Evaluation of a Flat CRT Monitor for Use in Radiology

Hans Roehrig, Elizabeth A. Krupinski, and Toshihiko Furukawa

Medical radiographs based on familiar projection techniques are planar images traditionally displayed by placing on a flat surface viewbox. Presenting these planar images in digital form on a traditional monitor with a curved surface may cause distortions, possibly affecting diagnoses. This would be true especially if physical linear dimensions of the anatomy are important. Reflections from ambient lights behind the observer also could be a problem with curved displays. The goal of this study was to compare physical and psychophysical performance of a flat-surface display monitor with a traditional curved-surface monitor. Two display monitors with different types of front glass-panel surfaces were evaluated. The first monitor had a traditional curved surface, and the other had a flat surface. Physical measurements included dynamic range, display function, veiling glare, and spatial uniformity. An observer performance study used low-contrast, square-wave patterns to determine just-noticeable differences. Ambient lights were turned off in one condition and on in the other. Physical measurements showed that the display functions were nearly identical, but uniformity, veiling glare, and signal-to-noise-ratio were better for the curved monitor. Observer performance was better overall with the curved monitor, but the degradation in performance between lights off and lights on was greater for the curved than flat monitor. The greater degradation with the lights on could be attributed to more reflections off the curved than the flat monitor. A flat-surface display monitor may be useful for viewing clinical radiographs.

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THE MONOCHROME CATHODE ray tube (CRT) currently is the most common electronic display device in radiologic PACS (Picture Archiving and Communications Systems) and Tele-radiology applications. The CRT is a highly developed and reliable system that has been used for a

number of years. High-resolution versions (5-megapixel monitors) are available with brightness levels as high as 200 ftL (686 cd/m^2)¹ and contrast ratios on the order of 500:1. The CRT is, however, not perfect. One problem with the CRT is that the faceplate is a curved surface. Radiographs based on the familiar projection imaging techniques are planar images, as are images of CT and MRI, because they represent slices through the patient's body. These images normally are displayed by placing the film of the film-screen detector or the film of the computed tomography (CT) and magnetic resonance imaging (MRI) slices on a light box, which has a flat surface. Presenting these radiographs in digital form (either as they are generated by a digital detector or after digitization with a film-digitizer) on a CRT with a curved surface will cause distortions. The problem is similar to making flat maps of the spherical earth.

There are several areas in which these distortions could present problems, especially in circumstances in which physical dimensions of anatomy are of importance. Orthopedic surgeons are concerned with the length of bones and need to know these dimensions to judge for presence or absence of abnormality. In stereotactic breast needle biopsies it is important to determine the x-y-z position of a tumor within the breast within at least a millimeter. Errors in this measurement could lead to missing the tumor when a biopsy is made, with grave consequences for the patient. In radiation oncology it is very important in the treatment planning process to know the exact physical dimensions of body structures surrounding the tumor so that the therapeutic radiation can be delivered to the tumor only and not to healthy tissue. In conventional techniques the decision for correct patient positioning is made by super-positioning of films, the simulator film (containing the exact specification of the treatment field) and the verification film (a radiograph with the patient in the treatment position on the couch, taken before the treatment begins). If a digital image with presentation on a curved CRT is used, errors in the positioning judgement of up to 1 cm can be envisioned with grave consequences.

There are other potential problems associated with the use of displays with a curved surface.

From the Department of Radiology, University of Arizona, Tucson, AZ, and DataRay Corporation, Westminster, CO.

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Address reprint requests to Hans Roehrig, PhD, Department of Radiology, University of Arizona, 1609 N Warren Bldg 211, Tucson, AZ 85724.

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Ambient light is reflected off the CRT faceplate and phosphor screen, adding to the light emitted by the phosphor and reducing the contrast of an image.^{2,3} If there are objects behind the radiologist, they can be reflected on the monitor faceplate as well, creating distractions. Although reflections occur off any glass surface, curved surfaces (convex ones) present a particularly difficult situation because they provide a larger field of view within which many more light sources could contribute to unwanted reflections (Fig 1). Antiglare coatings can be applied to CRT faceplates to help reduce the effect of glare and reflections, but they do not completely eliminate the problem.

An alternative to the CRT is the liquid crystal display (LCD).⁴ The LCD is a 2-dimensional (2-D) electro-optical modulator with a flat surface placed in front of a backlight, so the problems of glare and reflections associated with ambient light are reduced significantly. However, LCDs are limited significantly by viewing angle. Viewed straight ahead on-axis contrast ratios can be as high as 300:1, but if the viewer moves off axis either side to side or up and down the contrast ratio drops significantly.¹ A possible intermediate solution between the traditional curved-surface CRT and the LCD is a flat-surface CRT display. The goal of the

current study was to physically and psychophysically evaluate a flat-surface CRT display for possible use in radiographic interpretation.

MATERIALS AND METHODS

Two DataRay (DataRay Corp, Westminster, CO) DR96 monochrome portrait monitors were evaluated. One of the monitors had the traditional curved-surface glass faceplate, the other had a new flat-surface glass faceplate. The resolution of both of the monitors was 1600×1200 pixels. Both monitors were calibrated to the DICOM Grayscale Display Function Standard (GSDF).^{2,5,6} The monitors were the same in all other respects except for the curved or flat faceplate glass.

Veiling glare, display functions, uniformity, signal-to-noise ratio, and raster modulation were measured using methods described in the literature.² To measure veiling glare, a black disk (0% video signal) of variable diameter was displayed on a white background (100% video signal). Using a spot photometer with a baffle, the luminance in the center of the black disk was measured for different disk diameters and related to the luminance of the white background. The display function was measured using the Dome Calibration software Total Quality Assurance (TQA; Dome Inc., Waltham, MA), its associated photometer, and the DICOM GSDF display function test pattern.^{2,5,6} Uniformity was evaluated by displaying a uniform field at maximum command level of 255 ADUs (analog-to-digital units) and sampling the luminance in 40 equidistant locations over the whole display area. Signal-to-noise ratio (SNR) and raster modulation were measured using a high-performance CCD camera.² For this measurement a uniform field was displayed, and a portion of it was imaged with the

Fig 1. Illustration of reflections from curved surfaces and from flat surfaces

CCD camera Model (PS-CAL; DALSA/MEDOPTICS, Tucson, AZ) under a magnification of 8 CCD pixels per CRT pixel. The CCD images then were analyzed with respect to mean $\pm$ SD (for the determination of SNR) and with respect to the raster profile (for the determination of the raster modulation).

The psychophysical evaluation used the Just Noticeable Difference (JND) paradigm that we have used previously to evaluate monitors, and is a consideration in the DICOM GSDF (Digital Imaging and Communications in Medicine) display function standard.^{2,7-9} The stimuli used were bar patterns consisting of bars made up of 5 pixels on and 5 pixels off, with a total of 11 bars. The entire pattern measured approximately 2 cm $\times$ 2 cm, which subtended 2.3° visual angle when viewed from a distance of 50 cm. The command levels ("gray levels") were selected on a 10-bit basis to take advantage of the 10-bit DACS (Digital-to-Analog Converter) of the display controller.² Four luminance levels were evaluated, 16.5 cd/m² (4.8 ftL), 42.4 cd/m² (12.4 ftL), 81.9 cd/m² (23.9 ftL), and 198.4 cd/m² (57.9 ftL). The amplitudes of the bar-pattern stimuli ranged over 9 different command levels (ADUs) or gray levels to generate low-contrast square-waves from not visible to clearly visible in each of the 4 luminance conditions. The base gray level for the 16.5 cd/m² condition was 388 ADU, and levels ranged from 388 to 396 ADU. The base gray level for the 42.4 cd/m² condition was 568 ADU, and levels ranged from 568 to

576 ADU. For the 81.9 cd/m² condition the base gray level was 712 ADU, and levels ranged from 712 to 720 ADU. The base level for the 198.4 cd/m² condition was 924 ADU, and levels ranged from 924 to 932 ADU. Ten horizontal and 10 vertical renditions of each gray level were created for each luminance condition. There also were 63 blank (no bars) control patterns for a total of 243 stimuli per luminance level.

Viewing distance was set at 50 cm. The stimuli were displayed twice on the curved-surface CRT, once with the lights on and once with the lights off. The difference in ambient lights on versus off was 10 cd/m². The stimuli were displayed on the flat-surface CRT in the same 2 ambient light conditions. Fifteen undergraduate students participated in each viewing condition. The observers had to indicate whether each target was vertical, horizontal, or blank on a preformatted answer sheet. Observers controlled the pace at which they viewed the stimuli by using a mouse to click on a next image icon on the monitor. Viewing sessions lasted no more than 20 minutes to view all 243 stimuli.

RESULTS

Photographs were taken of the 2 monitors to illustrate the distorting effects of the curved surface on straight lines. Figure 2 shows photos of the 2 CRTs from the side under an extreme angle to

Fig 2. Visualization of surface profiles of flat CRT (A) and curved CRT (B) of actually straight vertical lines of the SMPTE pattern in comparison with straight edge of rigid ruler illustrates possible distortions as a result of surface curvature.

visualize the respective surface profiles while displaying the SMPTE pattern. A straight-edged ruler is lined up vertically with one vertical line of the SMPTE pattern. Notice in the image of the CRT with the curved surface (Fig 2B) the potential for errors in the estimate of distances, if such distances were measured with a rigid ruler. The distortion ("bowing" of the straight lines) is greater at the top and bottom edges of the monitor compared with the center portions. This error is minimized significantly for the flat-surface CRT (Fig 2A). However, close inspection of Fig 2B shows that the so-called flat surface CRT is not really flat either; there also is a finite curvature.

Veiling glare measurements for the 2 monitors are shown in Fig 3 as a function of disk diameter in units of number of pixels. For small and large disk diameters, the veiling glare ratio for the flat-surface CRT is higher ("worse") than that for the monitor with the curved surface. For instance, at the 100-pixel diameter disk (about 20 mm) the veiling glare ratio for the flat-surface monitor is about 2.2% compared with 1.9% for the curved surface monitor (veiling glare measurement is unitless because it is a ratio). At the 700-pixel disk (140 mm) the veiling glare ratio for the flat surface monitor is 0.56%, compared with 0.42% for the curved one. The display functions for the 2 monitors are presented in Fig 4. They are very nearly identical. The maximum luminance was 270 cd/m^2 whereas the minimum luminance was about 0.6 cd/m^2 for both monitors. The SNR for the flat-surface CRT was lower (53) than for the curved-surface CRT (72).

Figure 5 shows the uniformity of the 2 CRTs. In

Fig 3. Veiling glare of both monitors.

Fig 4. Display Functions of both monitors.

terms of the relative difference between maximum and minimum luminance as well as in terms of the variability of the luminance (ratio of mean to standard deviation of the luminance samples), the uniformity of the curved-surface CRT at a luminance of about 270 cd/m^2 is slightly better (15.3% and 4.2% max-min, respectively) than that of the flat-surface CRT at the same maximum luminance (19.3% and 5.2% max-min, respectively).

The results of the psychophysical JND study are shown in Table 1. The Just Noticeable Difference (JND) is defined as the point at which the average percent correct decisions (across all 15 observers) was 50%. The JND scale is based on the difference between the base gray level and the gray level amplitude of the bars. For example, the JND for the horizontal bars for the 81.9 cd/m^2 luminance level ambient lights on condition for the curved CRT was 3.0. This means that, on average, the observers had 50% correct decisions when the amplitude of the stimulus bars was 715 ADU (80 cd/m^2 ; base = 712 ADU). Higher JNDs mean worse performance because it means that it took higher amplitudes to detect the stimulus bars.

The first analysis of the JNDs compared the flat with the curved CRT with the lights on and off. When the ambient room lights were off, the curved CRT had lower (better) JNDs than the flat CRT at 16.5 cd/m^2 and 42.4 cd/m^2 ; but at the 2 higher luminance levels the JNDs were nearly the same for the two CRTs (column 4, Table 1, F-C Off Diff). When the ambient room lights were on, the

Fig 5. Uniformity of the flat surface CRT (A) and of the curved surface CRT (B) at their maximum luminance, reached by the command level 255 ADU.

differences between curved and flat JNDs were much smaller at all luminance levels (column 7, Table 1, F-C On Diff). The second analysis compared each CRT with itself for lights on and off. For both the flat and curved CRTs, the JNDs were higher when the ambient lights were on. However, for the curved CRT the difference in JNDs for lights off versus on (column 9, Table 1, C-C Off-On Diff) was greater than the flat CRT (column 8, Table 1, F-F Off-On Diff), especially at the 2 lower luminance levels. Thus, the degradation in JND performance between lights on and lights off was more severe for the curved-surface

CRT than the flat. This can be seen graphically in Fig 6.

DISCUSSION

The curved and flat-surface CRTs were very similar in many respects based on the physical evaluation, but, overall, the curved-surface CRT was better in terms of SNR, uniformity, and veiling glare. This superiority in physical parameters was reflected in the psychophysical study. Overall, the JNDs for the curved-surface CRT were lower (better) than the flat CRT when the ambient lights were turned off, especially at the

Table 1. JND Points in Each Viewing Condition for Vertical and Horizontal Stimuli for the 4 Luminance Levels (cd/m^2) With Ambient Lights Off and On for Flat and Curved CRTs

1	2	3	4	5	6	7	8	9
	Off Flat	Off Curved	F-C Off Diff	On Flat	On Curved	F-C On Diff	F-F Off-On Diff	C-C Off-On Diff
16.5 cd/m^2 (H)	1.5	0.8	+0.7	1.6	1.5	+0.1	-0.1	-0.7
16.5 cd/m^2 (V)	1.3	0.7	+0.6	1.5	1.8	-0.3	-0.2	-1.1
42.4 cd/m^2 (H)	2.2	1.5	+0.6	2.5	2.2	+0.3	-0.3	-0.7
42.4 cd/m^2 (V)	2.0	1.6	+0.4	2.5	2.5	0.0	-0.5	-0.9
81.9 cd/m^2 (H)	2.6	2.5	+0.1	3.1	3.0	+0.1	-0.5	-0.5
81.9 cd/m^2 (V)	2.5	2.6	-0.1	3.0	3.0	0.0	-0.5	-0.4
198.4 cd/m^2 (H)	2.7	2.6	+0.1	3.0	3.0	0.0	-0.3	-0.4
198.4 cd/m^2 (V)	2.6	2.7	-0.1	2.9	3.2	-0.3	-0.3	-0.5

NOTE. The differences for flat versus curved with lights off and lights on are shown in columns 4 and 7, respectively. A positive value means the JND was lower (better) for the curved-surface CRT. The differences for lights off versus on for the flat and curved CRTs are shown, respectively, in columns 8 and 9. A positive value means the JND was lower (better) with the lights Off.

Abbreviations: Vertical, V; Horizontal, H; Flat, F; Curved, C.

Fig 6. Graphic representation of the data presented in Table 1.

lower luminance levels. When the ambient lights were turned on, the JNDs for both CRTs increased (got worse) to the point at which performance was nearly equivalent for all luminance levels. What this means, however, is that the JNDs for the flat CRT generally were affected less by the ambient lights than the curved CRT (columns 8 and 9, Table 1), especially at the lower luminance levels. In a general sense, these findings confirm what others have found,³ that having ambient lights on has significant potential to degrade the detection of low-contrast signals. In radiology, low-contrast targets such as pulmonary nodules or mammographic masses could

be missed if care is not taken to optimize the ambient room lights. With respect to the choice of monitors, the results suggest that if the SNR, veiling glare and uniformity of the flat-surface CRT could be improved, it may well be a potentially useful display because it seems to be affected less by ambient lights than a curved-surface CRT.

The major benefit of the flat-surface CRT monitor appears to be a significant reduction in glare from reflections when there is ambient light in the room (Fig 7). This observation might be surprising at first glance because the veiling glare ratio of the curved monitor is slightly lower than that of the flat surface monitor. However, the reader should remember that veiling glare describes mainly scatter effects of light generated by the display's phosphor and not so much scatter of light by external light sources. A brief pilot study in which radiologists viewed clinical images on the 2 monitors confirmed this. Four radiologists viewed a series of 10 different (eg, chest, bone, mammogram) radiographs on both monitors side-by-side with the lights off and lights on. All of the radiologists expressed a preference for the flat-surface CRT monitor compared with the curved-surface CRT on all images displayed. Afterward the 2 main reasons

Fig 7. Reflections of bright structures in the room, seen on the curved surface CRT (B), but not seen on the flat surface CRT (A).

stated for this preference were that (1) images on the flat-surface CRT looked more like film on a view box so there were few or no linear distortions and (2) the flat-surface CRT had significantly fewer reflections from the surface. None of the radiologists could see any significant differences in terms of the overall quality of diagnostic information and details on the 2 monitors.

The radiologists' preferences create an interesting paradox. The physical data generally showed that the flat CRT was slightly inferior in performance compared with the traditional curved CRT, yet the radiologists seem to prefer it and felt that diagnostic information was not impaired. It seems that the benefits of less glare and fewer geometric distortions may induce radiologists to sacrifice some of the advantages in display performance. To properly determine if this trade-off is acceptable in the clinical environment, a full-blown observer performance (receiver operating characteristic [ROC]) study is warranted. An ROC study would determine if there is a performance cut-off point at which the curved CRT yields better performance

than the flat CRT despite the subjective preferences of the radiologists.

Differences might arise, however, in terms of increased eye strain and overall fatigue if radiologists were to spend a number of hours using the curved-surface CRT with greater glare and reflections than with the flat-surface CRT. The relationship between eye strain and fatigue in diagnostic radiology has not been studied to any great degree, but fatigue in general is known to influence performance in visual tasks. It is likely that the effects of ambient light on performance observed in this study with the flat-surface CRT monitor will be found with LCD and other types of non-CRT flat-surface displays that are being developed. Until these new monitors become more widespread and acceptable for use in clinical radiology, radiologists should be aware of the fact that glare and reflections can be a significant source of distraction and fatigue during extended periods of reading from monitors. They should take care to eliminate or at least significantly decrease the ambient light levels when reading images from monitors.

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