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Visual Assessment of Angular Response in Medical Liquid Crystal Displays

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In spite of having non-Lambertian emission, displays based on liquid crystal technology are becoming popular for medical diagnostic work stations. For all liquid crystal displays (LCDs), the contrast performance varies with viewing direction. Accurate measurements of the angular distribution of light emission require expensive instrumentation and extensive expertise. We investigated the possibility of using a test pattern to visually assess the angular response performance of LCDs. We found that this procedure offers the end user of displays a simple, fast, and relatively consistent technique to verify that the viewing angle performance of the display device is within certain acceptable limits.

KEY WORDS: Viewing angle, angular contrast, goniometric measurements, AMLCD, medical display, visual threshold

INTRODUCTION

The detection of subtle image features associated with disease in digital diagnostic imaging is affected by the fidelity of the visualization of the image data. In modern digital radiology operations, active-matrix liquid crystal display (AMLCD) monitors are increasingly being used in work stations, due mostly to decreasing costs and smaller footprint. However, one key deficiency of AMLCDs is its non-Lambertian luminance emission.[1] In a previous work, we characterized the angular emissions of 3-, 5-, and 9-million-pixel AMLCDs[2–4] and found that large departures from the desired luminance response are present even for the high-performance medical AMLCDs included in our studies. All of the monitors considered had similar pixel design because most available medical AMLCDs today utilize in-plane switching liquid crystal cells. These monitors exhibit similar viewing angle characteristics with reasonable performance in the horizontal and vertical angular directions, but degraded performance along the diagonal axes. The response at off-normal diagonal viewing directions are particularly problematic if one observer is inspecting different areas of a large medical display screen (which can reach more than 30 cm on a side). Moreover, this problem worsens when more than one individual is looking at the same image displayed on one screen, a common scenario at teaching medical institutions. In this case, the variations can be more severe because the angles involved are larger.

Display industry laboratories typically report viewing-angle performance by using a single metric corresponding to the angle at which the contrast decreases to 10% of the value for normal (perpendicular) viewing. This metric does not provide insight into the angular changes in contrast across the grayscale. A more useful description is

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one that involves measuring the angular changes of the contrast,[5] and calculating the luminance contrast ($\Delta L/L$) as a function of the gray level or JND index, according to the recommendations of the American Association of Physicists in Medicine Task Group 18.[6] This procedure for analyzing the angular response of non-Lambertian monitors with respect to the luminance response in the perpendicular direction dictated by the monitor luminance calibration, allows us to relate the angular changes in luminance and contrast with the departure from the desired luminance response.

The measurement of angular emission distributions from display devices requires expensive instrumentation and expertise.[3,4] Even with such instrumentation, the measurements are subject to uncertainties; results from one method cannot be reproduced generally with other methods.[7] This, along with the need for properly trained physicists, makes the measurement of the angular characteristics of a medical display not practical in hospitals.

In this study, we investigated a visual method that requires no equipment and little expertise. The method aims to quantify, although grossly, the performance of the display in terms of the viewing angle. The procedure relies on visually assessing a test pattern and comparing the results to a pass/fail criterion determined previously for that display and application. We present data that prove that such a test can be performed and that displays with relatively better viewing angle characteristics pass the test, whereas bad performers fail. We show that the visual assessment can be related to the thresholds of the human visual system, and that the results obtained are consistent among six observers with differing expertise in reading the pattern.

METHODS

Creating a test pattern for the visual assessment of viewing angle performance requires the separation of the capabilities of the graphics board to realize individual gray level steps with enough luminance contrast, and the device performance itself with respect to the angular emissions. In addition, the test pattern interpretation needs to be simple (capable of being performed by a relatively naive observer), fast (should not take more than a few minutes at most), reproducible, and relatively independent of the performance of the visual system of individual observers. Within these requirements, the test pattern or test pattern set needs to accommodate different display sizes and formats.

Displays

This study evaluated five displays, a 5-million-pixel (2,048 × 2,560) monochrome, a 1-million-pixel (1,280 × 1,024) monochrome, and three different 1-million-pixel (1,280 × 1,024) color AMLCDs. The 5-million-pixel system was a 5 MP BARCO (Belgium) medical display AM-SQ21-A9300 with an ASUS A9600SE graphics card (5 MP-mono). The 1-million-pixel monochrome system was a Phillips/FIMI (Italy) LCM18MPNA with a REAL 3D Starfighter graphics card (1 MP-mono). The first 1-million-pixel color display was a Samsung SyncMaster 910T MJ19BSASQ also with the REAL 3D Starfighter graphics card (1 MP-color1). The second 1-million-pixel color display was a medical display V3C-SX19A130 with a NVIDIA GeForce2 MX 100/200 graphics card (1 MP-color3). The third 1-million-pixel color system was an HP2335 P9615A with a REAL3D Starfghter graphics card (1MP-color3). All display systems were calibrated to DICOM (digital imaging and communication in medicine) 3.14 Grayscale Standard Display Function (GSDF).[8]

Test Pattern and Visual Task

The test pattern used in the visual study, depicted in Figure 1(a), consists of nine equally spaced circles in a 3 × 3 array. Each circle contains 12 slices correlated to the hour increments on a clock, with no transition line (or edge) at the five or eleven positions. Eight slices are shaded with different gray levels, whereas four have a gray level equivalent to the background gray level. Starting from the 12 o'clock position in the clockwise direction, the gray levels of the slices are +4, +3, +2, +1, 0, 0, −4, −3, and 2, and 1, 0, and 0 with respect to the background level [Fig. 1(b)]. For each image format of the test pattern needed in this study, the targets were generated with different pixel extensions so that they all had the same physical size in the screen (22.2 mm).

The observer is instructed to view the pattern with the center of the middle circle lined up with the center point between the eyes. The test is performed at three fixed distances from the display screens (20, 40, and 60 cm). At each distance, the test pattern is read at three gray levels (dark, medium, and light) corresponding to 10, 128, and 225 DDL in the 8-bit scale.

The observer is asked to determine how many edges, or transition lines between the slices, are visible in the circle located at the center of the screen. The inspection is then repeated for the circles at the eight other locations (top-center, top-left, top-right, center-left, center-right, bottom-left, bottom-center, and bottom-right) [Fig. 1(a)]. The score (S) of the test pattern is calculated by the ratio of the number of lines seen in an off-normal target, over the number of lines seen in the center target, a number always between 0 and 10.

Making the score relative to the number of lines in the center target separates the complication of poor calibration of displays (when less than 10 lines will be seen in the center target) from the focus of our effort, which is to assess the angular change of contrast.

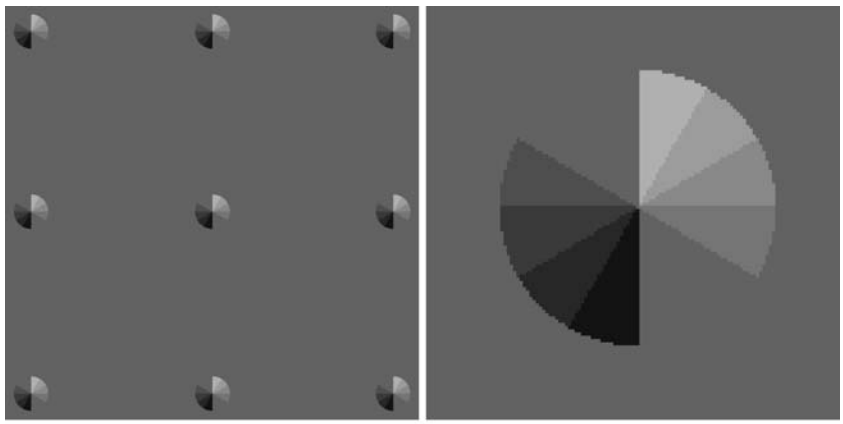

Fig 1. Test pattern for the visual assessment of viewing angle (a). In all display devices tested, the targets (b) were 2.5 cm in diameter and 13.2 cm apart from each other.

The initial criterion for a positive (pass) test result that can be considered is $0.5 < S < 2$. A score less than 0.5 implies that less than half of the lines are seen in the off-normal target. A score of more than 1, although unlikely, implies that off-normal targets would contain more lines than the center target. Scores higher than 1 are possible for displays optimized for off-normal viewing. As a test pattern on a display device provides eight different scores, the one most divergent from 1 is designated as the global score for the pattern at that luminance level on that display.

All display devices noted in Displays were evaluated through our visual technique by six readers in a dark room. The readers were scientists with some but varying experience in visual tasks and varying familiarity with the viewing angle problem in AMLCDs.

Measurements of Angular Contrast

In addition to the visual evaluation, the angular response of the displays was measured by using a goniometric system consisting of a conic collimated luminance probe,[9] a high-gain Si photodiode sensor with an active area of about 5.7 × 5.7 mm, a photopic filter, and a research radiometer (SHD 033 sensor, IL 1700 radiometer; International Light Inc., Newburyport, MA, USA). Strictly speaking, a goniometer is an instrument that measures angles. A goniometric system for viewing angle characterization measures the quantity of interest (in this work, luminance) at different viewing directions by moving either the display or the meter device (the latter in our implementation) to specific positions that correspond to specific viewing angles. The probe was positioned at a constant distance and at a specific angular viewing direction for each display. At each gray level, after a warming time of 10 s the average of 10 consecutive measurements of luminance, 0.5 s apart, was recorded by the software application. The standard deviation of these 10 measurements was typically in the order of 0.01 cd/m^2 or less. Although the probe is highly collimated, the contamination of luminance measurements by stray light is typically in the order of 10^{-59} and depends on the distance between the probe and the emitting surface. That distance was maintained constant.

The probe design ensures that light coming from other regions of the screen corresponding to a different emission angle is either absorbed in the interior chambers painted with flat black paint,[9] or is reflected out into the room. More details on the experimental set-up can be found in the report of Badano and Fifadara.[7] The results were analyzed with respect to their departure from the DICOM Part 3.14 GSDF by computing the luminance contrast ($\Delta L/L$). The expected contrast response was computed from the luminance values[5] associated with the DICOM GSDF (p. 16), Annex B.[8]

Measurements were made from the minimum gray level (0) to the maximum (255) at all 256 levels using a uniform test pattern. As a precaution against contamination by reflected light, all measurements were carried out in a display measurement laboratory with absorptive flat black walls, ceiling, and floor.

RESULTS

Figure 2 shows the results for the visual display test for each of the five displays at varying distances and gray levels. An empty peripheral circle corresponds to no change in the number of lines seen with respect to the center target. This is the case for (a), (b), and (e). As noted earlier, the score for each circle was measured by taking the number of lines visible divided by the lines visible in the center circle. Therefore, the score for each peripheral circle in (a), (b), and (e) is 1. In (c) and (d), there is visible change when looking at targets in different positions. For example, in the top-left corner corresponding to the darkest pattern viewed at 20 cm, only four lines are seen, whereas nine are visible in the center. The corresponding target-

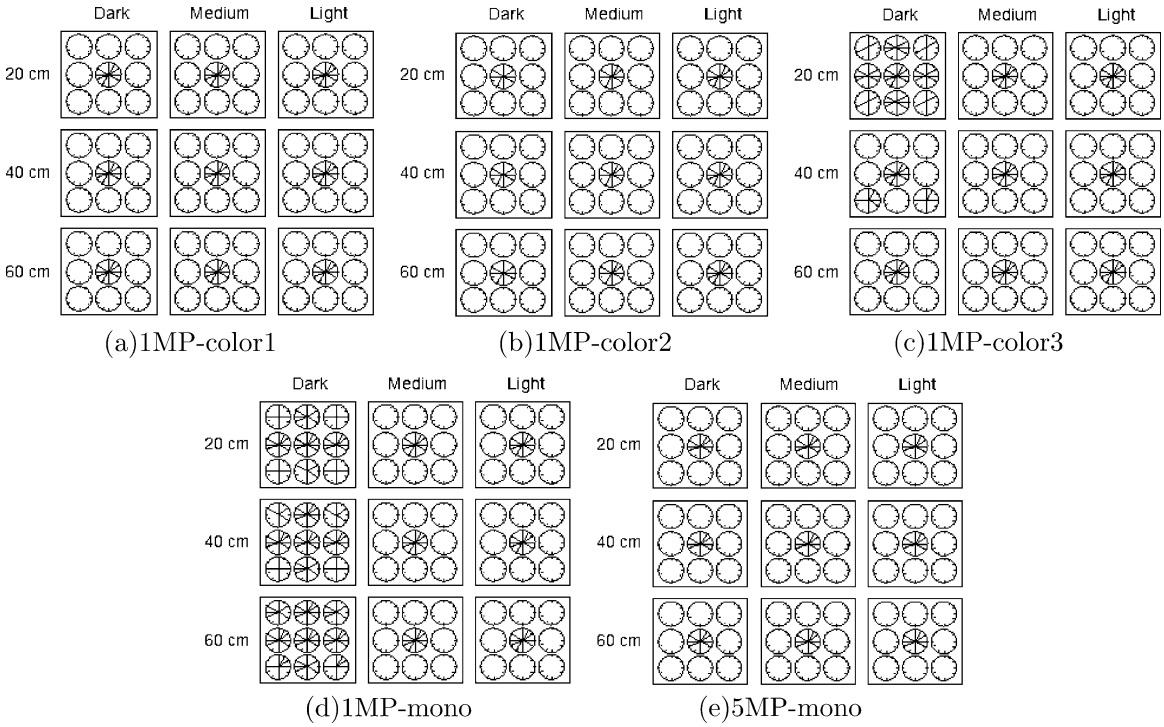

Fig 2. Test pattern results for the five displays, three eye-to-screen distances, and background gray levels. For clarity, an empty peripheral circle represents no visual change in the number of transition lines detected with respect to the center target. Otherwise, the number of lines represents the number of discernable transitions.

specific scores are 0.4. As this score falls below the arbitrarily chosen limit of 0.5, the display fails the test at that location.

The luminance and contrast performance of the display devices taken with the conic collimated luminance probe are shown in Figure 3. The results in terms of scores *S* are shown in Figure 4. Each of the targets is labeled corresponding to their position with respect to the center target: C is the center target, TC is the top-center target, TL is the top-left target, and LC is the left-center target.

Results in Figure 4 demonstrate reasonable agreement between the trends in contrast and the visual assessments. In most cases, both metrics follow the same trend: lower contrast yields lower scores. However, this relationship is complex because the contrast sensitivity is a function of the absolute luminance, which is not constant among the display devices. In particular, for the 5 MP-mono display the luminance in the background of the darkest test pattern was in the order of 1 cd/m^2 at normal viewing and around 10 cd/m^2 at off-normal viewing, the highest among the devices tested in this experiment. We postulate that this higher luminance contributed to a reduction in the sensitivity threshold, making transition lines slightly more visible. The result [see data point "TL" in Fig. 4(a)] seems to diverge from our hypothesis: even though the contrast is reduced for the "TL" target, the score remains high. However, because the 5 MP-mono display has an elevated luminance with respect to all the other devices, the transitions lie above the threshold. For all other data points in Figure 4, a decrease in contrast is followed by a decrease in score value.

Prediction Based on Visual Threshold

After the initial readings of the test pattern, we tested the robustness of the visual assessment by identifying an angle for which we could predict a "pass/fail" outcome based on the measured contrast. For this, we looked at the contrast plots of devices that scored below 0.5. In particular, and as the contrast sensitivity of the human visual system depends on luminance, we focus our analysis at the 10 DDL level, where most of the poor performance were found. With a DDL of 10, luminance

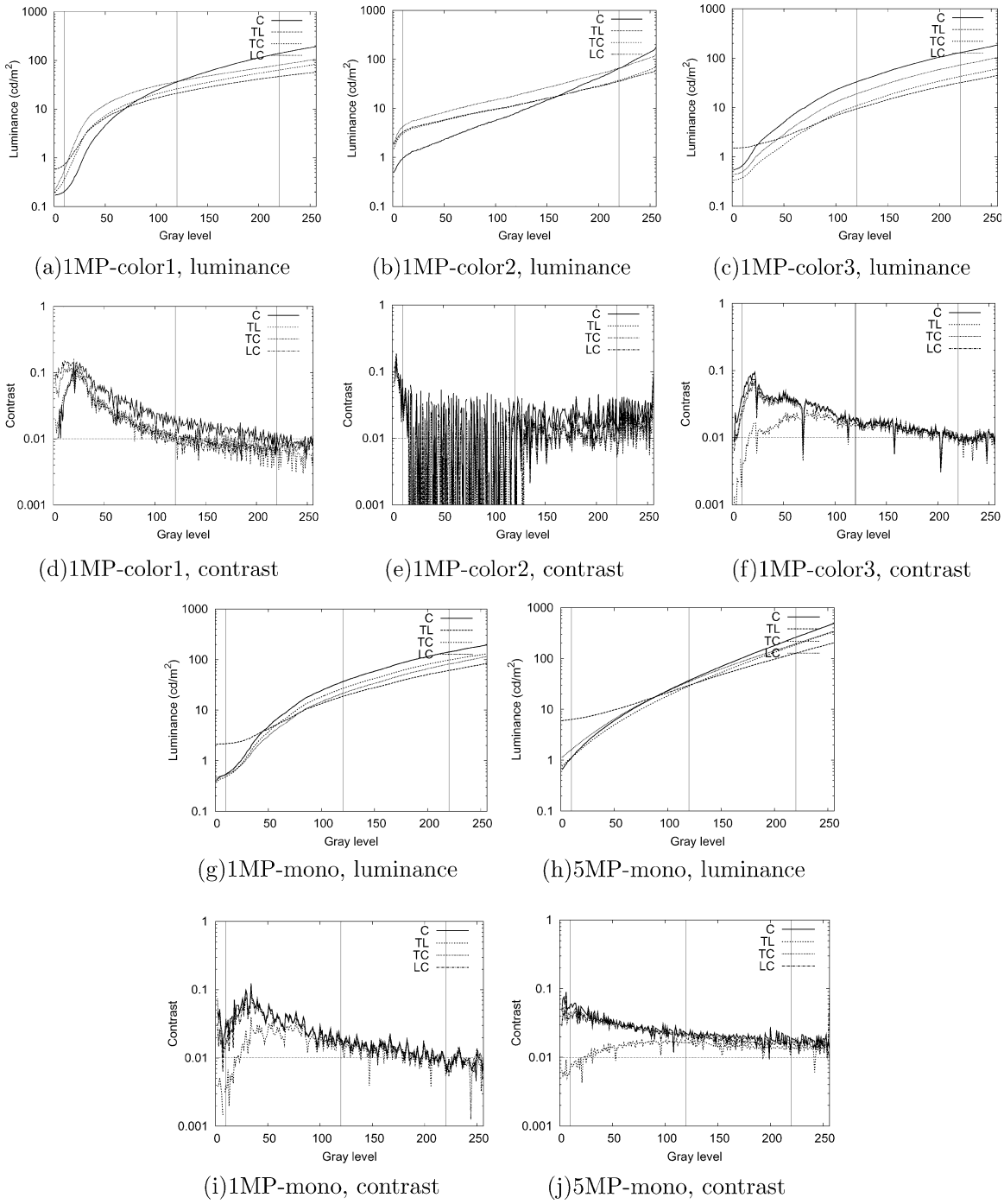

Fig 3. Luminance and contrast response of the five displays for the center, top-center, top-left, and left-center positions (top-left quadrant of the screen) The vertical lines indicate the gray levels of the three test patterns.

in the displays was about 1 cd/m^2, at a range of 0.2–8 cd/m^2. We noted that, at these luminance levels, when the contrast is below 0.01, the visibility of the transitions seems to decrease substantially. We therefore chose to locate an angle for which the contrast is below 0.01. The angle considered was 60° in the diagonal direction toward the top-left corner in the 5 MP medical

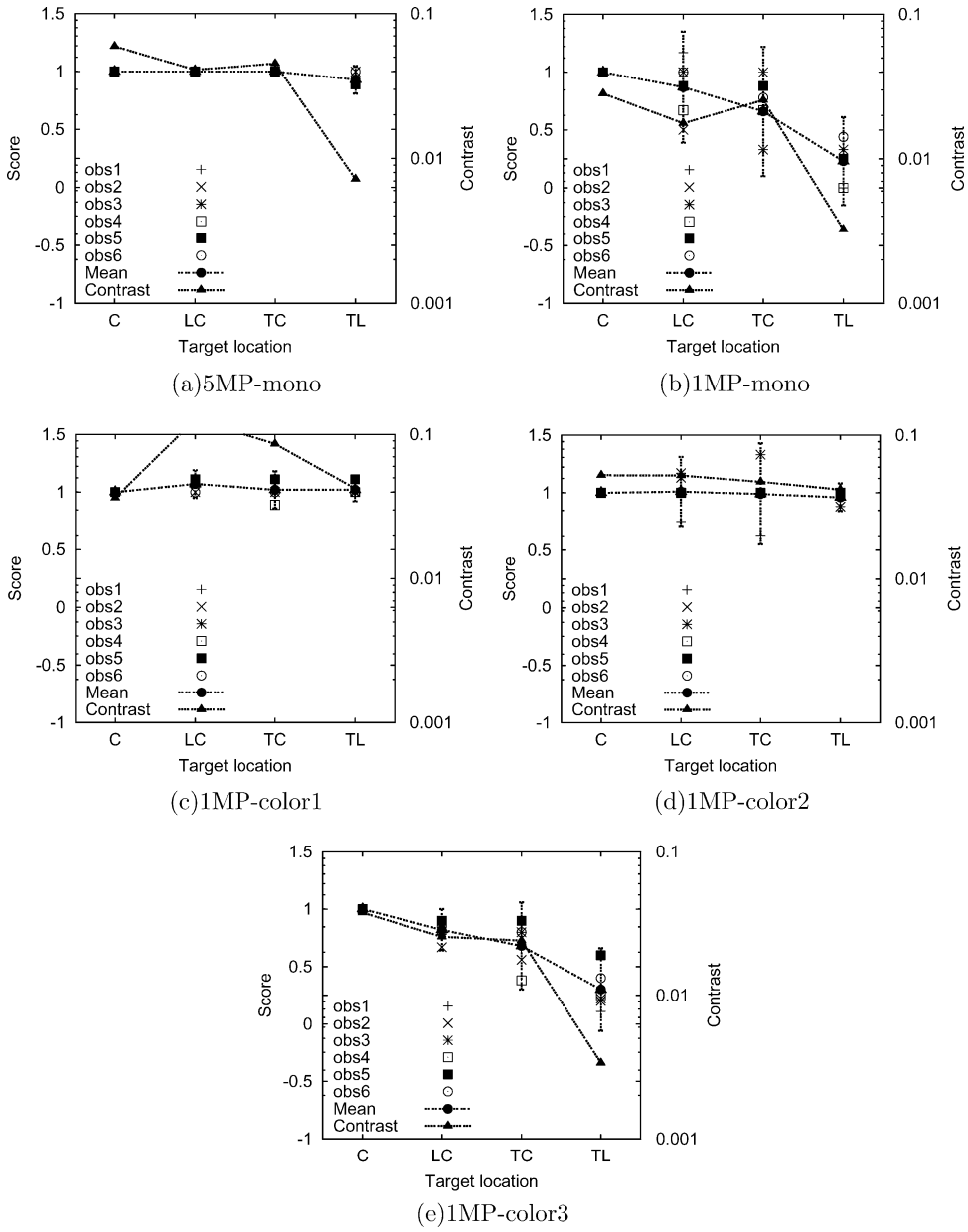

Fig 4. Numeric scores *S* for the six observers and their mean score. The error bars on the mean score are ±2 standard deviation based on the six individual scores. The x-axis is labeled with the positions on the targets with respect to the center target: C is the center target, TC is the top-center target, TL is the top-left target, LC is the left-center target. The left side of the graphs also displays the contrast scale.

display. The luminance and contrast plots for that angle and display are shown in Figure 5.

If our approach of relating the measured contrast to the visibility of the transitions is correct, the contrast of the slices should become infrathreshold and the corresponding scores should become lower than 0.5.

The results of the test pattern readings for three observers are shown in Figure 6. The corresponding scores are 0.67, 0.56, and 0.56. This result, strictly speaking, is a "pass" score (greater than 0.5). This result suggests that a "pass/fail" criterion of 0.5 is too relaxed and a value of 0.75 might be more appropriate. A score of 0.75 implies that

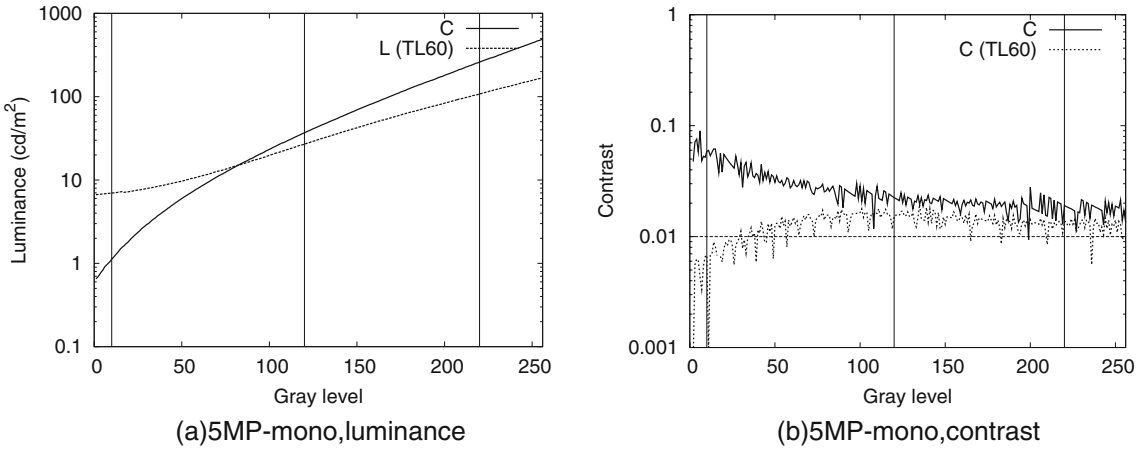

Fig 5. Luminance and contrast response of the five MP-mono display at 60° toward the top-left screen corner.

only two (or three) transition lines are missing in the off-normal target.

Observer Variability

The scores for a subset of the targets at the darkest luminance level are shown graphically in Figure 7 and numerically in Figure 4. The variability is small for high performing displays and larger for displays with poor angular emission characteristics. If we choose a threshold value for the "pass/fail" decision of 0.5, not all observers agree. However, for a threshold value of $S = 0.75$, all observers agree on "pass/fail" scores, with the devices in consensus for the top-left target location. This observation suggests that the use of the criterion $0.75 < S < 1.25$ leads to less variability between multiple observer results.

DISCUSSION

This visual testing method was designed as a simplistic and inexpensive means to test display monitors for viewing angle characteristics in clinical environments. Results of the visual assessment described in this article are not only influenced by the display viewing angle performance, but also by the type of video graphics card within each system. The number of lines visible in the center target is also dependent on the quality of the graphics card. The 5 MP-mono was only able to display nine of the possible ten gray level lines, whereas the 1 MP-mono displayed fewer lines because of the quality of the graphics card. The relative scoring procedure corrects for the difference in graphics boards in different systems. The scores are therefore dependent on the number of lines in the center target only for normalization of the results in terms of the intrinsic grayscale resolution of the system in normal viewing.

This study suggests that for a threshold score of 0.75, the results of the visual assessment of viewing angle performance are reliable and can be correlated to the physical performance of the display device. Validation of the results of this study, for instance, in a clinical application, could provide more insight into the usefulness of the approach.

One limitation of our approach lies in the situation where transition lines that are seen in a target can not be seen in the center target. This would suggest that the contrast in the off-normal

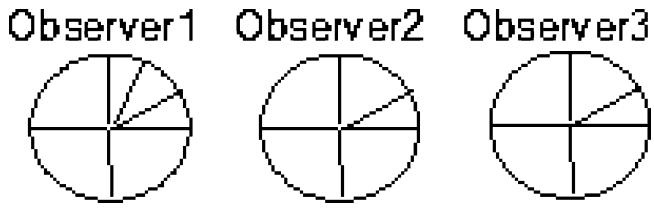

Fig 6. Visual results for the three observers in the prediction experiment at 60° for the 5 MP-mono display.

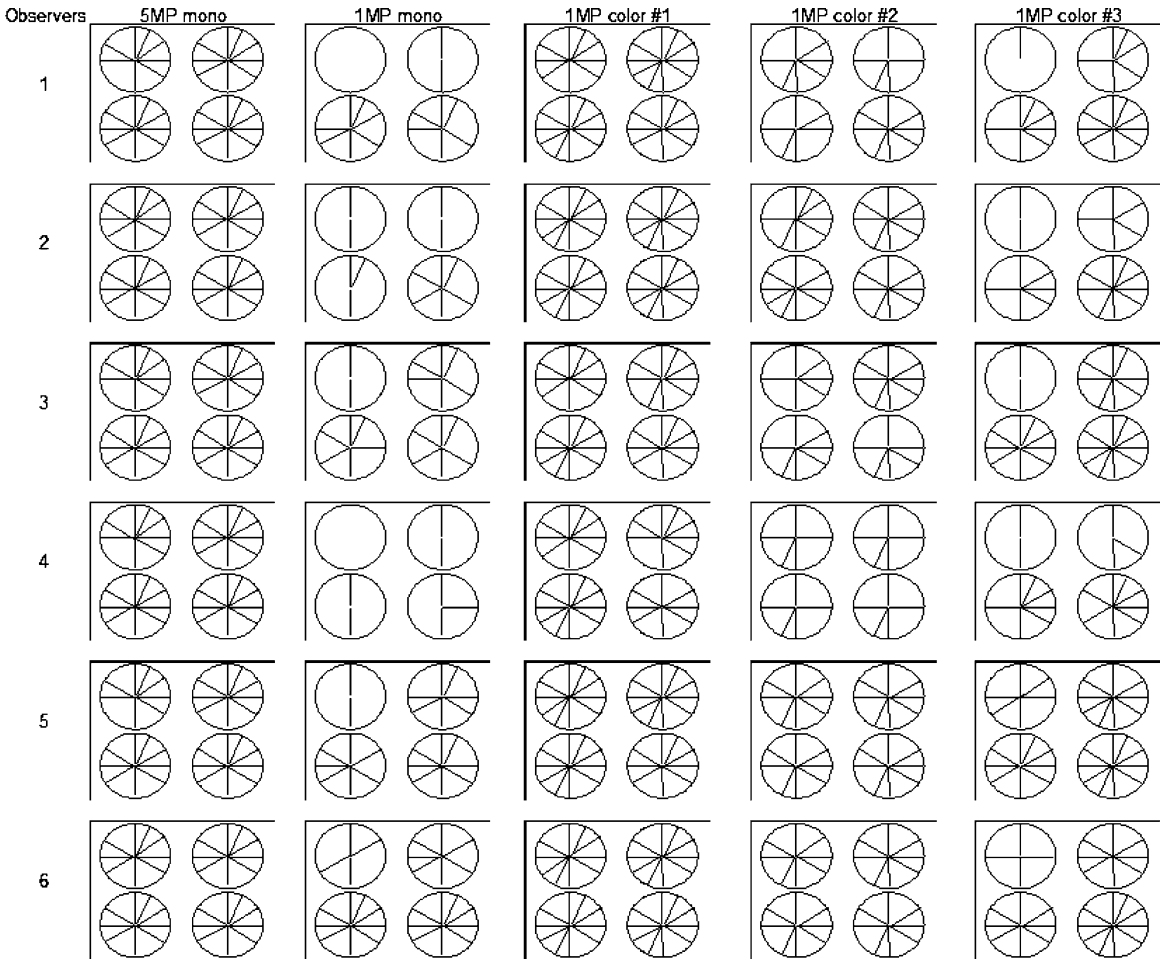

Fig 7. Test pattern readings of the upper left quadrant screen area encompassing the center target and three other targets, for the five displays and six observers participating in our study.

viewing direction is higher than the contrast for normal viewing. Although this situation is possible, it is rarely seen in medical AMLCDs. This problem results in confusing scoring. It can be addressed by modifying the score rules so that only lines that are visible in the center are counted for scoring purposes. For the display devices tested in this study, this modified scoring technique offered no significant difference with respect to our initial scoring rule.

Although this visual assessment is not directly related to the performance of an observer in a specific visual task, the observer scores seem to track with the changes in physical contrast with viewing direction. In this respect, the technique described in this article is only applicable for the coarse classification of display devices based on their viewing angle characteristics. The visual assessment technique should not be used to determine if a display device is suitable for use in a specific imaging modality. Rather, it should be used to assess the quality of the device and compare that to the desired specifications. The technique is therefore useful to discriminate display devices that have very poor viewing angle performance (scores lower than 0.5) and consequently might not be suitable for diagnostic viewing.

The technique is also useful in understanding and quantifying the changes in contrast and visibility when display devices are used in a particular configuration with respect to the observer. In such cases, we suggest that the method be slightly modified as follows. For circumstances where the display device will be used in a way that forces the

observer to always be at an angle (for instance, in a four-monitor work station with displays aligned horizontally), the initial reading, which in the original method is performed with the observer centered with respect to the screen and viewing in the perpendicular direction, could be performed at the angle defined by the typical viewing arrangement. Then, the observer could read the other targets and a score calculated with reference to the center target. The application of this suggested modification in the methodology needs to be further studied and validated.

The diagnostic performance of modalities relying on display devices for interpretation or review is affected by the display image quality. Our method to analyze the viewing angle dependence of contrast in medical LCDs without expensive instrumentation proves useful, particularly in acceptance testing of medical imaging display systems. The procedure described in this article offers the end user of displays a simple, fast, and consistent (within the limits of subjective evaluations involving human observers) technique to verify that the viewing angle performance of the display device is within certain acceptable limits.

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