to the recommendations of the American college of radiology (ACR) [8]. About half of the monitors failed to meet these recommended values. If a display workstation has more than one monitor, the maximum luminance should not differ by more than 10 % among monitors for comparison of images on these monitors confidently [8]. Monitors 17–18, monitors 21–22 and monitors 23–24 did not meet this recommendation because they used as dual monitor. The measured mean minimum luminance value was 0.60 (ranged from 0.15 to 1.80) cd m^{-2}. Calculated mean luminance ratio from measured minimum and maximum luminance for each display device was 273 (ranged from 31 to 548). Monitors 19–20, monitors 21–22, monitors 29–30, monitors 31–32, monitor 25 and monitor 33 were failed to meet the recommended value by AAPM TG18 protocol as luminance ratio should be at least 250 for primary class displays. Figure 2 shows the calculated luminance ratio for each tested monitor.

The compliance of two of the devices with respect to the DICOM GSDF for prior and after new calibration was given as an example in Figs. 3, 4, 5, 6. The measured luminance and contrast response for HP Touchsmart used in private mammography center diverges from ideal curve in the low luminance range before calibration and within 10 % tolerance of the ideal curve after calibration (Figs. 3, 4). The measured luminance and contrast response for Barco Coronis (3MP) used for general purpose radiology in hospital A were within 10 % tolerance of the ideal curve before and after calibration (Figs. 5, 6). The deviation of luminance and contrast response with respect to that of DICOM GSDF at prior calibration were 9.76 (ranged from 0.27 to 42.15) % and 2.35 (ranged from 0.04 to 10.24) %, respectively. The results for the same measurements after new calibration were 1.23 (ranged from 0.26 to 4.59) % and 0.26 (ranged from 0.04 to 0.96) %, respectively. Luminance and contrast response after new calibration for monitor 10, monitors 11–12, monitor 13, monitor 14, monitors 17–18, monitors 19–20, monitors 21–22 and monitor 33 were improved considerably. The deviation of contrast response of monitor 10 with respect to expected response of DICOM GSDF was out of AAPM TG18 recommendation before calibration. The measured contrast response should fall within ± 10 % of the DICOM standard for primary class displays according to AAPM TG18 protocol. For secondary class devices the measured contrast response should fall within ± 20 % of the DICOM standard. Graphs of JNDs per luminance interval were created from the tracking luminance measurements and graphs of two display devices were given in Figs. 7, 8. A rating of how well the individual values of the JNDs per luminance interval correlate with the expected JNDs per luminance interval, mean JNDs per luminance interval, and root mean square error are seen on the figures. The established mean maximum luminance non-uniformity was 16 (ranged from 0.79 to 41.68) %. According to AAPM TG18

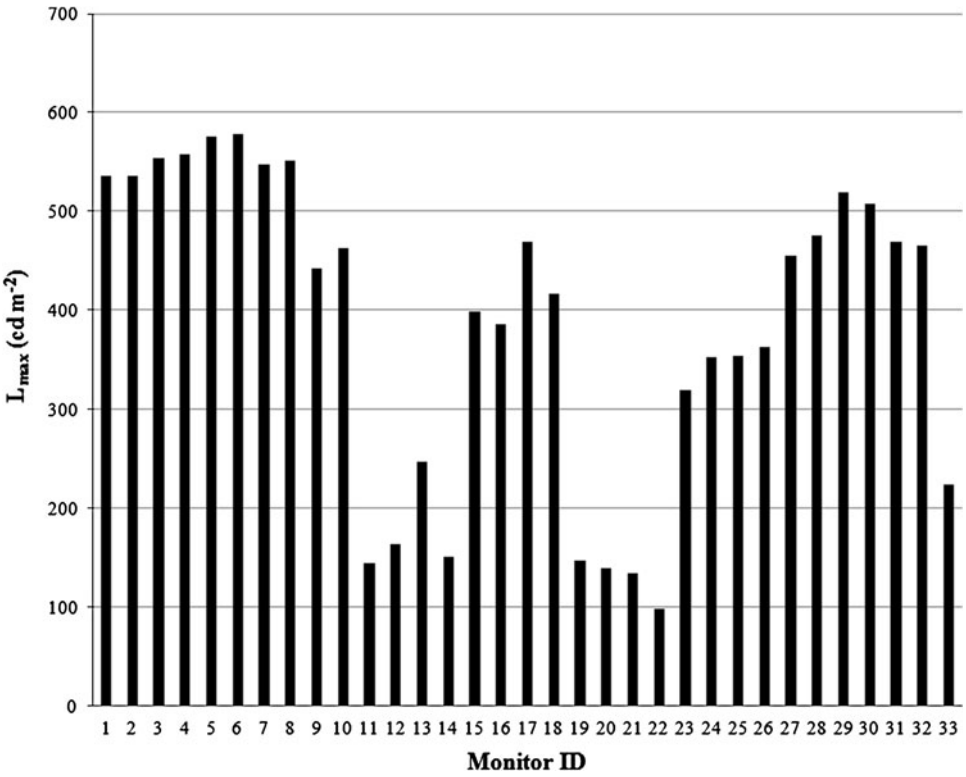

Fig. 1 Measured maximum luminance value for each tested monitor

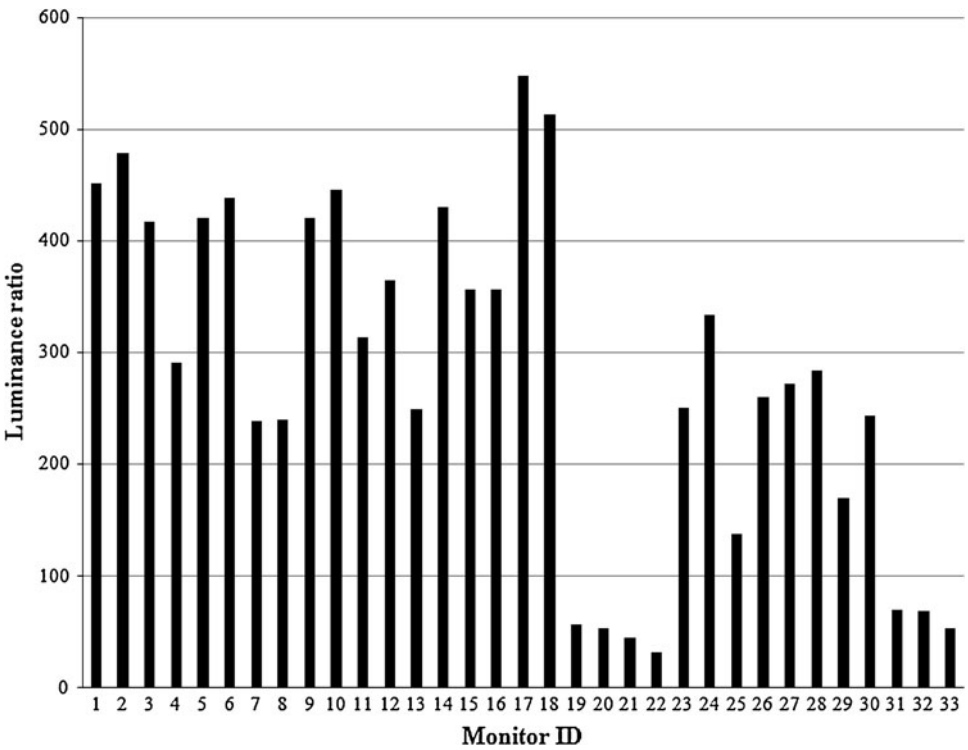

Fig. 2 Calculated luminance ratio for each tested monitor

the maximum luminance deviation for an individual display device should be less than 30 %. Monitor 18, monitor 22, monitor 24 and monitor 25 failed to meet the standard given for luminance non-uniformity. Figure 9 shows the measured luminance non-uniformity for each tested monitor.

Measured mean viewing angles that ensure a luminance ratio greater than 70 % of the tolerance limit, 175 (250 × 0.7),

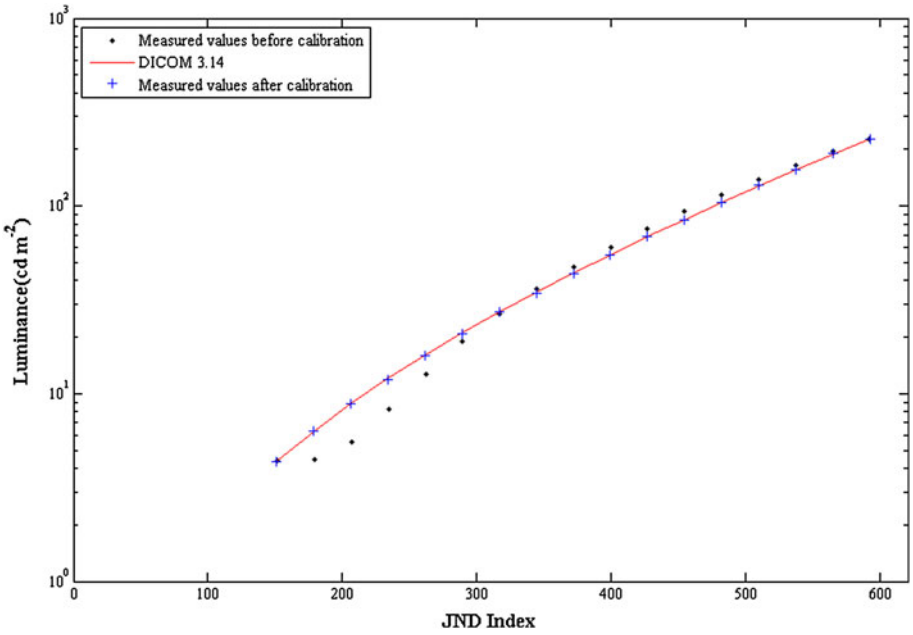

Fig. 3 Luminance response of the HP Touchsmart display device before and after calibration

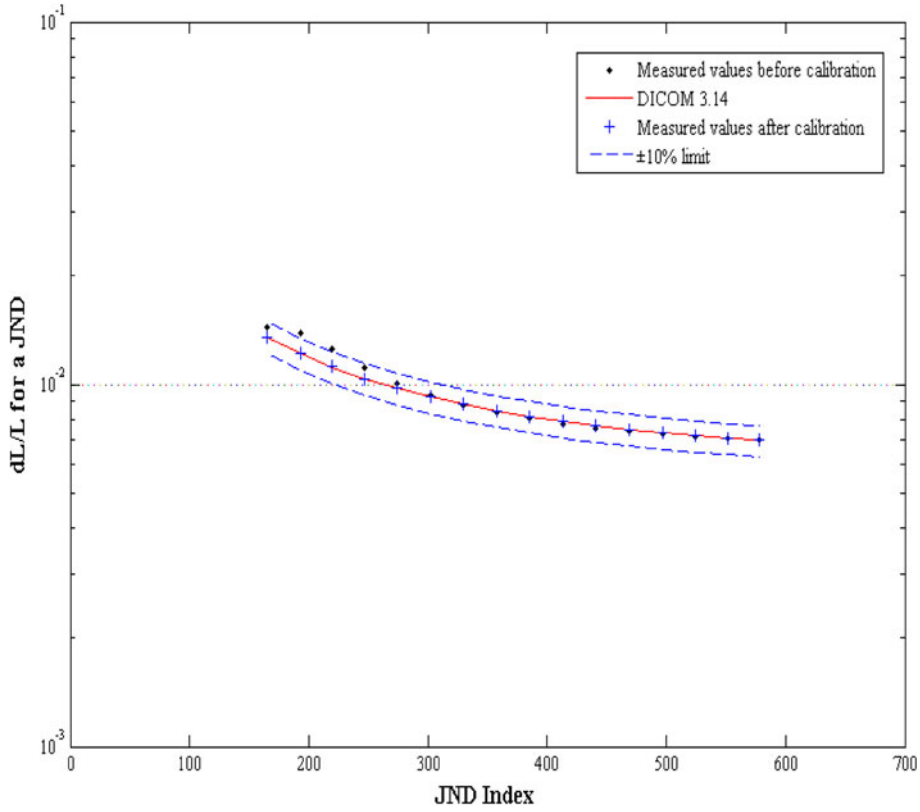

Fig. 4 Contrast response of the HP Touchsmart display device before and after calibration

for primary displays were found to be approximately -27° (ranged from $(-16)^{\circ}$ to $(-35)^{\circ}$) and 30° (ranged from 21° to 42°) for horizontal and -28° (ranged from $(-20)^{\circ}$ to $(-38)^{\circ}$) and 25°(ranged from 11° to 38°) for vertical directions. In the luminance based resolution test, the mean percent luminance difference at the center was 4.2 (ranged from 0.09 to 25.6) % for display systems except monitors 11–12, monitors 19–20 and monitors 21–22. The mean percent luminance difference at the

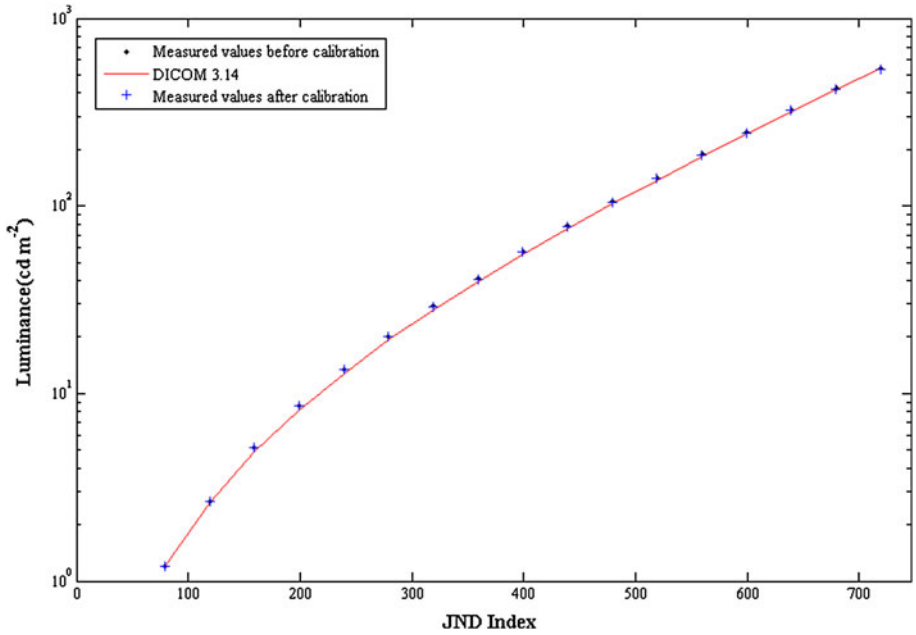

Fig. 5 Luminance response of the Barco Coronis (3MP) display device before and after calibration

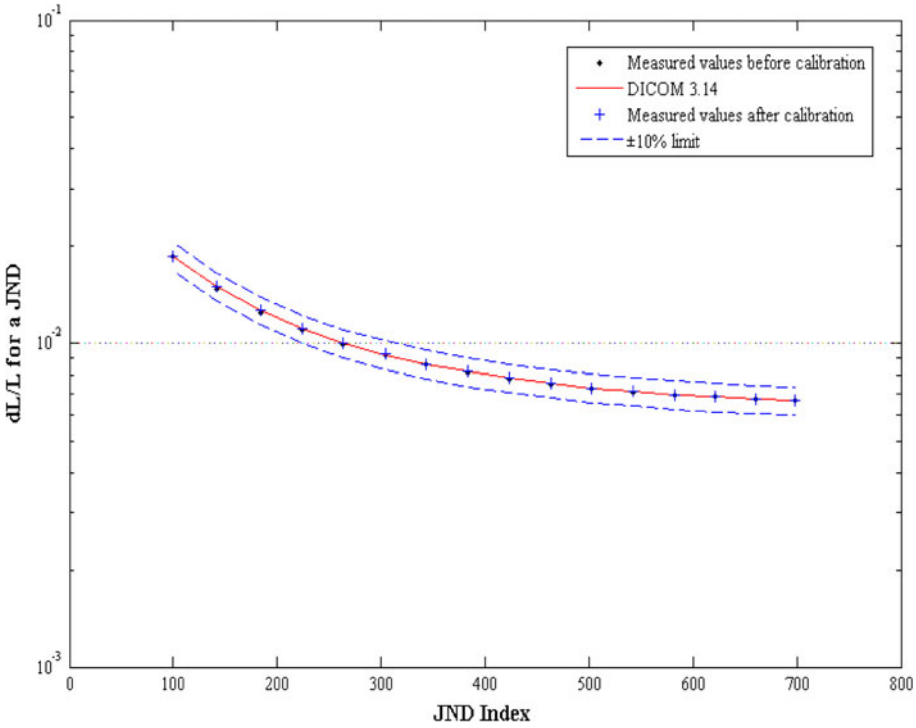

Fig. 6 Contrast response of the Barco Coronis (3MP) display device before and after calibration

center was approximately 50 % for these six display devices and higher than 30 % that is recommended value by AAPM TG18 protocol for primary class display systems. The rectangular targets in each square of the three quadrants of TG18-AFC test pattern were visible for all display devices in the visual evaluation of noise. AAPM TG18 suggests that all targets, except the smallest, should be visible for primary class displays. The established mean glare ratio was 1 154 (ranged from 217 to 4 166). The AAPM TG18 report recommends that the primary class displays should have a glare ratio greater than 400. Only monitor 19 failed to meet the recommended limit. Figure 10 shows the measured glare ratio for each tested monitor.

In quantitative evaluation of display chromaticity, the calculated mean color uniformity index across the display

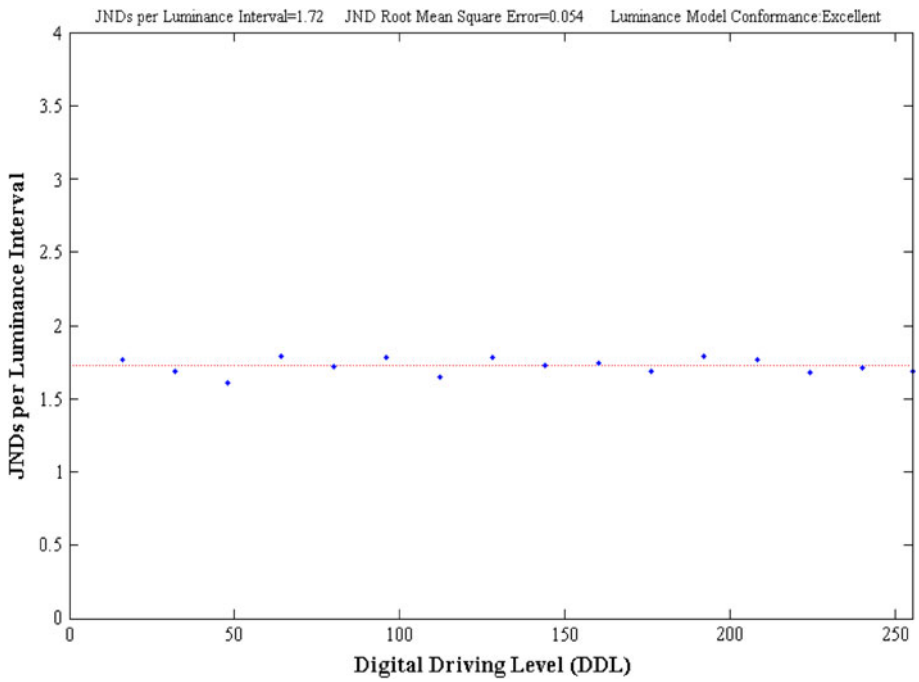

Fig. 7 Correlation of the measured individual JNDs per luminance interval with the expected JNDs per luminance interval for HP Touchsmart display device

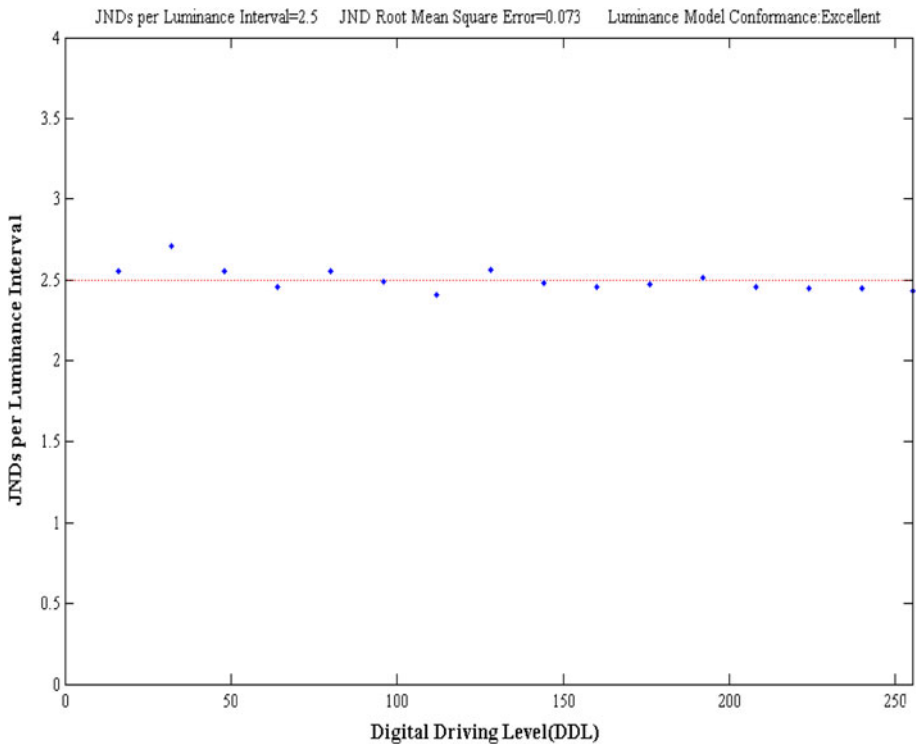

Fig. 8 Correlation of the measured individual JNDs per luminance interval with the expected JNDs per luminance interval for Barco Coronis (3MP) display device

area of each color display device was 0.0093 (ranged from 0.0052 to 0.0162). The chromaticity measurement results for color display devices according to measurement method explained in AAPM TG18 protocol were given in Table 2. Monitor 21 and monitor 33 were failed to meet the criteria recommended by AAPM TG18 protocol. The calculated average color uniformity parameter for the multiple display devices associated with a workstation was within acceptable limit. The recommendation for color uniformity parameter by the AAPM TG18 is 0.01 or less to assure acceptable color matching of primary class grayscale display devices of a workstation. The distance between any pair of color coordinates across the display area of each device should also not exceed this limit.

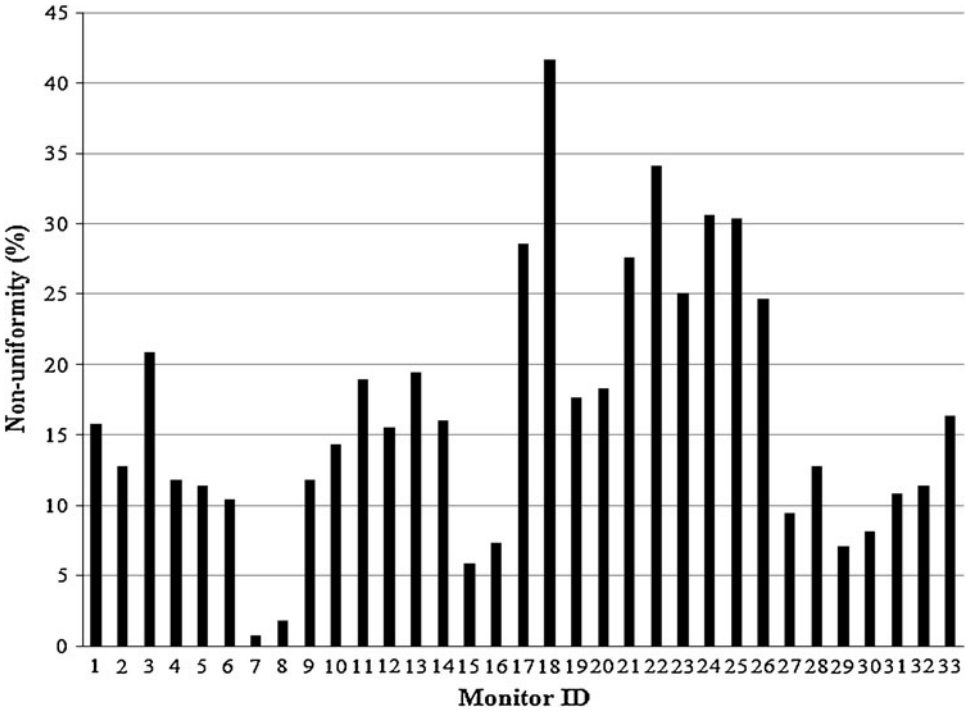

Fig. 9 Measured luminance non-uniformity for each tested monitor

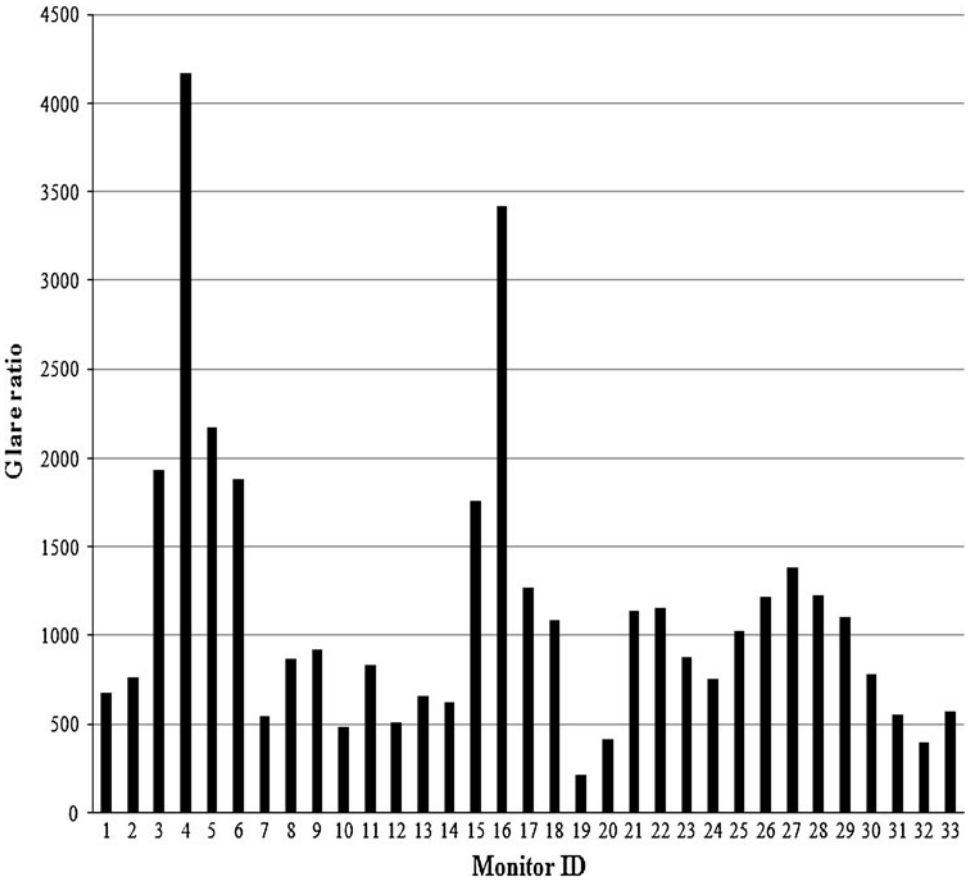

Fig. 10 Glare ratio for each tested monitor

Table 2 Computed color uniformity index for the color monitors used in this study

Monitor ID	Δ(*u*', *v*')
11	0.0082
12	0.0077
13	0.0095
14	0.0052
19	0.0082
20	0.0086
21	0.0117
22	0.0088
33	0.0162

Δ(u', v'): color uniformity index

Discussion

Ambient light levels in some rooms containing displays for general purpose radiology and mammography are not at optimal levels. We have observed unsuitable image interpretation conditions regarding of opened negatoscop lights next the image display used for mammography in hospital B and non-obscured window next the display device in the private mammography imaging center. The interference of light from such sources with the light emitted by monitor can result in the decrease of perceived contrast in the image by increasing black level due to diffuse reflection of ambient room light from the displays [9–11]. If there is a high level of ambient lighting in the room, the maximum luminance should be increased to maintain the required luminance ratio. During the image interpretation, light boxes should be switched off and the ambient light should be reduced to acceptable level that can be used in the image reading area without compromising the display presentation. Nearly half of the evaluated monitors failed to meet the maximum luminance requirements as suggested by ACR [8]. Failed display systems in this test are placed in the different image interpretation areas including mammography and general purpose radiology. Recommended luminance ratio value was achieved for 24 devices. Failed ones suffer from lower or just acceptable maximum luminance levels. Improvement in luminance and contrast response with respect to that of DICOM GSDF standard after new calibration was not significant in some Barco and Totoku monitors in the quantitative luminance response test. These monitors have optional photocell for ambient light detection, which allows the luminance response to be appropriately modified in response to changes in ambient lighting. Although the contrast response with respect to that of DICOM GSDF was not out of the recommended limit for monitors 17–18, the contrast response fall within 3 % of the standard before calibration and within 1 % after new calibration, whereas contrast response for other Barco displays fall within approximately 1 % of the standard before and after new calibration. The monitors 17–18 had also several points exceeding the AAPM guidelines at lower JND values in contrast response curve. The photocell for ambient light detection might be not worked properly for these monitors. Improvement in luminance and contrast response with respect to that of DICOM GSDF was noticeable for twelve devices after new calibration. This finding emphasizes that all display devices should be regularly checked to verify that the luminance response is compliance with the DICOM GSDF and to assure that no diagnostic information is lost over time [3, 8, 9, 12, 13]. Similar study was carried out with VeriLUM calibration kit by Seto et al. [13]. They investigated the distinguishability of the 5 % luminance square inside a larger 0 % luminance square and 95 % luminance square inside a larger 100 % luminance square in SMPTE pattern before and post calibration. They reported that the difference between 0 and 5 % luminance difference was discernable on 30 % of the piloted display systems before calibration. But it was discernible on all the monitors 100 % after calibration.

Although monitors 9 and 10 were used as dual monitors in hospital B, luminance and contrast response with respect to DICOM GSDF was out of the limit for one of them. Improvement in luminance and contrast response was prominently after calibration in monitor 10, whereas monitor 9 was in acceptable limit before and after calibration. This finding show that having the same monitors from some companies do not assure that monitors will work at consistent manner [9, 14]. In the luminance based resolution test, only the monitors used for MRI and CT, where low resolution images interpreted, were failed to comply with the standard. Our quantitative results for luminance angular dependence were in agreement with Samei et al. results [15]. Hatanaka et al. [16] reported that there was no significant difference in observer performance between 0° and 40°. On the other hand their results were showed a statistically significant difference in observer performance between 0° and 60°. Luminance spatial uniformity and color uniformity test results in our study are closer to the finding by Crespi et al. [17] for the same display models (Barco Coronis 3MP and Eizo FlexScan 1.3MP). In our study, the maximum luminance non-uniformity was 14 % whereas in the Crespi study for the Barco monitors was 18 %. Higher non-uniformity values may affect the reader's ability to detect low contrast objects in the image. Lower non-uniformity value is important for obtaining similar contrast sensitivity over the entire displayed area [18]. Luminance non-uniformity is usually not a problem with LCD monitors. For example, the non-uniformity value should be less than 20 % for flat panel displays according to the international electrotechnical commission (IEC) [19]. The average color uniformity parameter across the display area of Eizo monitors was 0.008 in our study. The reported value by Crespi et al. for the same test with the same monitors was 0.0064. Average glare ratio was 2 589 for two

Totoku displays used for mammography in hospital C. Very close mean value was reported by Jung et al. [18] as 2 350 for the same monitor model.

Classification of display devices used in our study as a primary class was done according to using aims in hospitals. Medical images that will be viewed influence the performance requirements for a given imaging modality. For example, all the diagnostic information for an MRI examination can be obtained at a matrix size significantly lower than that required for chest imaging. Especially specification of monitor 33 used for mammography is much lower than required ones for this imaging modality. AAPM TG18 was recommended telescopic luminance meter for the quantitative evaluation of luminance angular dependency, veiling glare and luminance measurements for display resolution test by luminance method. We hadn't telescopic luminance meter during our study. Alternatively, we used PTW Candela meter 2 for these measurements by using light blocking devices such as baffled cone to reduce contribution of stray light to the measurements. This was the sole limitation which we encountered during our study.

Conclusion

Majority of the test results were in good conformance with the criteria recommended by AAPM TG18 report. Considerable improvement was observed in display luminance and contrast response with respect to expected response of DICOM GSDF after new calibration for some displays. Routine quality control program for display devices should be implemented by imaging departments to assure acceptable display performance with respect to AAPM TG18 recommended standard and because the display performance can change over time.

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References

1. Badano A (2004) AAPM/RSNA tutorial on equipment selection: pACS equipment overview: Display systems. RadioGraphics 24: 879–889
2. Indrajit IK, Verma BS (2009) Monitor displays in radiology: part 1. Indian J Radiol Imaging 19(1):24–28
3. Samei E, Badano A, Chakraborty DP et al (2004) Assessment of display performance for medical imaging systems, report of the American association of physics in medicine (AAPM) task group 18, Medical Physics Publishing, Madison, WI, AAPM On-Line Report No:03
4. Digital imaging and communications in medicine (DICOM) part 14 (2004) Grayscale standard display function. National electrical manufacturers association (NEMA) PS 3.14
5. SMPTE Recommended Practice (1991) Specifications for medical diagnostic imaging test pattern for television monitors and hard-copy recording cameras. Society of Motion Picture and Television Engineers, New York
6. Indrajit IK, Verma BS (2009) Monitor displays in radiology: part 2. Indian J Radiol Imaging 19(2):94–98
7. ImageSmiths Inc. VeriLUM 5.2. (2006) "Video Display Calibration and Conformance Tracking". http://www.image-smiths.com/VeriLUM52UG.pdf
8. Norweck JT, Seibert JA, Andriole KP et al (2013) ACR—AAPM-SIIM technical standard for electronic practice of medical imaging. J Digit Imaging 26:38–52
9. Wade C, Brennan PC (2004) Assessment of monitor conditions for the display of radiological diagnostic images and ambient lighting. Br J Radiol 77:465–471
10. Goo JM, Choi JY, Im JG et al (2004) Effect of display monitor luminance and ambient light on observer performance in soft copy reading of digital chest radiographs. Radiology 232:762–766
11. Ckakrabarti K, Kaczmarek V, Thomas JA et al (2003) Effect of room illuminance on monitor black level luminance and monitor calibration. J Digit Imaging 16(4):350–355
12. Gutierrez D, Monnin P, Valley JF et al (2005) A strategy to qualify the performance of radiographic monitors. Radiat Prot Dosim 114(1–3):192–197
13. Seto E, Ursani A, Cafazzo JA et al (2005) Image quality assurance of soft copy displays systems. J Digit Imaging 18(4): 280–286
14. Thompson DP, Koller CJ, Eatough JP (2007) Practical assessment of the display performance of radiology workstations. Br J Radiol 80:256–260
15. Samei E, Wright SL (2006) Viewing angle performance of medical liquid crystal displays. Med Phys 33(3):645–654
16. Hatanaka S, Morishita J, Hiwasa T et al (2009) Comparison of viewing angle and observer performances in different types of liquid-crystal display monitors. Radiol Phys Technol 2:166–174
17. Crespi A, Bonsignore F, Paruccini N et al (2006) Acceptance tests of diagnostic displays in a PACS system according to AAPM TG18. Physica Med 22(1):17–24
18. Jung H, Kim HJ, Kang WS et al (2004) Assessment of flat panel LCD primary class display performance based on AAPM TG 18 acceptance protocol. Med Phys 31(7):2155–2164
19. Evaluation and routine testing in medical imaging departments part 2–5: Constancy tests-Image display devices. IEC Publication 61223-2-5, 1994