Quality Control of Cathode-Ray Tube Monitors for Medical Imaging Using a Simple Photometer

David M. Parsons, Yongmin Kim, and David R. Haynor

As computer monitors are used more in medical imaging and the use of picture archiving and communication system workstations with multiple monitors is increasing, quality control protocols become necessary to track subtle variations in performance characteristics. Several tests based on previously published work were applied to 10 monitors of three different types over a period of 5 months. Each test is explained, and the results are shown. For example, without corrective adjustments, 2 monitors from the same workstation showed a small but steady decline in maximum luminance of 8.1% and 7.6% over the course of 11 weeks that was not perceptible. From this experience, we took the first step toward developing a practical and useful quality control protocol. The proposed protocol requires only a photometer and the ability to generate the Society of Motion Picture and Television Engineers (SMPTE) test pattern, and takes approximately 5 minutes per monitor per week to gather data.

KEY WORDS: Quality control, picture archiving and communication system workstations, cathode-ray tube monitors, medical image display.

MANY MEDICAL facilities use computer monitors for consultation and, in some instances, diagnosis. Therefore, monitors should be required to meet quality-control standards at least as stringent as those applied to film-based radiography. For example, a simple smudge on the glass of the monitor caused by someone touching the screen could be mistaken for an abnormality. Poor focus of the electron beam inside the cathode-ray tube (CRT) could blur details to the point where a hairline bone fracture could be missed. Smudges on the screen and poor electron beam focus are both common occurrences that can be fixed, if detected. Thus, a quality-control protocol is necessary to detect problems before they affect medical diagnoses. This paper addresses this problem by taking the first step toward developing a quality-control procedure for gray-scale CRT monitors used for viewing medical images.

Small changes in the characteristics of a monitor over a long period of time are impossible to detect by simple observation. Periodic, quantitative tests are required to detect when a monitor is out of adjustment. Previous research[1,2] has suggested several tests that measure factors that are generally accepted as affecting image quality. These include gamma value, maximum luminance, and spatial resolution. We combined these tests into a preliminary quality-control protocol, which we then evaluated on 10 different monitors that are part of the Medical Diagnostic Imaging Support (MDIS) System at Madigan Army Medical Center (MAMC).[3]

The overall goal of a quality-control program is to ensure optimal display of medically significant information. A quality-control protocol must also be clinically practical. The tests must only require inexpensive equipment and must take a short time to perform. A few laboratories in the country are equipped to fully test CRT monitors. Full testing is appropriate for monitor characterization, but is too complicated and expensive for routine quality assurance. The other consideration is the time involved to perform the tests. MAMC is eventually planning on installing over 200 CRT monitors by early 1995. If each monitor required 20 minutes to test each week, more than one full-time person would be required just to perform the CRT quality control measurements. Because this is not practical, the tests were designed to be performed quickly.

Basics of CRT Operation

This paper is concerned with gray-scale CRT monitors. Although color monitors are becoming more common for viewing ultrasound and nuclear medicine images, and research is being conducted into using color for computed tomography and magnetic resonance images, the majority of medical images are still gray scale. The lower luminance and spatial resolution of color

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From the Departments of Electrical Engineering and Radiology, University of Washington, Seattle, WA.
Supported in part by a grant from the US Army.
Address reprint requests to Yongmin Kim, PhD, Department of Electrical Engineering, FT-10, University of Washington, Seattle, WA 98195.

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monitors are further reasons why gray-scale monitors are preferred. Another competing technology is that of flat-panel displays such as liquid-crystal displays. Although flat-panel displays are becoming more popular for use in laptop and notebook computers, their luminance and spatial resolution are currently much inferior to those of CRT monitors. CRT monitors will remain as main devices for displaying medical images in the foreseeable future.

CRT monitors consist of several parts, including an electron source, control grid, acceleration electrodes, focusing and deflection sections, a phosphor screen, and a glass envelope for containing a high vacuum.[4] The display is the portion of the screen that is illuminated by the image. The neck of the glass tube is where the electron beam is generated, accelerated, deflected, and focused at a particular spot on the screen. The control grid is used to control the flow of electrons. Adjusting the voltage applied to the control grid affects the brightness of the pixels on the screen. The inside of the face has a phosphor coating that converts the electron beam energy into visible light. The light is then transmitted through the glass on the front of the screen. To increase the contrast of the display and reduce the effects of ambient light, many monitor screens are etched or have an antireflective coating. This typically reduces the maximum luminance and spatial resolution of the monitor.

To approximate the experience of viewing images on a light box, monitors used for viewing medical images should be relatively large and flat.[5] This causes problems with focusing the electron beam because the corners of the screen are farther away from the neck of the tube than the middle of the screen. Advanced monitors attempt to overcome this problem by dynamically adjusting the focus of the beam depending on its current location. All of these factors add complexity to the operation of the monitor, further emphasizing the need for quality-control tests to detect monitor malfunctions and misadjustments.

An additional need for quality control arises from the fact that some picture archiving and communication system (PACS) workstations have multiple (two to eight) monitors. This allows a radiologist to view different images of the same patient at one time and compare old and new images if necessary. This also adds complexity to the quality-control procedure, because an image should look the same independent of the monitor used to display it. If an image looks different on one monitor versus another, then the ability to compare images could be hampered.

Current Research

Most research in the area of CRT testing has been directed at identifying the tests required to accurately characterize a monitor.[1,6-8] Characterizing a monitor is a one-time procedure that is intended to definitively measure a monitor's performance on many different tests, such as input impedance and luminance as a function of CRT beam current. The tests performed for monitor characterization are typically time consuming and require sophisticated analysis tools such as a vibration-free bench, video test-pattern generator, and charge-coupled device camera. Some of the tests require disassembling the monitor to measure internal characteristics. This requires special training because there are dangerously high voltages present inside a CRT monitor. On the other hand, quality-control tests should be simple, so they can be performed frequently by less highly trained people using inexpensive equipment.

Other papers have suggested tests that should be performed for CRT quality control,[9-13] but did not say how often the tests should be performed or what kind of results to expect. An early paper[14] discusses the use of the Society of Motion Picture and Television Engineers (SMPTE) test pattern for adjusting the brightness and contrast of displays used for MRI, but does not cover other aspects of monitor image quality. Other researchers[15,16] concentrate on the display function (luminance versus gray-scale curve) of a monitor, but do not cover tests for other factors of monitor image quality.

MATERIALS AND METHODS

In this research, tests were performed on 10 CRT monitors over a period of several months. The bulk of the tests were based on reports from two leading laboratories studying CRT monitor performance: the National Information Display Laboratory at the David Sarnoff Research Center,[1] and the Monitor Characterization Laboratory at the University of Arizona.[9] This section describes the equipment used and the tests performed.

The 10 monitors that were tested were located in a single viewing room with controllable overhead lighting in the MAMC Radiology Department. The manufacturer, model number, and addressable resolution for each monitor are shown in Table 1. The monitor types are referred to as A, B, or C in the discussion that follows. The 10 monitors are connected to three different workstations, with the 4 A monitors connected to one workstation, the 4 B monitors connected to a second, and the 2 C monitors connected to the remaining workstation. A number after the letter indicates which monitor is being referred to. For example, B-2 refers to the second from the left of the 4 B monitors.

Equipment

The main equipment used was a J17 Luma Color (Tektronix Inc, Beaverton, OR) photometer with a J1803 luminance sensor head. The hand-held unit displays the digital luminance reading to within a tenth of a foot-Lambert (fL; 1fL = 3.426 cd/m^2 or nit). The attached sensor with an ambient-light shield to block external light was placed against the monitor screen. Use of a sensor with an ambient light shield is a distinct advantage in hospital settings such as an emergency department or intensive care unit where it is not possible to control or eliminate ambient light. Measurements of a dark monitor screen taken with the overhead lights off and on at full brightness showed a difference of less than 0.1 fL. A disadvantage of this meter is that it is not easy to determine exactly what area of the image is being measured.

Figure 1 shows the image, developed by the SMPTE specifically for monitor testing that was used for most of the tests.[11,17] It has several useful features, including a set of 11 different areas of gray-scale intensity ranging from 0% to 100% luminance in increments of 10%. There are also 5% and 95% areas located on top of the 0% and 100% areas, respectively. These are used for determining the contrast present at the two ends of the luminance scale. Spatial resolution test patterns are located in the four corners and the center of the image. These consist of six horizontal and vertical modulation gratings. Three of these have a 100% modulation grating at three different spatial frequencies. The other three gratings share the same frequency, but have intensity modulations of 1%, 3%, and 5%, respectively. The test pattern also has white on black and black on white windows for testing the unit response of the monitor. Finally, a grid that covers the entire background of the test image can be used to detect spatial nonuniformities. Normally, the pattern is presented so that it just fills the display of the monitor. However, the workstations at MAMC can also zoom and pan the pattern.

Most of the tests can be done with the SMPTE test

Table 1. Monitors Used for Measurements

Label	Manufacturer	Model	Addressable Resolution	Number
A	Tektronix	GMA212	1,536 × 2,048	4
B	Image Systems	M21P	1,152 × 1,536	4
C	Image Systems	M24LMAX	1,024 × 832	2

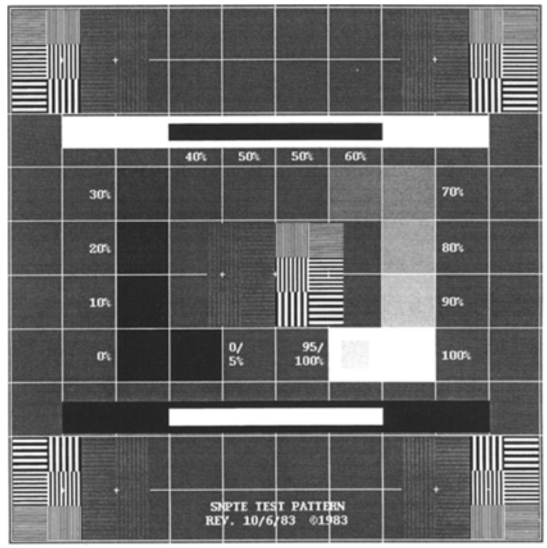

Fig 1. SMPTE test pattern.

pattern. However, some of the tests can be performed more quickly and accurately using special test patterns that are described in the sections where they are used.

Monitor Preparation

To prepare the monitors for testing, fingerprints and dust were removed with a glass cleaner and soft cloth. Measurements at MAMC show that these smudges decrease luminance output by as much as 10%. The static charge present on the screens of the monitors also attracts dust, which adversely affects image quality.

When a monitor is first turned on after being left off for a few hours, its luminance output can vary. The luminance stabilizes once the monitor has warmed up, which typically takes 2 to 6 hours.[1] Because the monitors at MAMC were always on, they did not require any warm-up during testing.

Brightness and Contrast Adjustment

The first procedure to perform is to adjust the brightness and contrast of the monitors. According to several papers,[9,11,14,15] the best method for adjusting these values is to use the 5%/0% and 95%/100% areas of the SMPTE test pattern. When both of these patches are just discernible from their background patches, contrast is good across the whole range of gray-scale values. Although these patches only display the contrast at the extremes, the contrast in between these two extremes is usually a linear function of gray scale. Thus, the contrast in the middle should also be good.

At MAMC, all brightness and contrast adjustments are done by the PACS vendor. During the period when measurements were being taken, the brightness controls of the monitors were periodically adjusted by vendor personnel to meet specific maximum-luminance requirements. A log was kept of when adjustments were performed so that a correlation to the measurements for this paper could be made. Unfortunately, the brightness and contrast of the monitors were not adjusted using the SMPTE test-pattern method described above. Instead, the entire display was set at 100% luminance and the brightness was adjusted to meet specific maximum-luminance requirements established for each monitor. In most cases, no adjustments were made to the contrast of the monitor.

Gamma Value

The luminance emitted by a pixel on a CRT monitor is not directly proportional to its gray-scale value.[18] Brightness (B) is related to the gray-scale value or gray-scale percentage (G) by

$$B \propto G^{\gamma}, \tag{1}$$

which is equivalent to

$$\log(B) = \gamma \log(G) + C, \tag{2}$$

where C is a constant and γ is the gamma value of the monitor that characterizes the relationship between brightness and gray-scale value. The gamma value can be found by measuring the luminance output for several different gray-scale values, and then computing the best linear fit of the logarithm of the luminance values to the logarithm of the gray-scale inputs. The slope of the linear fit is the gamma value.

To measure the luminance output, the SMPTE test pattern was used. However, readings from the darker patches were affected by veiling glare. This is caused by light scattering in the glass of the screen.[9] To reduce this effect, the SMPTE test pattern was zoomed as large as possible until a single square nearly filled the display area. To increase the accuracy of the measurements, they were all taken from the same location on the screen. Thus, the photometer was kept stationary for each reading. The SMPTE test pattern was panned to read the different gray-level patches at the same physical location on the screen. This reduced the effect of spatial nonuniformities on the readings.

Maximum Luminance

The maximum luminance output from a typical x-ray light box is around 500 fL.[8] Most monitors are currently capable of emitting less than 100 fL. This means that less contrast information can be conveyed through a monitor. Thus, it is important to keep a monitor as bright as possible. However, if a monitor is too bright, spatial resolution will be reduced and intense localized heating may occur resulting in damage to the screen.[19] We used the luminance at the center of the display of the 100% square of the SMPTE test pattern, measured in the gamma test, for the maximum-luminance test.

Geometry

Geometry refers to the positioning of pixels on the screen. If pixels are not displayed in their proper position, the image will be distorted. There are many types of geometric distortion with varying causes. The most well known are pin cushion and barrel distortion. Pin-cushion distortion occurs when one or more sides of the image are bowed inward, and barrel distortion occurs when the sides are bowed outward. Geometry can be accurately measured with sophisticated monitor characterization equipment that detects the position of grid lines displayed on the monitor through a time consuming process. This equipment can quantitatively detect distortions that are not visible to the human eye. Instead, we used a qualitative test combined with a simple quantitative test because of the additional expense and time required for complex quantitative tests.

To detect distortion, a special test pattern consisting of a grid of evenly spaced white lines was displayed on the monitor. At a distance of at least one meter, the test pattern was examined to determine if the outside edges were bowing inward or outward. To detect disproportionate horizontal or vertical stretching, the full height and width of the test pattern at the midsection were measured with a flexible, transparent, plastic ruler. This was not a straightforward operation because the actual image is a few millimeters behind on the back surface of the glass. Incorrect sighting of the edge of the test pattern can cause errors in the measurements. Local distortions in the image are also possible. This can be caused by nearby magnetic devices or static buildup on the screen. We examined the grid test pattern and looked for areas that did not appear square.

Spatial Resolution

The spatial resolution of a monitor determines how much detail a monitor can display. Discerning small details in an image requires high spatial resolution. This is often different from addressable resolution, which is the number of locations in the video display buffer that can be individually addressed and displayed. Because of the Gaussian profile of the light emitted by a single pixel on a CRT screen, an ideal spacing between neighboring pixels is difficult to determine. When pixels are placed close together, the number of resolvable pixels is often less than the addressable resolution.

The modulation transfer function, originally developed for photography,[20] can be used to quantify the resolution of a monitor.[4,19] However, it has drawbacks to be used in quality control. It requires measuring the luminance of the monitor in small steps, which is time-consuming and requires complicated and expensive equipment, including a slit photometer and vibration-free bench. An alternative method is to use the frequency response of the human eye to estimate the spatial noise and square wave response (contrast transfer) function of a monitor.[9] This requires several measurements from several observers, which would not be practical for routine quality assurance. Because of these drawbacks, a qualitative method was chosen for evaluating the monitors.

To assess the focus of each monitor, the spatial resolution test patterns in the corners and middle of the SMPTE test pattern were examined and compared. The sharpness of the grids was qualitatively assessed and recorded. If the transitions between the dark and light areas in the spatial resolution grid were discernible, the grid was judged to be sharp, otherwise it was considered to be blurry.

Temporal Luminance Stability

The purpose of the temporal luminance stability test is to determine how much the luminance output of a monitor changes with respect to time after an image is first displayed following a long period of displaying a blank screen. Immediately after displaying a zoomed version of the 100% square of the SMPTE test pattern, measurements of the luminance output were taken every 5 seconds for the first 30 seconds. During the next 30 seconds, measurements were taken every 10 seconds.

Spatial Uniformity of Luminance

Spatial nonuniformity of luminance refers to the variation in luminance output of the screen as a function of location. Because of unavoidable variations in the phosphor coating on the screen, there will always be small variations in luminance.[2]

The 100% gray-level square of the SMPTE test pattern was zoomed so that it filled the display area. The screen was divided into nine squares, and measurements of the luminance output were taken at the center of each of these squares. Next, the screen was examined to determine if there were any obviously light or dark areas. Additional measurements were taken at these locations.

Another important characteristic of a monitor is high frequency noise.[9,21,22] Characterizing the noise of a monitor requires special measuring equipment which is too expensive and time consuming for a practical quality-control protocol. For this reason, it is neither covered by this paper nor included in our tests.

Veiling Glare

When light is emitted from the phosphor layer, it enters the glass of the screen. Although most of the light is transmitted straight through the glass, some is scattered causing the spatial resolution to be lowered. Veiling glare is a measure of how much light is scattered by the glass of the CRT screen.[2] Because spatial resolution is an important factor for viewing most radiologic images, it is important to measure the veiling glare of the monitor. While a nonzoomed SMPTE test pattern was displayed, luminance readings were taken at the 100% and 0% gray-level squares. Next, the luminance of a completely blank screen was measured.

The veiling glare data is expressed as a percentage using the following formula:

$$VG = \frac{L_0 - L_{blank}}{L_{100} - L_{blank}} \times 100, \qquad (3)$$

where L_0 is the luminance of the 0% square, L_{100} is the luminance of the 100% square, and L_{blank} is the luminance of the blank screen. Another useful measurement is practical dynamic range which is computed by dividing L_{100} by L_0.

RESULTS

This section presents the data collected from the tests of the previous section. It describes how the data was analyzed and discusses the results for each test. Where possible, a single number was computed for each monitor to quantify the results. All luminance readings were taken in units of foot-Lamberts.

Gamma

The gamma values for the four A monitors over 11 weeks are plotted in Fig 2. The results for the B and C monitors were similar. Over this period, the brightness and contrast controls of the monitors were not adjusted except between August 31 and September 10. The large drop in gamma value for the A-4 monitor on September 22 was caused by a change in the method used for taking measurements. The luminance of the A-4 monitor drops steadily during the first few minutes after an image is displayed. Before this date, the monitor was not allowed to fully stabilize when an image was first presented. This was a quicker method of collecting data, but the results were not repeatable. Figure 3 shows how the display functions vary when the gamma value is different. To produce similar luminance outputs at all gray levels, neighboring monitors should have similar gamma values as well as similar maximum luminance output.

Maximum Luminance

Figure 4 shows the maximum luminance readings taken from the A monitors. The sudden drop on September 22 of the A-4 monitor's maximum luminance is again caused by the fact that beginning on this date, the monitor was allowed to stabilize after the test pattern was displayed. This graph shows that the monitors are not well matched. When the monitors were

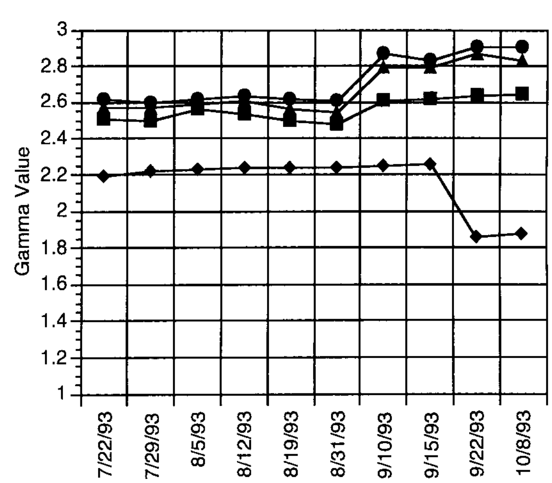

Fig 2. Plot of gamma values for A monitors. (■), A-1; (●), A-2; (▲), A-3; (◆), A-4.

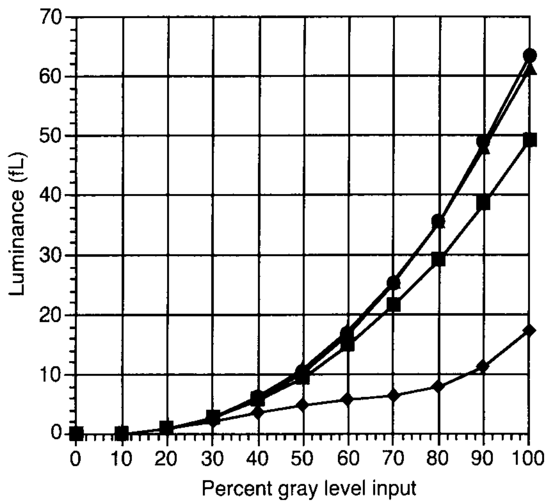

Fig 3. Plot of luminance versus gray-level input for A monitors on October 8. (■), A-1; (●), A-2; (▲), A-3; (◆), A-4.

compared by simply viewing them, there was a noticeable difference in luminance from the A-4 monitor, but the others appeared about the same even though they varied by up to 15 fL.

As described later, there are variations across the surface of the screen in the luminance produced. Thus, to get exactly repeatable results, the luminance must be read from the same position on the screen each time. Because this is impractical in a clinical setting, some variation in the data is expected.

It can also be seen from this chart that the maximum luminance of a monitor, in the absence of adjustments, is a relatively stable value. However, there is a small, steady decline in the luminance of the A-2 and A-3 monitors of 8.1% and 7.6%, respectively. Over the course of 11 weeks, this change was not perceptible. This shows that without periodic testing, over several months a monitor may emit a much lower or higher luminance than desired.

Screen Geometry

Data was collected for all three screen geometry tests. None of the monitors were found to have significant pin-cushion, barrel, or local distortion. Height and width measurements were taken on all 10 monitors at two different times with a 3-week separation. The height versus width ratios are plotted in Fig 5. Two observations can be made from this graph. The first is that all but one (B-1) of the monitors fall within 10% of a one-to-one ratio. The second observation is that the ratio of height to width does not change significantly over a period of 3 weeks.

Comparing text displayed on monitors B-1 and B-2, two observers were able to detect a difference in the ratio of height to width. Although this does not necessarily indicate that diagnostic image quality is being compromised, it does show that a 10% variation in the height versus width ratio is noticeable.

Spatial Resolution

Qualitative evaluation with the SMPTE test pattern showed that of the three types of monitors, the B monitors were the most out of focus, with the focus at the screen corners being

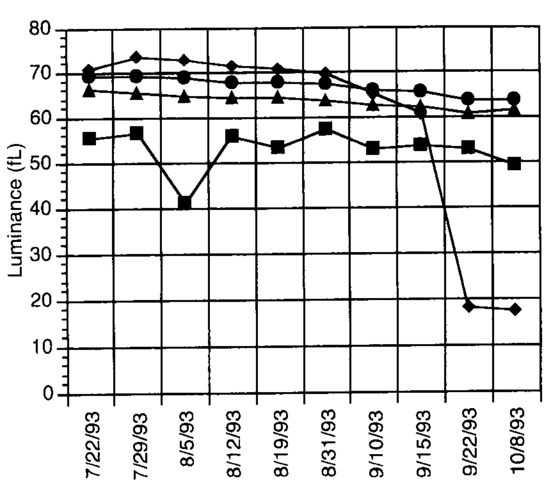

Fig 4. Maximum luminance of A monitors. (■), A-1; (●), A-2; (▲), A-3; (◆), A-4.

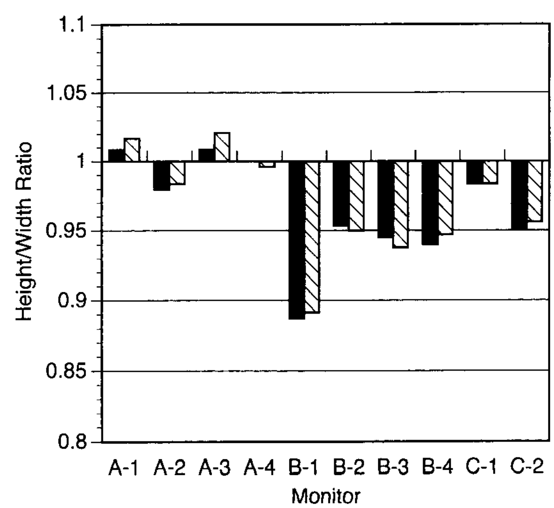

Fig 5. Screen geometry. (■), 9/24/93; (▨), 10/15/93.

worse than that in the center. All four were blurry at the top of the screen, and B-2 was also blurry at the bottom. The A monitors were all sharp except for A-4, which was very blurry over the entire display. The C monitors were both sharp. The spatial resolution did not change noticeably over several weeks.

Temporal Luminance Stability

Figure 6 shows the results of the temporal luminance stability test. The readings are normalized so that the measured value at time zero is 100%. Notice that all of the monitors remain within 5% of their original luminance level after 60 seconds, except for the A-4 monitor. The luminance of this particular monitor decreases for over 4 minutes from an initial value of 63.2 fL to around 20 fL. This is clearly unacceptable performance because the monitor is specified to display 60 fL of luminance.

Spatial Uniformity of Luminance

The coefficient of variation (standard deviation of the nine measurements divided by the mean) gives an approximate value for the amount of luminance variation present in the display. The ideal value is 0%. Figure 7 shows the coefficient of variation for each monitor on three separate dates. All of the monitors performed better than 10%, but even in the worst case these nonuniformities are not detectable by mere visual inspection. From our experience, a coefficient of variation of 10% corresponds approximately to a 25% range in luminance of a monitor. Figure 7 also shows that the coefficient of variation does not change appreciably over a 1-month time period.

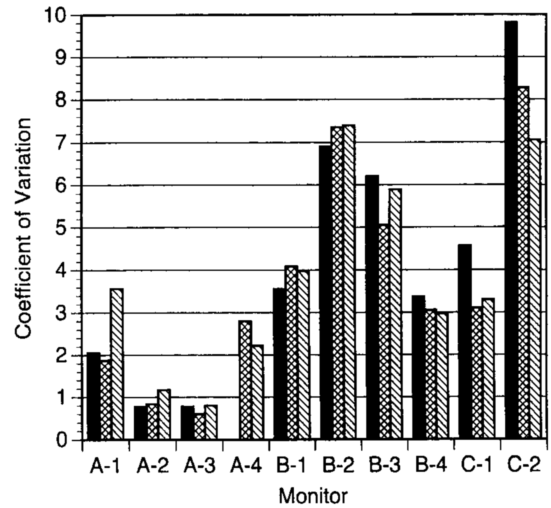

Fig 7. Spatial uniformity coefficient of variation. Readings were not taken for the A-4 monitor on September 15 because of the instability of the luminance with respect to time. (■), 9/15/93; (▩), 9/22/93; (▧), 10/13/93.

Veiling Glare

Figure 8 shows the veiling glare percentages computed with equation 3 for all 10 monitors on two separate dates. Similar model monitors produce similar results. This is expected because the veiling glare is caused by the glass of the screen, and each type of monitor has different screen characteristics. The A monitors did

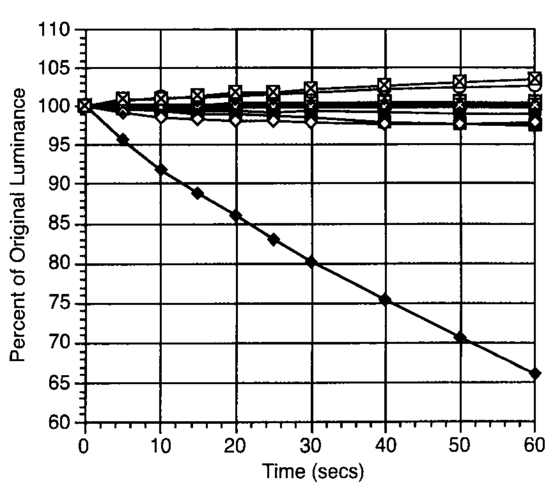

Fig 6. Temporal luminance stability, percentage of original luminance. (■), A-1; (●), A-2; (▲), A-3; (◆), A-4; (□), B-1; (○), B-2; (△), B-3; (◇), B-4; (⊠), C-1; (⊠), C-2.

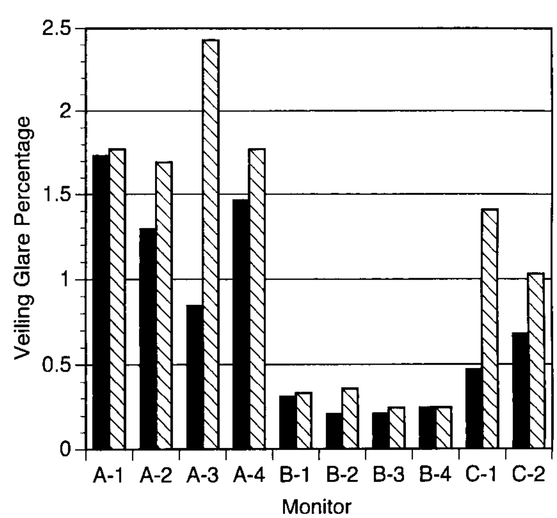

Fig 8. Veiling glare percentages. (■), 9/22/93; (▧), 10/15/93.

not perform as well compared with the B or C monitors. Between September 22 and October 15, all of the values increased slightly. The average practical dynamic range measurements for the A, B, and C monitors were 52.9, 349.8, and 82.8, respectively.

A QUALITY-CONTROL PROTOCOL

This section presents our initial recommendation toward a quality-control protocol for medical displays. The procedure for performing each test is presented along with the method for analyzing the results. The recommendations for tolerance levels in the measurements are not specific, because the tests have only been performed on three types of monitors. The recommended frequency values are based on the Results section.

A few recommendations apply to all of the tests. Each time the test pattern is changed, the luminance output should be observed for a few seconds to make sure the monitor has stabilized before taking any readings. For each test, a single method should be chosen and adhered to as much as possible. Many photometers have serial output capability. This can be used to directly enter the data into a spreadsheet via a portable computer, significantly reducing the time required to record and analyze the measurements.

Equipment

Because of its ease of use and relatively low cost, the most important piece of equipment for these tests is a photometer. The sensor should be shielded from ambient light. The angle between the sensor and the screen should be nearly perpendicular when readings are taken. Most of the tests use a SMPTE test pattern. Some tests can be performed more quickly and accurately with additional test patterns. These are described below in the test in which they are used.

Monitor Preparation

Before performing any tests, the monitor should be cleaned with a glass cleaner and soft cloth. For frequently used monitors, this should be done as frequently as once per week. Fingerprints are easier to see if a light image is displayed on the monitor. The monitor should be turned on for more than two hours, with or without displaying an image, before the tests are performed to ensure that it is properly warmed up.[1]

Brightness and Contrast Adjustment

The brightness and contrast controls should be adjusted so that the 5% and 95% areas of the SMPTE test pattern are discernible from their background patches. When properly adjusted, the luminance of the 100% square should not exceed the maximum luminance specified for the monitor, the dark area surrounding the test pattern should not be easily distinguishable from the outer edge of the screen, and bright areas should not be out of focus. If any of these occurs, the brightness and possibly the contrast settings need to be reduced.

The brightness and contrast adjustments are the two most easily changed values of a monitor, and they also have the most profound effect on image quality.[11] Thus, adjustment should be performed weekly.

Gamma

For this test, the SMPTE test pattern can be used. It should be zoomed so that one square fills the display area. The pattern can then be panned to read each square. More accurate results will be obtained by using 11 different uniform fields set to gray levels that are 0% to 100% of maximum by increments of 10%. A luminance meter is used to measure the luminance output from each gray-scale value from 0% through 100%. The gamma is then computed from these measurements.

Once the gamma value is determined, it should be compared with previous values obtained for the monitor in addition to the gamma values of the other monitors at the same workstation. Large changes in the gamma value from week to week or from monitor to monitor should be investigated by checking the brightness and contrast settings.

Maximum Luminance

A luminance meter is used to measure the output at the center of the display from the zoomed 100% square of the SMPTE test pattern or from a uniform field at 100% gray level. If the measured luminance value deviates from the specification of the monitor by a large amount, or if the luminance emitted by different monitors at the same workstation differs, the brightness adjustment should be checked. If the external brightness control is not sufficient for adjusting the maximum luminance, there is usually a beam cutoff control inside the monitor that can be adjusted by a technician. A monthly test will detect any long-term degradation in performance.

Geometry

To check the geometry of the display, a grid of evenly spaced lines should be displayed. Alternatively, the background grid of the SMPTE test pattern can be used. While viewing the display from a distance of one meter, the grid should be examined to see if the lines appear to be straight. If the grid is unusually distorted, the area around the monitor should be checked for magnetic objects. If the sides of the outside border appear bowed inward or outward, the monitor needs adjustment. High-quality monitors typically have an internal control for this effect. While still displaying the test pattern, the width and height of the outside border should be measured. Dividing one measurement by the other, the resulting value should be close to 1.0. This distortion can be controlled by a control on the inside or sometimes on the outside of the monitor.

Spatial Resolution

While displaying the SMPTE test pattern, the bar patterns in the middle and corners of the display should be examined. If they are unacceptably blurry, the focus of the monitor may need to be adjusted. This is usually an internal adjustment. It is usually difficult to have the corners and the middle of the screen perfectly focused at the same time. If this is the case, an intermediate setting should be chosen that slightly favors the center of the screen, because this is where the area of interest is usually located. Because the focus does not appear to change noticeably over a few weeks, this is recommended as a monthly test.

Temporal Luminance Stability

On a monitor that is already warmed up but has been blank for over 10 minutes, a large white area should be displayed on the screen, such as the 100% square of the SMPTE test pattern. Because the monitor must be blank for a period of time, this test should be performed before the others. A luminance reading should be taken immediately after the white area is displayed, and then again after 30 seconds. If the luminance increases or decreases by a large amount, the monitor should be checked. This attribute does not typically change month to month, so it is recommended as a quarterly test.

Spatial Uniformity of Luminance

A solid test pattern that covers the area of the display is required for this test. A gray level of 100% will show the most variations because it has the highest luminance output, but a gray level of 50% represents a more typical viewing condition. The important characteristic is that the entire display is the same gray level. The display is preferably divided into sixteen squares, four across and four down for a larger number of data points. The luminance at the center of each square is then measured. Additionally, any areas that appear light or dark should be measured. The coefficient of variation is computed by dividing the standard deviation of these measurements by the mean. Large values should be investigated. A quarterly check is sufficient, as this characteristic does not change much with time.

Veiling Glare

If the ability to create special test patterns is available, two images should be created. The first pattern should consist of a small black square, 1 cm per side, in the middle of the screen, surrounded by a 100% square, 7 cm per side, surrounded by a black border. The luminance of the center small black square is measured (L_0). The other test pattern is the same except that the center black square is changed to the 100% gray level. The luminance output from the center of the 100% square is measured (L_{100}). If special test patterns are not available, the luminance output of the 0% and 100% squares of a regular (unzoomed) SMPTE test pattern can be substituted for L_0 and L_{100}, respectively. Finally, the luminance output of a blank screen is measured (L_{blank}). The veiling glare percentage (VG) is computed using equation 3. Typical values for this measurement range between 0% and 3%. Larger values may indicate a problem with the monitor. Because veiling glare is caused mainly by the glass of the computer screen,[2] then this value should not change much over time. Thus, this test can be performed quarterly. Another useful measurement which can be derived from this test is the practical dynamic range. This is computed by dividing L_{100} by L_0.

Measurement Time

Table 2 presents the approximate time required to perform the measurements for each test. All of the weekly tests combined require about 4.5 minutes per monitor, the monthly tests take 1 minute per monitor, and all of the quarterly tests combined require 3 minutes per monitor. Analyzing the results and performing any required corrective actions will take additional time. These tests can be arranged such that the monthly and quarterly tests are performed on the monitors on a rotating basis. Assuming this, all of the tests combined will take approximately 5 minutes per monitor per week, excluding data analysis.

CONCLUSION

Like most analog equipment, the characteristics of a CRT monitor vary with time. Because CRTs are being used to view medical images, they must be tested periodically. Our long-term goal is to develop a clinically important yet practical quality-control protocol for maintaining high image quality from gray-scale CRT monitors used in medical imaging. As a starting point, tests from leading monitor characterization laboratories were performed and refined in a clinical setting over a period of 5 months. The tests use quantitative measurements, except where expensive equipment or time-consuming processes would have been required. In these cases, qualitative tests were developed to make the protocol more practical.

To be implementable in a medical center setting, our tests were designed to be performed by personnel without specialized training in monitor testing and to use inexpensive equipment. Because PACS workstations may have more than one monitor, another important consideration was intermonitor variations in characteristics such as gamma and maximum luminance. Based on the results from performing the tests, a preliminary quality-control protocol was presented with recommendations for how frequently to perform the tests. Characteristics that change rapidly and that most affect image quality should be tested weekly. Similarly, the other tests have been categorized as monthly or quarterly tests. The time required to perform all of the tests combined is about five minutes per monitor per week.

Table 2. Frequency and Measurement Times (per monitor) for Quality Control Tests

Procedure	Time (sec)
Weekly tests	
Monitor preparation	30
Brightness and contrast adjustment	60
Gamma	165
Maximum luminance	15
Total	270
Monthly tests	
Geometry	45
Spatial resolution	15
Total	60
Quarterly tests	
Temporal luminance stability	30
Spatial uniformity of luminance	90
Veiling glare	60
Total	180

Future Research

There are several areas where more work could be done in finalizing the quality control procedure. The most useful addition to this work would be to further apply and evaluate the quality control tests. Additional studies and experience applying these tests to many different types of monitors would allow definitive tolerance levels to be established for each test. Also, the recommended test frequencies could be adjusted to lower the time required to perform the tests without compromising display quality.

To decrease the amount of time required for testing, a more efficient means of recording and analyzing the data could be developed. The Tektronix J17 photometer has a serial output port that could be connected directly to a computer to record the measurements. Custom software could then analyze and track the data for each test. The user would be alerted when a monitor performed outside of prescribed tolerance levels. Another possibility for future work is to better quantify the spatial resolution test. This could be done by developing an inexpensive test instrument to quickly measure pixel spot profile or modulation pattern output. This instrument would need to be relatively portable and easy to set up so that it could be carried around to each workstation on a regular basis. Further testing would need to be performed to justify the additional expense of the equipment.

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