Calibration of Medium-Resolution Monochrome Cathode Ray Tube Displays for the Purpose of Board Examinations

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This report discusses calibration and set-up procedures for medium-resolution monochrome cathode ray tubes (CRTs) taken in preparation of the oral portion of the board examination of the American Board of Radiology (ABR). The board examinations took place in more than 100 rooms of a hotel. There was one display-station (a computer and the associated CRT display) in each of the hotel rooms used for the examinations. The examinations covered the radiologic specialties cardiopulmonary, musculoskeletal, gastrointestinal, vascular, pediatric, and genitourinary. The software used for set-up and calibration was the VeriLUM 4.0 package from Image Smiths in Germantown, MD. The set-up included setting minimum luminance and maximum luminance, as well as positioning of the CRT in each examination room with respect to reflections of roomlights. The calibration for the grey scale rendition was done meeting the Digital Imaging and communication in Medicine (DICOM) 14 Standard Display Function. We describe these procedures, and present the calibration data in tables and graphs, listing initial values of minimum luminance, maximum luminance, and grey scale rendition (DICOM 14 standard display function). Changes of these parameters over the duration of the examination were observed and recorded on 11 monitors in a particular room. These changes strongly suggest that all calibrated CRTs be monitored over the duration of the examination. In addition, other CRT performance data affecting image quality such as spatial resolution should be included in set-up and image quality-control procedures.

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FOR MORE THAN two decades, physicians, scientists, and engineers have had the dream that soft-copy display systems would replace film-based systems for radiology. Much progress has been made, and even though the dream has not yet been fully realized, digital techniques are being widely used with respect to acquisition and image interpretation. Soft-copy reading is on its way to becoming commonplace.¹⁻³

In keeping with the image interpretation and soft-copy reading trends seen in the radiologic clinics, the American Board of Radiology (ABR) decided to follow suit and offer the entire oral portion of the certification examination in digital form. All cases of the pertinent radiologic specialties were digitized and presented to the examinees

for interpretation on medium-resolution monochrome cathode ray tubes (CRTs). As a result, the issue of calibration and image quality control of the electronic display devices needed to be addressed.

IMAGE QUALITY CONTROL AND CALIBRATION FOR SOFT-COPY DISPLAYS

Calibration procedures and their value are well understood with regard to many radiologic imaging modalities and tools. Radiation sources, film processors, and laser film printers all have a long history of calibration. In most cases this calibration consists of the process of measuring the response of a component or system and, if necessary, correcting it to that expected. For some time, hospital accreditation organizations have required that a log of this monitoring and correction be kept, and it is only natural that calibration procedures will be developed for imaging workstations.

At present, virtually all workstations use CRTs for the display device. The limitations of the CRT are well known, and methods to overcome these limitations are being developed. One of the major problems facing users of soft-copy displays is the multitude of display functions possible depending on the settings of the contrast and brightness controls. It is crucial that the same image displayed on different workstations looks the same to the observer.⁴ Otherwise data can be compromised because of different internal display adjustments at

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different workstations. This can only be guaranteed if a standard display function is chosen. Furthermore, the monitors need to be operated so that the image quality is constant over time so that images retrieved later will have the same display characteristics as the same images displayed earlier. These issues are not trivial. Nevertheless, much progress has been made with respect to calibration and image quality control in the picture archiving and communications system (PACS) environment.

Of particular interest to the calibration and image quality control of CRTs is the display controller, commonly referred to as a graphics card or video controller. This device translates the digital information in the computer into the analog signals, which the CRT understands. It accepts the digital values and returns analog video signals. The conversion from digital signals to analog signals is done with the aid of digital-to-analog-converters (DACs). The digital-to-analog conversion is the most important function of the display controller.

The second most important function of the display controller is to provide the calibration for the CRT. Most display controllers provide look-up tables, which are essential in creating special display functions ("gamma correction"). As noted earlier, a major problem facing users of soft-copy displays such as CRTs is the multitude of display functions possible depending on the settings of the contrast and brightness controls. Working Group 11 of the American College of Radiology (ACR)/National Electrical Manufacturers Association (NEMA) Committee has recognized the importance of standardizing the display function of soft-copy displays for the medical imaging community. This group has developed the Digital Imaging and Communication in Medicine (DICOM) 14 gray-scale display function standard, to which all medical imaging devices will convert.^{5,6} Figure 1 shows this display function standard.

The specific display function selected by Working Group 11 is based on perceptual linearization. The specific function to be adopted, however, is not as critical as reaching agreement on an industry-wide approach. If accepted, the standard will allow devices from multiple manufacturers to exchange data and to present images consistently. Otherwise, if a system presents different images to different users or images that change with time,

Fig 1. DICOM standard display function. The function is defined for the luminance range from 0.05 to 4000 cd/m^2 . The JND applies to 2-degree targets with sinusoidal modulation of 4 c/deg calculated with the Barten model of human contrast sensitivity.

that system will not be an effective and productive tool. This is also true for images within the radiology department, as well as for those distributed to referring physicians or specialists.

The calibration tools of the display controller consist usually of a photometer and look-up tables in the display controller's random access memory digital analog controls (RAMDAC). The photometer uses a suction cup for placement right on the CRT's faceplate to measure the luminance of the CRT for the specific drive voltage applied. The data from the photometer are digitized and used to generate the CRT's display function. The resultant gamma is compared with the desired gamma and corrections are made in the drive voltages to restore the desired gamma, taking advantage of additional look-up tables stored in the display controller's RAMDAC.

While it is inherently not important which function is used for the standard, the fact that the DICOM standard is based on perceptual linearization does have an advantage. It ensures that differences in digital values (ADUs) are presented to the viewer in luminance steps of just noticeable differences (JNDs), the smallest luminance increments a human observer can discern for a particular size object.^{5,7-11} Suffice it to emphasize that this choice of the display function standard will permit per-

ception to be maximized for the observer. However, maximization of perception requires that the display controller has a DAC in the output stage that allows the 8-bit digital values to be mapped to significantly more than 256 voltage levels. Display controllers with 10-bit DACs can display smaller contrasts ($C_{\min} = 1/1024 = 0.00098$) than those with 8 bits only ($C_{\min} = 1/256 = 0.0039$). This capability is imperative for applications to perceptual linearization, where the greysteps or JNDs are spaced nonuniformly.

Calibration to the DICOM standard is useful not only for high-resolution displays with resolution matrices of $2,048 \times 2,560$, which use high-performance display controllers and which come with their own calibration software, but also for medium resolution in imaging situations with image matrices of $1,600 \times 1,200$ pixels or smaller. Here, low- and medium-performance display boards are used (VGA, etc), and many of them come with look-up tables, permitting gamma correction. Software is available for these display boards also, permitting calibration procedures to workstations even with color monitors used for display of monochrome radiographs.¹² An example is the VeriLUM (Image Smiths, Germantown, MD) Version 4 package, which was used for this project. However, a word of caution is raised here for the reader to understand that the contrast resolution for the specific calibration may be limited if the display controllers do not have DACs with 10-bit resolution.

THE VeriLUM VERSION 4.0 CALIBRATION SOFTWARE

VeriLUM version 4.0 is a simple tool for ensuring consistent video display by performing calibration, tracking, acceptance testing, and visual verification of a video display system. In the past, evaluation software had been provided by video card vendors such as DOME (Waltham, MA) and BARCO (Duluth, GA)/Metheus. With VeriLUM, assuring the quality of soft-copy displays has become commonplace and is now easily available to every computer owner.

VeriLUM can be used to perform gamma correction in conformance with the DICOM Part 14 grey scale standard display function, a user-specified gamma model, or any other user-defined luminance response model. Loading a look-up table at system start-up is possible if a grey scale video

Fig 2. The positioning of the monitors in most of the hotel rooms.

board is used that has the facility for onboard gamma correction. Currently VeriLUM provides onboard gamma correction using BARCO Display Systems (Metheus) and DOME Imaging Systems grey scale video boards. If the operating system is Microsoft (Redmond, WA) Windows 95, 98 or (reportedly) 2000, and if the color video card supports downloadable gamma ramps, then VeriLUM will use that capability.

VeriLUM software can be installed on as many workstations as desired; no additional licenses are required. That allows a VeriLUM luminance pod to be taken from workstation to workstation to perform measurements. The VeriLUM luminance pod uses a serial communications port on the PC, and thus a simple extension cable from the serial port to the front of the PC minimizes the aggravation of searching behind the PC for the proper connector.

Recently, Image Smiths improved the software and now offers VeriLUM Version 4.1. It is available on the internet at www.image-smiths.com.

METHODS OF PROCEDURE

Ninety-eight Image Systems (Minnetonka, MN) M21LMAX monochrome monitors were set up and calibrated for the oral portion of the board examinations of the ABR). The board examinations covered the radiologic specialties cardiopulmonary, musculoskeletal, gastrointestinal, vascular, pediatric, and genitourinary.

The examination took place in the rooms of the 4th, 5th, and 6th floor of the Executive West Hotel in Louisville, KY. There was one display station (a

A. Adjustment of raster geometry of monitor with the aid of a displayed circle

B. Measurement of luminance in squares for black level and white level

Fig 3. Equipment diagram showing the luminance pod attached to the computer.

computer and the associated CRT display) per hotel room.

To maintain image display quality, set-up procedures were developed for arranging the hotel rooms used for the examinations. Consideration was given to room lighting and monitor settings. Of particular importance was the elimination of direct illumination of the display, mainly in order to keep the black level, the minimum luminance, low and permit good contrast, but also to keep specular reflections of room lights out of the display's field of view. On the other hand, there was to be sufficient ambient light close to the display for the examiner to be able to read material concerning the examination. This room illumination

Table 1. Black Level, White Level, and Dynamic Range Statistics of the Initial Values of all 98 Monitors

	Black Level (cd/m ²)	White Level (cd/m ²)	Dynamic Range
Mean	0.504	199	397
SD	0.036	4.7	28

was provided by a lamp positioned between the display and the window. This strategy is in line with the age-old problem of the radiologist in the reading room, namely, providing an environment for the eye that allows good perception of the display and retains the ability to read material concerning the radiograph. After the room was arranged with a minimum of specular reflections, as shown in Fig 2, it was estimated that the final room lighting permitted a minimum luminance of less than 0.5 cd/m². A maximum luminance of 200 cd/m² was found to be obtainable without blooming by a random sampling of eight of the monitors resulting in a dynamic range of 400:1.

The procedure used to adjust the monitors is illustrated in Fig 3. The raster geometry is adjusted with the aid of a circle, displayed by VeriLUM. The minimum and maximum luminance settings are adjusted with the aid of the brightness and contrast controls, while the photometer pod is placed into the appropriate windows placed by the VeriLUM program on the CRT screen. Subsequently the program "Mea-

Fig 4. Plot of the dynamic range, and maximum and minimum luminance of the 98 monitors. Data for each monitor were sorted by minimum luminance value.

Table 2. Drift of Dynamic Range, and Minimum and Maximum Luminance in cd/m² and Their Statistics

	Min	Max	Dynamic Range		Min	Max	Dynamic Range
GU 375				375 CP			
13-May	0.52	201.81	388.10	13-May	0.49	195.41	398.80
14-May	0.70	211.35	301.93	14-May	0.26	182.98	703.77
15-May	0.68	209.25	307.72	15-May	0.66	207.93	315.05
16-May	0.77	210.26	273.06	16-May	0.81	209.59	258.75
17-May	0.87	212.04	243.72	17-May	0.81	209.66	258.84
Mean	0.71	208.94	302.91	Mean	0.61	201.11	387.04
SD	0.12	3.69	48.32	SD	0.21	10.51	166.45
375 BRST				446 Left			
13-May	0.49	202.48	413.22	13-May	0.48	204.11	425.23
14-May	0.44	200.37	455.39	14-May	0.52	214.41	412.33
15-May	0.48	201.51	419.81	15-May	0.31	193.59	624.48
16-May	0.52	201.45	387.40	16-May	0.55	199.74	363.16
17-May	0.52	203.80	391.92	17-May	n/a	n/a	n/a
Mean	0.49	201.92	413.55	Mean	0.47	202.96	456.30
SD	0.03	1.15	24.25	SD	0.09	7.59	99.82
375 MSK				446 Right			
13-May	0.52	202.22	388.88	13-May	0.52	197.02	378.88
14-May	0.45	202.22	449.38	14-May	0.64	202.76	316.81
15-May	0.54	206.88	383.11	15-May	0.35	189.62	541.77
16-May	0.64	208.58	325.91	16-May	0.48	198.77	414.10
17-May	0.71	210.56	296.56	17-May	n/a	n/a	n/a
Mean	0.57	206.09	368.77	Mean	0.50	197.04	412.89
SD	0.09	3.37	53.21	SD	0.10	4.76	82.16
375 VS				607			
13-May	0.49	200.89	409.98	13-May	0.52	198.60	381.92
14-May	0.39	199.05	510.38	14-May	0.58	199.95	344.74
15-May	0.59	209.23	354.63	15-May	0.61	203.01	332.80
16-May	0.67	210.91	314.79	16-May	0.42	189.84	452.00
17-May	0.72	210.46	292.31	17-May	0.48	189.84	395.50
Mean	0.57	206.11	376.42	Mean	0.52	196.25	381.39
SD	0.12	5.08	78.00	SD	0.07	5.42	42.16
375 PEDS				608			
13-May	0.45	197.87	439.71	13-May	0.58	197.20	340.00
14-May	0.45	197.77	439.49	14-May	0.39	199.12	510.56
15-May	0.57	203.79	357.53	15-May	0.49	203.33	414.96
16-May	0.64	204.54	319.59	16-May	0.49	203.13	414.55
17-May	0.68	204.73	301.07	17-May	0.49	203.13	414.55
Mean	0.56	201.74	371.48	Mean	0.49	201.18	418.93
SD	0.09	3.22	58.52	SD	0.06	2.54	54.19
375 GI							
13-May	0.45	202.24	449.42				
14-May	0.42	200.05	476.31				
15-May	0.46	204.56	444.70				
16-May	0.48	203.27	423.48				
17-May	0.48	203.72	424.42				
Mean	0.46	202.77	443.66				
SD	0.02	1.55	19.38				

sure Luminance Response for Gamma Correction” is selected followed by the program “Measure Luminance Response for Tracking.” The VeriLUM configuration for these measurements

was set to 33 luminance measurements for tracking, 64 luminance measurements for gamma corrections, 0.25 cd/m² for the estimated luminance off-set due to ambient illumination, 9,300 K, and

DICOM 14 standard was chosen as the desired luminance response model. The results of "Measure Luminance Response for Tracking" are stored in a file and can be recalled for viewing on the monitor or printed out to determine how close the calibration is to the ideal DICOM 14 standard.

RESULTS

Figure 4 shows a graph of the initial black levels and white levels, as well as the corresponding values of dynamic range for the monitor. The mean value and standard deviation for the black level, white level, and dynamic range are listed in Table 1. Considering that setting these black and white levels accurately and precisely is very difficult on these CRTs ("screwdriver adjustment"), it may not be surprising that in the average the desired settings were reached within only 5% to 8% on the black level and within about 2% to 3% at the white level. Note that setting the black level is generally less accurate than setting the white level.

Table 2 covers the drift of black level and white level for the monitors in the preview and the emergency room, as well for two of the monitors of the cardiopulmonary category. Some of the monitors were set back to the initial values, while others were left alone but monitored daily. Notice that substantial changes in

Fig 5. Drift of white level, black level, and dynamic range for the tracked monitors during the exam.

Fig 6. Plot of the calibrated display functions of 3 monitors from the preview room over the 5 days of the examination. Variations appear minimal and curves are very close to the DICOM 14 standard curve.

black level and dynamic range of up to 25% did occur, suggesting that a system of daily monitoring of the monitors is definitely appropriate. Ideally, a system of network control would allow easy control of the image quality of monitors. Figure 5 plots the content of Table 2—the drifts of white level, black level, and of dynamic range for monitors of the preview room during the examination. Again one notices that the relative stability of the white level is much better than the relative stability of the black level. Also, changes in the dynamic range are mainly affected by changes in the dark level.

Figure 6 is a plot of the calibrated display functions of three monitors from the preview room over the 5 days of the examination. The variations appear minimal and the curves are very close to the DICOM 14 standard curve.

CONCLUSION

The monitors showed little difference when they were initially set-up. The small standard deviations in the black and white levels combined with the calibration data demonstrate consistent imaging across monitors. The small variability in maximum and minimum luminance values is due to the brightness and contrast control on the monitor. The levels are set by adjusting a potentiometer that did not allow fine adjustment.

A subset of 11 monitors was tracked for the 5-day duration of the examination. Some drift was noticed in the settings of the monitors and is shown in Fig 6. The monitors are not designed for the daily power cycling necessary during the

course of the examination. The relevance of the drift is under investigation. Employing a replacement strategy of the older monitors with newer technology that uses digital controls will be necessary in the future.

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