Acceptance tests of Diagnostic Displays in a PACS System according to AAPM TG18

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Abstract
In a filmless environment it is necessary to execute acceptance and constancy tests on monitors used for interpretation of medical images. Performances of Barco CRT MGD521 MKII, Barco LCD Coronis and EIZO LCD L685EX monitors have been evaluated. Acceptance tests were executed following AAPM Task Group 18 guidelines. Visual and instrumental evaluations of geometric distortions, reflections, luminance response, contrast, uniformity, resolution, angular response and veiling glare were made. Barco monitors showed optimal performances, while EIZO monitors were accepted with some reserve on their quality level.

Finally a comparative evaluation between monitors and film (the actual gold standard) was performed by an interview of ten radiologists: the monitors showed a quality at least equal to film. These monitors are currently in use for routine medical interpretation.

KEYWORDS: AAPM TG18, Display device, Calibration, PACS.

1. INTRODUCTION
The installation of a PACS system was the first step at S. Gerardo Hospital in Monza towards a transition to a paperless and filmless environment. Softcopy interpretation requires the use of dedicated workstations with high quality monitors. Monitors used for medical interpretation of radiological images must provide a high and constant quality of the image displayed [1, 2]. Digital image displaying is the last link in the digital radiology chain and its image quality must be comparable to all the other steps.

This work consisted of performing acceptance testing of the monitors, which have different technology and resolutions: CRT high resolution, LCD high resolution and LCD medium resolution. Periodic quality controls and calibration are necessary to ensure adequate image quality [3]. Actually these monitors are in use for reporting images produced by various diagnostic systems: digital plates, DR, CT, MR and angiography.

AAPM TG18 guidelines [4, 5] were followed as guidelines for system acceptance, choosing among the tests proposed according to the instrumentation available and the feasibility for “on the field” execution [6].

All the tolerances reported below are taken from the TG18 guidelines [4].

In addition, a subjective quality evaluation using anatomical images was performed via interviews to radiologists.

2. MATERIAL AND METHODS
The display workstations of St. Gerardo Hospital's PACS system include 15 couples of high-quality monitors (plus a monitor dedicated to RIS) of 3 different kinds: 7 colour LCD EIZO (1MP, 1280*1024 pixels), 4 monochromatic CRT Barco MGD521 MKII (5MP, 2500*2000 pixels), 3 monochromatic LCD Barco Coronis (3MP, 2000*1500 pixels). EIZO monitors are high-end products for graphical applications, not specifically created for medical use. All the monitors are used as primary interpretation devices. The monitors are placed in the different radiological departments of the hospital including an external facility located in a town nearby.

Near-focus colorimeter/photometer X-Rite DTP-92 was used for calibrating the monitors, and it was interfaced with the Barco MediCal Pro calibration software, which can be used on EIZO stations too. X-Rite DTP92 has a measure range of 0-500 cd/m², an accuracy of ±0.003 (chroma) and ±4% (luminance).

Telescopic photometer Hagner S3 was also used: it has an acceptance angle of 1°, a measure range of 0.01-200,000 cd/m² and an accuracy of ±3%.

Many of the tests require an appropriate digital pattern to be viewed on the display in order to make instrumental measurements and visual evaluations. AAPM TG18 patterns were used. The patterns were downloaded from the TG18 website in DICOM format and then uploaded into the PACS system from a
workstation using the “eFilm” software. The images were displayed with the software used by radiologists for diagnostic reading (Agfa DS 3000 Workstation), using a linear LUT (Look-Up Table) not to alter the original contrast of the image. The patterns were always viewed in 100% zoom, ensuring a 1:1 visualization without pixels rescaling. A warm-up time of at least 30 minutes was assured before any measure.

2.1. Geometrical distortions

Monitors with CRT technology often lack in geometric regularity on the surface due to electron beam deflections during image formation and this may produce a distorted image.

Geometrical distortions of the image were measured using the all-purpose TG18-QC pattern (Figure 1), which includes square-shaped areas of different dimensions and in different locations of the screen. The measure was done evaluating the height and width of the squares with a flexible ruler (1mm step), as suggested by AAPM TG18 [4]. The test was repeated for each monitor. LCD monitors were measured too although we do not expect any distortion, because of the fixed array structure of the screen.

The tolerance suggested is 2% as the maximum percent deviation between the measurements in horizontal and vertical direction, and among the same measurements in the different areas of the screen. The TG18-QC pattern can also be used for a quick daily check of overall monitor quality.

2.2. Display reflection

The effects of ambient light reflection were evaluated using the visual pattern TG18-AD (Figure 2); this image contains 49 low contrast inserts at different frequencies: on a black background each insert consists of horizontal line pairs with pixel value from 0 to 49. TG18 recommends that the number of visible inserts remains the same with and without ambient light; it means that reflections do not interfere with the perception of low luminance and low contrast details. Room illuminance should be adjusted in order to fulfil this requirement. In our evaluations it was considered a bad situation with some lamps turned on, including the view box lamp.

2.3. Luminance and contrast

Maximum luminance ($L_{\text{max}}$) is measured during the calibration process and is set according to the specification of the monitor in “calibrated mode”. Barco monitors have indicated this value which is lower than the “peak” luminance, allowing to compensate the decrease in maximum luminance.

Eizo monitors, in order to achieve the minimal requirements, must work at 100% luminance setting, with the risk of a fast decrease in the monitor performance, which would later require the substitution of the monitor.

The minimum luminance $L_{\text{min}}$, corresponding to pixel value 0 was also measured.

The calculated contrast ratio ($CR=L_{\text{max}}/L_{\text{min}}$) de-
pends on the value of $L_{\text{max}}$, but its value is limited by reflection requirements: a too low value of $L_{\text{min}}$ will make dark pixels undetectable because of the luminance level similar to ambient light reflections. Tolerances in cited by AAPM TG18 [4] are: $L_{\text{max}} > 170 \text{ cd/m}^2$ and $\text{CR} > 250$.

2.4. Luminance response
Luminance response is the most important characteristic of a high-quality monitor.

The calibration procedure is specifically done to correct it in order to obtain "perceptual linearization": pixel values should be approximately related to human perceptual response [7]. The display curve of the monitor was therefore corrected also considering the intrinsic response of the human visual system [8]. Calibration according to the DICOM curve was used [7,9].

The calibration procedure is automatic using MediCal Pro software in conjunction with the X-Rite photometer. The calibration was repeated in Barco CR monitors for each one of the pair. Two EIZO monitors are driven by the graphic card as one monitor; the calibration procedure can only be done on one of the two monitors; the resulting curve is applied to both displays and the calibration has to be checked on the other monitor too.

A different procedure was used for the Barco LCD monitors: these monitors have an internal photometer that allows automatic continuous check of maximum luminance level. This sensor is also used by MediCal Pro for monitor calibration. No details about the calibration are given to the user.

Calibration checking measures were done using sixteen patterns from the TG18-LN set and the X-Rite near-focus photometer. The patterns consist of a 20% luminance background area and a central square with a pixel value varying from 0 to 1023 in 16 steps, one for each image in the set (Figure 3). The photometer is placed in the centre of the pattern. The luminance interval $(L_{\text{min}} - L_{\text{max}})$ was then divided into 16 JND (Just Noticeable Difference) levels in order to obtain the luminance response curve. Contrast response was considered point by point and then compared with the 10% difference with the DICOM contrast curve, which is the tolerance suggested by TG18.

In addition MediCal Pro software can perform a calibration check, using the X-Rite photometer, on the greyscale levels giving a parameter in percentage of correspondence with the DICOM curve. This test can be used for Quality Control routine, checking the constancy of the agreement to DICOM curve.

2.5. Luminance uniformity
The uniformity of luminance on the screen surface has been measured using a pattern included in the

2.6. Display resolution
The resolution of a monitor is not simply the size of the pixel matrix, but includes its capability of making each pixel emit the right luminance without influence from adjacent pixels. This is critical for CRT technology, especially along the scan direction.

The resolution was tested with a visual test using the TG18-CX pattern (Figure 4), composed of many inserts shaped as "Cx" and a scoring reference with a value between 0 and 9. The tolerance given for this test is a score lower than or equal to 4.

Instrumental measures were also made using the "Luminance Method" according to AAPM TG18. It consists in measuring the average luminance of two targets with maximum modulation at Nyquist frequency placed vertically (modulation along the scan direction) and the other horizontally. The two patterns will have different luminance because of the motion of the electron beam in raster scan. High frequencies along the scan direction are difficult to reproduce sharply, so the average luminance of the pattern will be lower than the luminance of the horizontal pattern. These inserts are located at
2.7. Display noise

The influence of noise in workstation monitors is very complex to quantify. Its effect is mainly to conceal small details with very low contrast to the background. Visual tests were conducted, using the TG18-AFC pattern (Figure 5). This pattern contains four quadrants with many forced multiple choice inserts. Each quadrant contains details of a given size and contrast. AAPM TG18 suggests that the details of at least 3 out of 4 quadrants are visible.

2.8. Veiling glare

Internal reflections of the monitor surface have the effect of increasing the luminance of a dark area surrounded by a bright area.

A simple visual evaluation of this effect was done using the test patterns provided by AAPM (Figure 6): in the central dark area surrounded by a big circular bright area five low contrast objects are placed. Masking the bright area to avoid adaptation of the observer's eye, the central area is observed to locate the maximum number of visible objects.

According to AAPM TG18 at least three objects must be visible.

2.9. Angular response

Light emission on LCD monitors is not Lambertian, thus luminance response is highly related to the viewing angle of the screen. Contrast ratio in particular varies with angle, and eventually even a contrast inversion is possible for angles near 90°. It is important to define these limits of the monitor in order to avoid reading the images in incorrect positions.

$L_{max}$ and $L_{min}$ were measured using the telescopic photometer with the screen placed at different angles in horizontal and vertical directions. The first and last TG18-LN patterns (black and white) were used. The photometer was placed on a tripod pointing at the centre of the display and the monitor was placed on a calibrated rotating base, in order to reach the desired viewing angle.

AAPM TG18 suggests that contrast ratio at different angles must not drop below 30% of the suggested limit of 250. Thus the maximum angle useful for interpretation is where CR reaches the limit of 175 (0.7*250).

2.10. Chromaticity

The two monitors of the couple, although calibrated in greyscale, should also match in chromatic appearance. Only EIZO monitors (colour LCD) were considered because of a software limitation of the X-Rite colorimeter. Chromatic differences are visible even in native greyscale monitors, which often show a chromatic shift towards red or blue. Chromatic agreement is not demonstrated to be critical in medical use but it can surely be considered for the operator's comfort.

The colour coordinates ($u',v'$) of white squares placed at the middle of the two monitors of the...
couple were measured and thus the chromatic difference \( \Delta(u',v') \) in the CIELAB colour space calculated using the expression

\[
\Delta = \sqrt{(u'_1-u'_2)^2 + (v'_1-v'_2)^2}
\]  

The tolerance suggested by AAPM TG18 is 0.01.

2.11. Anatomical images

Ten radiologists with different levels of experience were chosen to perform the test. TG18-CH (chest) and TG18-KN (knee) images were showed to the radiologists in four different formats: film (the actual gold standard), Barco CRT monitor, Barco LCD monitor and EIZO LCD monitor. Each image in each modality was scored from 1 (poor) to 6 (excellent) for each clinical criteria as suggested by TG18. Such criteria include overall brightness and contrast and sharpness, reproduction of bony and soft tissue, sharp reproduction of the diaphragm, visibility of small details and more.

3. Results and Discussion

3.1. Geometric distortions

CRT monitors had an optimal behaviour: distortions are below 1% for each monitor (Table I), perhaps because of the correction circuits present in these high quality displays. In LCD monitors distortions are totally absent because of the fixed structure of the crystal matrix. All the monitors showed a nearly perfect geometrical image.

3.2. Display reflection

The last column of Table II shows the minimum pixel value visible in darkness and ambient light condition. Barco monitors have higher numbers due to the 12 bits p-values.

Although specular reflections are avoided, diffuse reflections from undesired daylight, RIS monitor's light emission and light boxes can become too high. EIZO LCD monitors do not have a glass protection: in front of the screen: this reduces the impact of scattered light [10]. Barco monitors suffer from brighter reflections despite the anti-glare coating; even the RIS monitor can become a source of light pollution. Light boxes and other unnecessary light sources should be turned off before image reading.

3.3. Luminance and contrast

Table II shows the results obtained. Nearly all the values are well above tolerance, and the differences between the different types of monitors are evident.

Eizo's contrast is below the tolerance value of 250, this is due to the \( L_{\text{max}} \) value very near to the lower limit and the relatively high \( L_{\text{min}} \). This may not be considered a major problem as far as adequate window width and level are applied to soft-copy images [11].

It has been decided to delay the decision of a possible substitution of the monitor until the next constancy check, in order to have more data to evaluate.

Barco LCD are in the same condition for \( L_{\text{min}} \) but a high contrast ratio is granted by the very high maximum luminance.

3.4. Luminance response

Results from a Barco CRT monitor and a EIZO monitor have been reported as example (Figure 7) and the data obtained have been displayed as contrast ratio \((dL/L)\) versus JND. The contrast ratio should fall within 10% of the contrast ratio calculated from the DICOM curve for each grey level step, according to AAPM TG18. All the monitors were within this limit.

The calibration procedure showed to be very sensitive to photometer positioning on the screen (especially tilting), and to the presence of dirt or dust on the screen surface. In this cases the calibration procedure failed and it had to be repeated.

<table>
<thead>
<tr>
<th>Workstation</th>
<th>Distortion</th>
</tr>
</thead>
<tbody>
<tr>
<td>All EIZO</td>
<td>0%</td>
</tr>
<tr>
<td>All Barco LCD</td>
<td>0%</td>
</tr>
<tr>
<td>Barco CRT 1</td>
<td>0.1%</td>
</tr>
<tr>
<td>Barco CRT 2</td>
<td>0.56%</td>
</tr>
<tr>
<td>Barco CRT 3</td>
<td>0.54%</td>
</tr>
</tbody>
</table>

Table I. Geometrical distortions.
### TABLE II. Maximum and minimum luminance, contrast ratio, uniformity values and minimum p-value visible.

In Barco monitors independent values for left and right monitors are presented.

<table>
<thead>
<tr>
<th>Workstation</th>
<th>$L_{\text{max}}$ (cd/m²)</th>
<th>$L_{\text{min}}$ (cd/m²)</th>
<th>Contrast ratio</th>
<th>Uniformity</th>
<th>TG18-AD (darkness/ambient light)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIZO</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EIZO1</td>
<td>206</td>
<td>0.93</td>
<td>222</td>
<td>9.9%</td>
<td>15/15</td>
</tr>
<tr>
<td>EIZO2</td>
<td>196</td>
<td>0.84</td>
<td>233</td>
<td>9.2%</td>
<td>15/15</td>
</tr>
<tr>
<td>EIZO3</td>
<td>176</td>
<td>0.79</td>
<td>224</td>
<td>15.2%</td>
<td>15/15</td>
</tr>
<tr>
<td>EIZO4</td>
<td>200</td>
<td>0.90</td>
<td>222</td>
<td>12.4%</td>
<td>15/15</td>
</tr>
<tr>
<td>EIZO5</td>
<td>190</td>
<td>0.86</td>
<td>221</td>
<td>5.2%</td>
<td>15/16</td>
</tr>
<tr>
<td>EIZO6</td>
<td>197</td>
<td>0.86</td>
<td>229</td>
<td>16.6%</td>
<td>15/15</td>
</tr>
<tr>
<td>EIZO7</td>
<td>196</td>
<td>0.86</td>
<td>228</td>
<td>5.5%</td>
<td>15/15</td>
</tr>
<tr>
<td>Barco CRT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BarcoCRT1</td>
<td>283</td>
<td>0.20</td>
<td>1416</td>
<td>1.6%</td>
<td>32/48</td>
</tr>
<tr>
<td>BarcoCRT2</td>
<td>284</td>
<td>0.21</td>
<td>1356</td>
<td>4.3%</td>
<td>32/48</td>
</tr>
<tr>
<td>BarcoCRT3</td>
<td>296</td>
<td>0.19</td>
<td>1560</td>
<td>2.0%</td>
<td>32/48</td>
</tr>
<tr>
<td>BarcoCRT3</td>
<td>297</td>
<td>0.18</td>
<td>1653</td>
<td>2.0%</td>
<td>32/48</td>
</tr>
<tr>
<td>Barco LCD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BarcoLCD1</td>
<td>434</td>
<td>0.98</td>
<td>443</td>
<td>18.3%</td>
<td>52/60</td>
</tr>
<tr>
<td>BarcoLCD2</td>
<td>446</td>
<td>1.40</td>
<td>319</td>
<td>20.4%</td>
<td>52/60</td>
</tr>
<tr>
<td>BarcoLCD2</td>
<td>452</td>
<td>1.56</td>
<td>290</td>
<td>18.1%</td>
<td>48/64</td>
</tr>
<tr>
<td></td>
<td>441</td>
<td>1.57</td>
<td>281</td>
<td>18.9%</td>
<td>48/64</td>
</tr>
</tbody>
</table>

3.5. Luminance uniformity

All the monitors respect the 30% tolerance limit (Table II).

Barco CRT monitors present the lowest value, even if CRT technology is the most affected by non-uniformity. This behaviour can be explained because advanced CRT displays (as Barco ones) have uniformity correction circuits that equalize the luminance over the total screen area [4].

3.6. Display resolution

Table III reports Cx scoring grouped by monitor type.

All the monitors are well below the tolerance indicated by AAP TG18 ($0 \leq \text{Cx} \leq 4$); in particular LCD monitors, as expected, have a perfect Cx scoring. Luminance differences are above tolerance (30%) for both the Barco CRT monitors considered (Table IV): the luminance method shows then that the nominal resolution of the Barco CRT systems doesn’t correspond to a high MTF value. This means a loss in contrast in high frequency details, but such details are poorly visible by a standard observer even in optimal conditions [8]. Half the Nyquist frequency was also investigated (Table IV), showing an optimal luminance ratio. The resolution is slightly better in the centre of the screen.
Table III. Results of visual evaluation of monitor resolution using TG18-2X pattern.

<table>
<thead>
<tr>
<th>Monitor type</th>
<th>CX scoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIZO LCD</td>
<td>0</td>
</tr>
<tr>
<td>Eizo LCD</td>
<td>0</td>
</tr>
<tr>
<td>Eizo CRT</td>
<td>From 0 to 3</td>
</tr>
</tbody>
</table>

Table IV. Lumiance difference in the center and five corners of the monitors: (a) Workstation BarcoCRT1, (b) Workstation BarcoCRT2. The values are referred to the Nyquist frequency, while the bracketed ones are at half the Nyquist frequency. Results for both monitors (left and right) of each workstation are presented.

<table>
<thead>
<tr>
<th></th>
<th>Left monitor</th>
<th>Right monitor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Le: monitor</td>
<td>Right monitor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>54% (5%)</td>
<td>46% (9%)</td>
</tr>
<tr>
<td></td>
<td>22% (6%)</td>
<td>42% (6%)</td>
</tr>
<tr>
<td></td>
<td>52% (7%)</td>
<td>48% (7%)</td>
</tr>
<tr>
<td></td>
<td>(a)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>56% (9%)</td>
<td>48% (10%)</td>
</tr>
<tr>
<td></td>
<td>42% (12%)</td>
<td>50% (11%)</td>
</tr>
<tr>
<td></td>
<td>57% (11%)</td>
<td>48% (12%)</td>
</tr>
<tr>
<td></td>
<td>(b)</td>
<td></td>
</tr>
</tbody>
</table>

3.7. Display noise

On Barco monitors 3 kinds of inserts out of 4 are visible in TG18-AFC pattern; on EIZO monitors only 2.

This visual test is highly affected by contrast resolution, which is low in lower luminance screens.

In LCD monitors we don't expect a sensitive noise on image so it is easy to conclude that the third group of inserts is not seen because of too low contrast ratio as confirmed by the low L_max and contrast ratio values obtained by EIZO monitors (Table II).

3.8. Veiling glare

In all cases at least 3 inserts were visible. This is a good result for both CRT and LCD monitors. It is known that veiling glare is mostly an issue in CRT monitors because of the light scattering inside the glass [4].

3.9. Angular response

Figure 8 reports the angular behaviour of contrast ratio for a Barco LCD and a EIZO monitor. The angles reported in Table V are the limit angles for contrast acceptability (CR>175 according to AAPM TG18).

Table V. Viewing angles that ensure a luminance ratio greater than 70% of the tolerance limit.

<table>
<thead>
<tr>
<th></th>
<th>LR&gt;175</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Eizo</td>
<td>vertical &lt; -36°, +30°</td>
</tr>
<tr>
<td></td>
<td>horizontal &lt; -33°, +18°</td>
</tr>
<tr>
<td>Barco</td>
<td>vertical &lt; -35°, +52°</td>
</tr>
<tr>
<td></td>
<td>horizontal &lt; -57°, +58°</td>
</tr>
</tbody>
</table>

3.10. Chromaticity

The chromatic difference is evaluated considering the maximum difference in Δ(u',v') among each couple of measurements. In all cases the values are within the suggested tolerance of 0.01 (Table VI).

3.11. Anatomical images

The scoring was analyzed using the Two-Sample Student t Test, comparing the scoring of each type of monitor with film's scoring. In Figure 9 is shown the percentage of radiologists that judged a monitor of lower, equivalent or higher quality than film (the gold standard).

Only in a few cases the monitor quality was judged lower than film. Some radiologists judged Barco monitors even better than film. EIZO monitors are never better than film but are mostly scored equivalent to the gold standard, even if they are not supposed to be used for high resolution images such as chest and knee radiograph.

4. Conclusions

The measures confirmed the overall good quality of the system and are comparable to other results in literature [12,13]. According to the different results obtained it was decided to dedicate EIZO monitors for medical interpretation of low resolution images,
like MRI or CT. Barco monitors are dedicated to more demanding applications such as interpretation of digital plates and DR.

A QA program of daily, quarterly and yearly tests was also prepared, which include some of the mentioned measures.

REFERENCES


![Fig. 9. Radiologist's scoring of monitors compared with film, in percentage.](image)

Fig. 9. Radiologist’s scoring of monitors compared with film, in percentage.

performance of radiographic monitors. Radiation Protection Dosimetry 2005: 114(1-3); 192-197.