Active Matrix Liquid Crystal Displays for Clinical Imaging: Comparison With Cathode Ray Tube Displays

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Fifteen large-area, flat-panel displays used for clinical image review were evaluated for image quality and compared with 30 comparably sized cathode ray tube (CRT) monitors. Measurements were of image display patterns by Video Electronic Standards Association (VESA) and a commercial product. Field measurements were made of: maximum and minimum luminance, ambient lighting, characteristic curve (gamma), point shape and size, high-contrast resolution, uniformity, and distortion. Assessments were made of pixel defects, latent image patterns, ghosting artifacts, and viewing angle luminance. Also, a questionnaire was generated for users of the flat-panel and CRT units. Seventeen respondents indicated no preference for either flat panel or CRT. Results show these flat panels to have higher luminance (mean, 177.7 cd/m²); larger number of just noticeable differences (JNDs; n = 555), higher gamma, comparable uniformity, and warm-up time. CRTs had less angle viewing dependence and far fewer artifacts (ghosting and latent images). Our questionnaire showed active matrix liquid crystal displays (AMLCD) to be fully acceptable for clinical image viewing. Furthermore, the statistical results show that further testing for new AMLCDs of this type is unwarranted.

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MAYO CLINIC SCOTTSDALE has enhanced its electronic environment with the deployment of a clinical image distribution system. A desktop viewer application¹ provides immediate access throughout the campus of images and reports from the radiology picture archiving and communication system (PACS).^{2,3} In addition to rapid access to results, clinicians felt that an ergonomic and quality image presentation in the patient setting is essential to eliminate film usage.⁴ Fully deployed, a total of approximately 800 PCs are primarily in three areas: hallways, physician workrooms, and patient examination rooms. We installed flat-panel displays in the workrooms and hallways due to physical constraints of space. However, cathode ray tubes (CRTs) were installed in the patient examination rooms. The flat-panel devices were active matrix liquid crystal displays (AMLCDs), which have an enhanced viewing angle. AMLCD advantages included shorter depth; lower weight, power consumption, and heat output; ease of installation and handling; and longer warranty. The approximately 100 monitors in use for the Radiology Department PACS are on a quarterly

quality-control program. This would be unacceptable for PC monitor support. The choice of the AMLCD used followed a comparative evaluation of eight different offerings from AMLCD vendors. This earlier testing, which included CRT data from our teleradiology monitors, allowed for the development of our draft standards. The purpose of this presentation is to report our test results of AMLCD for clinical imaging and the advisability of routine testing for new AMLCD devices. See the Appendix for further discussion.

SYSTEMS TESTED AND PHOTOMETERS

Fifteen AMLCD were compared with 15 standard PCs and 15 teleradiology CRTs.

AMLCD

The AMLCD flat-panel models were manufactured by NEC Technologies, Inc, Itasca, IL (#2010, 399 mm × 319 mm and #1810, 179 mm × 134 mm). Operation is possible in either landscape or portrait mode; they are true color, in-putting analog video signals following digital conversion. Resolution is 1,280 × 1,024 (pixel size .31 .32 mm) with a 60-Hz refresh rate.⁵ The AMLCD is specified as being normally black, with in-plane switching (IPS). Anti-glare and diffusion coverings are provided, but unspecified. Front panel controls allow "brightness" and "contrast" and temperature settings. Backlighting is not described other than providing 150 cd/m² using cold cathode fluorescent lamps. The monitor is warranted for 3 years. Grayscale is a nominal 8 bit, using Matrox (Montreal, Canada) Millennium G2 video cards. No mapping to a perceptually linear grayscale is provided.⁶

CRTs

Two CRT vendors provided comparison: Sony (Park Ridge, NJ) Multiscan 220 GS and 520 GS,

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and Cornerstone (Freemont, CA) CD2192A/03. Monitor sizes are 17, 21, and 20 inches, respectively. Matrix size is $1,280 \times 1,024$ for the Cornerstone and $1,024 \times 768$ for the Sony CRTs. The same graphics card was used. No anti-glare coverings were provided.

Test Equipment and Software

A Minolta (Ramsey, NJ) LS-110 Photometer providing a 0.33-degree field of view at 50 cm that covers an approximately 7-mm diameter area (~ 500 pixels), with a stated accuracy of $\pm 2\%$. Also used was a suction-cup photometer by Tektronix (Wilsonville, OR) G-17 LumaColor. Test software included DisplayMate (DisplayMate Technologies, Amherst, NH), Video Electronics Standards Association (VESA Version 1.0) test patterns,⁷ and the Society of Motion Picture and Television Engineers (SMPTE) test pattern (as modified by VESA).⁸

METHODS

Three evaluations of the AMLCDs were made: a basic set of tests for purchase, additional tests to further compare AMLCDs with CRTs, and a clinician user questionnaire. The same set of tests for the CRT products (with the exception of pixel defect testing) were also performed. The methodology followed the recommendations of VESA Flat Panel Display Measurements (FPDM) Standard Working Group⁷ unless otherwise stated. The Suite of Basic Measurements (VESA) was modified to obtain measurements in the "field." It was considered important to measure display performance at actual clinical locations. Following warm-up, all displays were verified as to proper matrix settings, contrast/luminance as per manufacturing recommendations, display size, refresh rate (60 Hz for AMLCDs, 75 Hz for CRTs), color palette, black level, and maximum luminance. Room and hallway lighting levels were as used during patient care. No displays were located such that they might receive direct sunlight. The FPDM Standard provides comprehensive procedures and metrics for assessment of flat-panel display performance. This 281-page document contains more than 50 tests with more than 40 appendices for metrology and technical discussion. Test results reported followed procedures described in detail in the VESA handbook:

- #305-3 Warm-Up Time Measurement (30 minutes to stabilize the display)
- #301-3 Display Set-up (verification of matrix, temperature settings, etc)
- #302-5 Grayscale of Full Screen (primary test for luminance, gamma)
- #303-2 Grille Luminance (test for resolution—must visualize each pixel)
- #303-4 Shadowing (an artifact caused by electronic circuit crossover)
- #303-6 Defective Pixel Analysis (pixel malfunction)
- #304-7 Halation (light leakage in the display)
- #305-2 Residual Image (latent image)

#306 Uniformity (nonuniform response)

#307-1 Viewing Angle Performance (four-point viewing angle)

For public use, the VESA ftp site (<ftp://ftp.vesa.org/pub>) provides the patterns employed. All testing was of grayscale images using the color temperature recommended by the vendor for the display device.

Tests Performed for Purchase Acceptance of AMLCD

Grayscale response was measured using the photometer and 16 incremental pixel value settings at 50 cm as recommended by VESA. Data were analyzed for black level, maximum white level, log-gamma, and number of just noticeable differences (JNDs).⁹ Horizontal and vertical resolution was measured using rows and columns of single pixels ON-OFF. To "pass," separate rows and columns of pixels must be visible throughout the display. Viewing angle performance was recorded at 0, 30, 40, and 50 degrees, both horizontally and vertically. Uniformity was performed at five locations, rather than four, as described in #307-1. The presence of artifacts (shadowing #303-4, defective pixels #303-6, latent images #305-2, and flicker 303-4) was recorded.

Additional Tests Performed to Compare With CRTs

Warm-up tests (#305-3) were compared with CRT products. Halation (the leaking of light through internal reflections) was tested (#304-7). It was desired but considered not possible to accurately field test for reflections.¹⁰⁻¹² The authors simply noted the presence of strong or weak reflections. One AMLCD monitor was left "ON" for 9 months (without calibration beyond initial set-up) to obtain information of backlight luminance stability.

Questionnaire

A questionnaire was developed that provided users with opportunity to remark on keyboard usage, monitor screen (acceptability), and display (image) size. A total of 17 physician staff (cardiology, hematology, and endocrinology) responded.

RESULTS

The warm-up times for the AMLCD and CRT products show that AMLCDs differ little from the CRTs in this metric. In 20 minutes, stability is achieved, but immediate use with any display appears quite acceptable. Figure 1 provides log luminance values versus log pixel values. Black levels, full white, gamma, JNDs, uniformity, and reflectance are given in Table 1, as well as the results of resolution testing. All AMLCD units passed this test. Viewing angle dependence is depicted in Fig 2, and the results of the halation tests are given in Fig 3. The questionnaire was noteworthy in that no difference in quality or preference of display was identified between AMLCD and CRT displays. It was noted that approximately one third of the respondents felt the

CRT displays removed important "workspace" even though these CRTs were placed in countertop corners. Flat panels were also preferred since they could be physically moved to the desired viewing angle during viewing. Although one display presented strong reflections, no note of this was made by the participants.

DISCUSSION

The electronic display environment has until recently been exclusively comprised of CRT monitors based on vacuum technology. In comparison, AMLCD manufacturing is based on thin-film transistor (TFT) technology used in photolithography.

It offers the potential for substantial improvements in the display of images. At least four technologies reduce the effect of ambient light with the displays we tested. These displays are flat. The distance between the liquid crystal forming the pixel and the display front is much less (a few millimeters) in comparison to CRTs (~1.2 cm). This reduces external light from reflecting internally (veiling glare).¹³ Pixels are surrounded by a black matrix of light-absorbing material that reduces the impact of external light.¹⁴ The AMLCD units have an anti-glare matte covering (unspecified), which reflects light in a quasi-Lambertian manner. It was found to substantially eliminate any structured content in a

Table 1. Summary Data of Field Measurements of the Clinical Displays

	VESA	NEC AMLCD	Cornerstone CRT	Sony CRT
Horizontal size		40 cm	40.5 cm	40.5 cm
Vertical size		32 cm	30.5 cm	30.5 cm
Diagonal size		51 cm	51 cm	51 cm
Matrix		1,280 × 1,024	1,280 × 1,024	1,024 × 768
Warm-up time	305-3	20 min	30 min	10 min
Black (cd/m ²)		1.2 ± 0.6	0.7 ± 0.6	0.6 ± 0.3
White (cd/m ²)		177.7 ± 28.8	100.4 ± 1.49	118.4 ± 19.1
Uniformity	306	2.7% ± 1.9	2.7% ± 1.0	1.6 ± 0.7
Gamma	302-5	1.82 ± .10	1.63 ± .005	1.73 ± .06
Resolution	303-2	Pass	Pass	Pass
JNDs		555 ± 25.1	477 ± 1.7	499 ± 26.7
Halation	304-7	1.03% ± 0.3%	3.67% ± 1.26	2.81% ± 0.8%
Shadowing	303-4	0.70%	1.40%	0.60%
Residual image	305-2	Yes	No	No
Pixel loss	303-6	No	No	No

Fig 2. Data show the off-axis viewing of AMLCDs to be less than that of CRTs. Data are for displays in the landscape setting, and are acceptable for clinical viewing.

reflection. These technologies may make it possible for fairly high levels of room illumination during normal diagnostic viewing.¹⁵ The slim profile is helpful in reducing weight and space. Only one individual is needed to replace a display. Lower cost of ownership occurs as a result of this, as well as longer warranty, less heat output (air-conditioning costs), and cabinetry.

Resolution and Gamma

Image quality and luminance was not found to be dependent on the region of the display being viewed (Table 1) with AMLCDs. An image displayed in the upper left was of equal quality to that in the center of the display. We specify a minimum number of JNDs as 256, which is met by these displays. We found the AMLCD gamma to be within 1 SD of our benchmark (teleradiology CRTs) using Barnard's *U* test (Appendix). The

maximum luminance of the AMLCD exceeded that of the CRT, but only marginally. AMLCD displays have been reported to be superior to CRTs for discovery of objects in a scene.¹⁶ It has also been reported that a high ($> 300 \text{ cd/m}^2$) maximum luminance, although preferred, is not statistically significant in viewing clinical images with electronic displays.^{17,18} We note the superiority of AMLCD on the halation test results (Fig 3). This expected finding should aid in the quality of the display especially in dark regions of the image. Contrast loss for CRTs is substantial with ambient light.

Uniformity

AMLCD uniformity is a function of backlight and diffusion filter construction. Strongly diffusing filters can reduce light transmission and build up heat; too little diffusion can cause an unevenly lit

Fig 3. Halation data are substantially improved with the AMLCD. Minimum box size is 2.5% of display diagonal measurement.

display. Our measurements show marginally better uniformity of the AMLCD in comparison to CRTs.

Off-Angle Viewing

Until recently, viewing an AMLCD at an angle resulted in a substantial reduction of image quality and luminance. The NEC AMLCD uses in-plane switching by locating both the ground and common electrodes of the TFT on the back glass substrate.¹⁹ The electrical field so generated improves molecular orientation of the LCD material in a manner favorable to wide-angle light transmissions.¹⁹ Figure 2 compares CRT and AMLCD data for angular viewing. This amount of loss (the off-axis angle equals the loss of luminance, ie, at 30 degrees, a 30% loss of luminance is observed) appears acceptable. We measured radiologist viewing preferences with PACS monitors during periods of consultation with a colleague. Our data suggest that 45 degrees is the maximum angle encountered for two-person viewing.

Artifacts

AMLCDs were found to have substantial artifacts. These were not identified during the questionnaire, but may nevertheless impede the acceptance of these displays for use with primary interpretation.

Shadowing

Shadowing (ghosting or streaking) artifacts were substantial with the tested AMLCD and were not seen with CRTs. These artifacts occurred in the row direction (shadows appeared to the right), but not in the column direction. Cross-talk of the electronic circuitry (leakage capacitance) causes adjacent pixel(s) to undergo an unwanted partial ON. This affects image quality, especially at locations of high contrast.

Pixel Loss

Pixel loss (pixel fixed ON or OFF) was not found with the AMLCDs we tested.

Latent Images

Latent images are "burn-in's" of previously displayed images. We found this artifact to be

pervasive. Its presence appeared inherent in the display technology. LCD material is at a noematic phase that has a molecular directionality between isotropic and a fixed crystalline phase. Once the electrical field of the TFT switches ON, the LCD material responds and becomes oriented in a "twist." Linearly polarized light follows this molecular alignment and twists through 90 degrees, since the "pitch" of the LCD material is large in comparison to the wavelength of the light. The light passes through the polarizer on the front glass substrate and is transmitted to the viewer. Once the voltage is OFF (normally black in this case) a significant remembrance (residual orientation) of this molecular material occurs. Light passes through, resulting in nonuniformity of the display. The significance of this artifact for medical displays is not understood at this time.

Flicker

"Flicker" can be described as any perceptual temporal observation of a normally static image. We observed subtle flickering with CRTs, but not with the AMLCD. No preference was given for type of display.

CONCLUSIONS

The AMLCD units tested had a mean black and white level of 1.2 and 177.7 cd/m², respectively. A mean of 555 JNDs were measured. Our statistical comparison²⁰ described in the Appendix cause us to accept these units as meeting (exceeding) the measured benchmark data. Further testing (upon receipt) of this model for future deployment is not felt warranted. While resolution testing "passed," we noted the presence of shadowing and latent image formation in the display, which degraded image quality. Questionnaire results of 17 clinicians noted no preference for either CRT or AMLCD monitors. AMLCD monitors were readily accepted by clinicians. Improvements in this technology will likely occur and lead to their acceptance for primary interpretation.

APPENDIX

It is not feasible to fully test all clinical displays (AMLCDs and CRTs). However, some assessment^{21,22} appears needed to both validate the clinical image quality^{23,24} and, in the case of AMLCDs, to acceptance test for these expensive displays. Davis and Stewart²⁰ discuss the advisability of using *sequential* testing as opposed to sampled (*nonsequential*) testing. With nonsequential testing, the sample size must be established in advance, using the probability values for type I and II errors, and the desired difference between the means (standard deviation units) as a measure of significance. With this information, the sample size can be calculated using statistical formulae. With sequential testing, the sample size is *not* determined a priori. Rather, the validity of the hypothesis is determined after the results of *each* measurement. However, it requires that normally distributed “benchmark” display data have been obtained *before* testing, even though sample size is not. Our benchmark database was the comprehensive data we collected on the Cornerstone monitors we purchased for teleradiology.

Sequential testing has obvious practical advantages and can take several forms. For our purposes, we chose Bernard’s *U* test.²⁵ Testing was as described above and data were entered into an Excel spreadsheet as it was acquired. Bernard’s *U* was computed and testing stopped when $U < U_0$.

Barnard’s *U* Test of Significance for Sequentially Acquired Data

Risk of finding a significant difference when none exists	α
Risk of not finding a significant difference when one does exist	β
Determine the difference between the means that is significant to the user (units of standard deviations)	D
From the CRT data give a score for the metric (ie, gamma)	x_0
From the AMLCD data, obtain a score for the same metric	x_1
Compute the difference between the AMLCD and the CRT	$x_1 - x_0$
Compute the sum of the differences (T)	$T = \sum x_1 - x_0$
Compute the sum of the squared differences (S)	$S = \sum (x_1 - x_0)^2$
Compute the <i>U</i> statistic	$U = T / \sqrt{S}$
Determine U_0 and U_1 from reference (25)	
If U falls between U_0 and U_1 , then testing must continue	
If $U < U_0$, the null hypothesis is not rejected—display passes	
If $U > U_1$, the alternate hypothesis is not rejected—display fails	

Sequential testing appears helpful in this instance. If the mean value of the test results is the same as or superior to the benchmark data, than the fewest number of tests will be performed. If the measured metric results are quite poor, then the fewest number of tests will also be performed. It is only when the test data computed mean values are at, or close to the mean determined by D, the number of units needed to be tested will increase. For example, for $\alpha, \beta = 0.05$, $D = 0.5$, the minimum number is likely to be 15 units.²⁰ This was found to be the case in our measurements of gamma, maximum white, and JNDs. Our tests of the 15 AMLCD units has shown that further acceptance testing for this product is unwarranted at this time. It has shown to our satisfaction that this model’s performance in the tested population has met our benchmark data.

The AMLCD units do need to be initially “set-up” and we have placed the VESA modified SMPTE test pattern on our intranet for use by users or the Support Call center. This pattern differs from the original SMPTE in that with additional test objects, it has a 4:3 aspect ratio that better fits a computer display. It has also been authorized by SMPTE/VESA for public distribution.

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