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Effect of Viewing Angle on Luminance and Contrast for a Five-Million-Pixel Monochrome Display and a Nine-Million-Pixel Color Liquid Crystal Display

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Digital imaging systems used in radiology rely on electronic display devices to present images to human observers. Active-matrix liquid crystal displays (AMLCDs) continue to improve and are beginning to be considered for diagnostic image display. In spite of recent progress, AMLCDs are characterized by a change in luminance and contrast response with changes in viewing direction. In this article, we characterize high pixel density AMLCDs (a five-million-pixel monochrome display and a nine-million-pixel color display) in terms of the effect of viewing angle on their luminance and contrast response. We measured angular luminance profiles using a custom-made computer-controlled goniometric instrument and a conoscopic Fourier-optics instrument. We show the angular luminance response as a function of viewing angle, as well as the departure of the measured contrast from the desired response. Our findings indicate small differences between the five-million-pixel (5 MP) and the nine-million-pixel (9 MP) AMLCDs. The 9 MP shows lower variance in contrast with changes in viewing angle, whereas the 5 MP provides a slightly better GSDF compliance for off-normal viewing.

KEY WORDS: Active-matrix liquid crystal display (AMLCD), viewing angle, gray-scale display function (GSDF)

IN SOFTCOPY VIEWING ENVIRONMENTS, the display of medical images has traditionally been done with cathode ray tube (CRT) devices. As flat panel displays, including active-matrix liquid crystal displays (AMLCDs), become more popular in the mass markets, there is growing interest in using them in medical displays. While these displays have a number of attractive characteristics as compared to CRTs, they introduce new issues, such as the angular emission characteristics. These new features of display performance need to be investigated and understood in the context of a medical imaging application.

Angular emission characteristics refer to the changes in the luminance and contrast that occur with varying viewing directions. These changes are caused by the fundamental nature of the liquid crystal material and the technology architecture involved in creating AMLCDs. They differ from angular changes observed in CRT displays in that they are a function of the gray level. These variations in contrast can lead to decrease visibility of a subtle image feature when a single observer inspects the image region in the corners of the display screen. In radiology workstations, this effect translates into undesired changes of the luminance, as determined by the Gray Scale Display Function (GSDF)[1,2] Compliance with a standard GSDF is important for uniform

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image presentation across different display devices. The degradation in display calibration often becomes an issue if the display is not perfectly centered with respect to a radiologist, when an image feature examined is in the corner of the screen, or if multiple radiologists are reviewing a case at the same time, as often happens at teaching institutions.

The viewing-angle performance of AMLCDs is typically reported by measuring their angular luminance and contrast responses. Two of the most common methods used to measure these responses are the goniometric method and the conoscopic or Fourier-optics method. In the goniometric approach, a probe is positioned at different angles with respect to the display, and the luminance is measured for a set of gray levels. The second method relies on Fourier-optics to map luminance intensity to angular luminance using a cooled charged-coupled device camera.[3] This method is the most commonly used technique in display industry laboratories because it can fully characterize a display system in minutes, whereas the goniometric method is considered laborious.

Although monochrome displays are standard in radiology at this time, new possibilities open up as commercial color AMLCDs achieve greater luminance and resolution. In this article we present the viewing angle characteristics of a 5-million-pixel (5 MP) monochrome AMLCD and a 9-million-pixel (9 MP) color AMLCD. Both monitors have been initially calibrated to comply with the DICOM GSDF standard when measured perpendicular to the screen. We chose to investigate the viewing properties of 5MP and 9MP devices because they represent the highest available pixel density AMLCDs that have been considered or are being used in medical imaging workstations. The properties of these two devices can then be compared with previously published angular response of other devices, including lower resolution AMLCDs. In radiology applications such as digital mammography, high-resolution LCDs provide a way to display full field radiographs without panning or zooming. Also, higher pixel density LCDs provide a way to utilize images from multiple modalities within one screen, while color capabilities open up possibilities for modalities that require the use of color coding and color overlays.

METHODS

Two methods were used to obtain information relating to the angular variation in luminance and contrast: the Fourier-optics method and the goniometric method. The Fourier-optics method was used to obtain a complete mapping of the luminance and contrast profiles, while the goniometric method was used to obtain accurate measurements of luminance and contrast at specific viewing angles. The goniometric measurements are especially important for the lower gray levels, as the Fourier-optics method is known to be affected by light contamination in that region.[4]

The Fourier-optics method involves using a commercial measurement system called EZContrast 160D (ELDIM, Herouville St. Clair, France). This system has a special lens that is able to gather light emitted at all angles from a small area on the screen. Light from a spot on the LCD screen is captured by a Fourier lens that delivers it to different locations on a CCD imaging sensor. This sensor measures the intensity arriving at the imaging plane with a correspondence between the location of incidence and the emission angle. Because all of the angular information is obtained by a single sensor, no rotation of the measuring device or display unit is required. The main advantage of this method is its ability to record viewing angle profiles with a single acquisition of the CCD sensor. The measurements from the Fourier-optics system can be visualized using polar plots that represent the angular luminance profile in a circular pattern, where each concentric circle represents a different viewing angle, and the intensity of the shade represents the luminance. Each value as obtained from a different location on the screen is mapped onto the polar plot in terms of its polar and azimuth angles (θ, ϕ). The angular contrast ratio profile is then calculated by combining the viewing angle plots for the maximum and minimum gray level.

The goniometric method requires small-spot luminance measurements made with a photopic probe. We have developed an automatic goniometric setup that consists of a 5-axis motorized stage, a conic collimated luminance probe,[5] a high-gain Si photo-diode 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). In this method, the probe has to be positioned at a constant distance and at a specific angular viewing direction from the test LCD, and the required pattern has to be displayed before luminance measurements are made. After a warming time of 10 s, the average of 10 consecutive measurements of luminance, 0.5 seconds apart, is recorded by the software application. The standard deviation of these 10 measurements is typically in the order of 0.001 cd/m^2. Although the probe is highly collimated, the contamination of luminance measurements by stray light is typically in the order of 10^{-5} and depends on the distance between the probe and the emitting surface.[5] To minimize the contribution of this effect, automatic corrections based on the angle with respect to the display normal are made in order to ensure that, at each angle, the distance between the probe and the test LCD remains constant. The probe design ensures that light coming from other regions of the screen corresponding to a different angle of emission is either absorbed in the interior chambers painted with flat black paint[5] or is reflected out into the room. In the goniometric method, the collimated probe has a measuring spot that depends on the distance between the probe and the screen. In our case, we used a distance of 150 mm, which corresponds to a spot size of about 7 mm. Within that spot, there are in the order of 5000 display pixels. The measured luminance is therefore the average across a large number of pixels.

The test pattern consisted of a uniform field occupying the entire display screen, and measurements were made from the minimum gray level (0) to the maximum (255) in steps of 15. The 5MP display system used for these measurements consisted of a C5i (Beaverton, OR) display, with a R5 (PLANAR Systems, Beaverton, OR) graphics card, and the 9MP display system consisted of a T221 (IBM Corp., Somers, NY) display with a Fire GL4 graphics card (ATI Technologies Inc., Toronto, Ontario, Canada). The 5MP display was calibrated to the manufacturers recommended luminance levels using proprietary software. The minimum and maximum luminance was 0.67 cd/m^2 and 509 cd/m^2. The 9MP display was calibrated with pseudo-gray steps via the VERILUM software (IMAGESMITHS Inc., Gaithersburg, MD), and a measuring probe was used in close proximity to the display face plate. This resulted in a minimum luminance of 1.11 cd/m^2 and a maximum luminance of 380 cd/m^2 to achieve DICOM conformance. Maximizing the dynamic range of the 9MP display was an important factor in calibrating the display. The differences in calibration software prevented us from calibrating the two displays to the same minimum luminance. A detailed discussion of the calibration issues on the 9MP display was presented elsewhere.[2]

Angular luminance variation profiles were acquired for the positive and negative directions of the horizontal, vertical, and diagonal axes, at a perpendicular viewing direction and at an off-normal viewing direction corresponding to 45°, using the goniometric method. We chose to investigate the viewing direction at 45° because it occurs frequently in the diagnostic imaging setting. Consider a dual-head workstation consisting of 2 LCD monitors approximately 40-cm wide placed next to each other. If the observer's eyes are aligned perpendicular to the center of the dual-head combination, at 40 cm distance from the screens, the inspection of the farthest edge on either display would represent a viewing angle of 45°. In this scenario, the corners of each display are at about 35° from the normal viewing direction. The positive and negative directions correspond to changing the viewing direction from perpendicular toward the right (positive) and left (negative) sides of the screen. As a precaution against contamination by light reflection, all measurements reported in this article with both the Fourier-optics and goniometric methods, were carried out in a display measurement laboratory with absorptive flat black walls and a black ceiling and floor.

The results were analyzed with respect to their departure from the GSDF by computing the normalized contrast ($\Delta L/L$) as a function of the just noticeable difference (JND) index and plotting the experimental results along with the expected luminance response with 20% tolerance limits (see Figs 3 and 4). The values of the tolerance limits correspond to those being considered by the American Association of Physicists in Medicine (AAPM) Task Group number 18[6] as recommended values for the acceptance testing and clinical quality control of medical display devices. The expected contrast response was computed from the luminance values associated with the GSDF. We also calculated the point-by-point difference between the measured and desired contrast ($\Delta L/L$ per JND) as well as the corresponding standard deviation of those differences. The variation in the contrast differences can be used as a somewhat simplistic, scalar figure of merit for viewing angle performance.

In addition, we calculated the luminance ratio (LR) as the maximum over the minimum luminance. We report on the variations of LR with different viewing conditions. The significance of angular changes of LR is explained next. A reduction in the LR is associated with a reduction in the number of just-noticeable-differences, or small luminance increments, that correspond to increments in the image data pixel values. This reduction can translate into a range of gray levels in the image data that are mapped to the same luminance value in the screen, with the corresponding reduction in display or luminance contrast.

RESULTS

Figure 1a and b shows the angular luminance variation response for the 5MP display. Figure 1a shows the results from the positive and negative directions of the horizontal and vertical axes, whereas Figure 1b shows the results for the positive and negative directions of the diagonal axis. Figure 2a and b shows the angular luminance variation response for the 9MP display. Figure 2a shows the results from the positive and negative directions of the horizontal and vertical axes, whereas Figure 2b shows the results for the positive and negative directions of the diagonal axis. Additionally, all four plots include the results obtained for the perpendicular or normal viewing direction, as a guide to the extent of differences between different angles. A similar pattern is seen for both display devices in terms of their angular luminance response in each axis. For the diagonal axis, all the measurements start at a slightly higher luminance value at the lower gray levels but eventually converge to the perpendicular values. In the case of the horizontal and vertical axes, the luminance values are seen to be similar and much closer to the normal values at the lower gray levels, and the difference continues

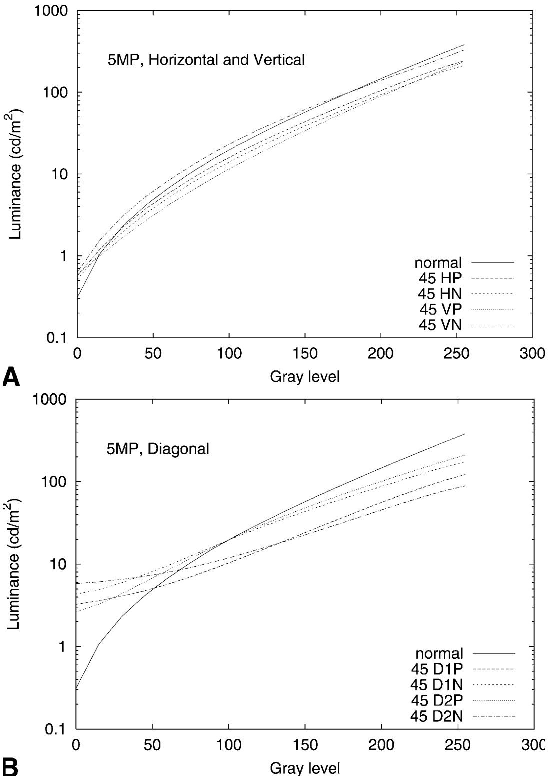

Fig 1. Luminance response as a function of viewing angle for the 5MP display in the horizontal and vertical (a) and diagonal axes (b). HP: horizontal positive; VN: vertical negative.

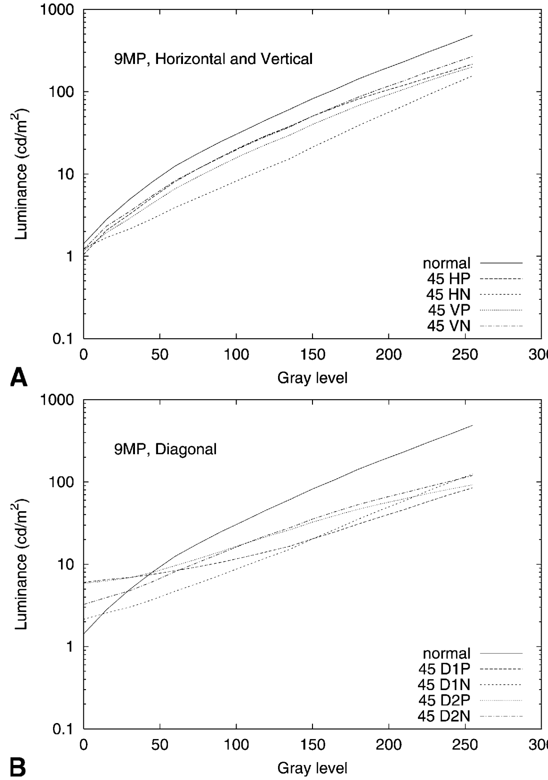

Fig 2. Luminance response as a function of viewing angle for the 9MP display in the horizontal and vertical (a) and diagonal axes (b).

to decrease with increasing gray levels. As a whole, the angular luminance response in the vertical and horizontal axes is seen to be much better than in the diagonal axis for both systems. Comparing the plots for the two display systems, the differences between the perpendicular and each individual axis are smaller for the 9MP display at the minimum luminance, and are slightly larger otherwise.

Figures 3 and 4 show the contrast response results for the 5MP and 9MP displays, in terms of the normalized contrast ($\Delta L/L$) and the JND index, for each measured viewing direction. Additionally, the plots include the expected response of a DICOM-compliant system (GSDF), and the recommended 20% tolerance limits. The results displayed in Figures 3a and 4a show that, overall, the performance of the 5MP display stays within the 20% tolerance limits, whereas the values for the 9MP display do not fall within this range for the horizontal negative (HN) viewing direction (45 HN). Figure 3b and 4b prove that both displays perform better in the horizontal and vertical directions than in the diagonals.

Tables 1 and 2 show the comparison of the LR characteristics for the 5MP and 9MP displays, respectively. Each display is characterized in terms of the angles required (θ) to achieve a drop of 10%, 20%, and 50% from the maximum measured LR in each of the eight viewing directions. Similarly to the luminance response, the angular response in the horizontal and vertical directions is better than that in the diagonal directions. Comparing Tables 1 and 2 shows that the angular LR response of the 9MP display is better than that of the 5MP display, because the angle required in every viewing direction, for every percentage drop in luminance ratio, is larger for the 9MP LCD.

Figures 5 and 6 show the angular luminance and LR responses for the 5MP display. Figure 5 represents the angular luminance response

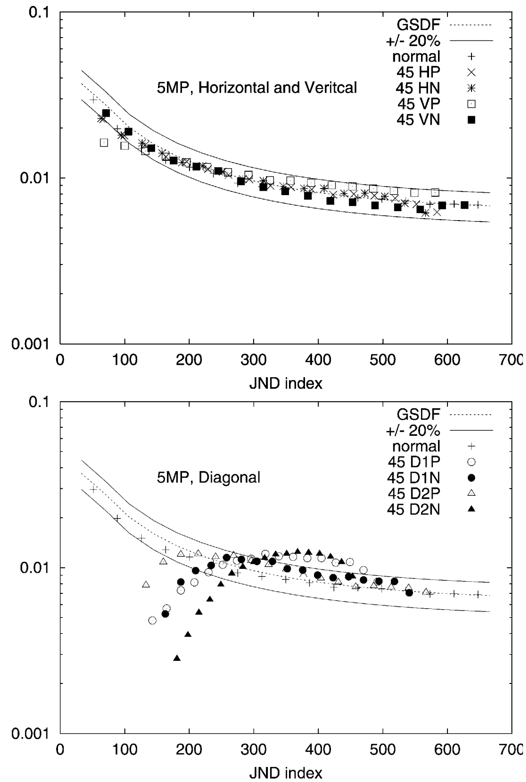

Fig 3. Contrast response as a function of viewing angle for the 5MP display in the horizontal and vertical (a) and diagonal axes (b).

at the highest measured gray level (242) in (a) and at the lowest measured gray level (0) in (b). Both plots show that the intensity of each measurement is highest for the maximum and lowest for the minimum near the center, but that it deteriorates with the viewing angle. Figure 6 is a luminance ratio plot for the 5MP display and serves as a graphical illustration of the data presented in Table 1, whereby the borderlines now indicate each percentage drop in contrast ratio, and the concentric circles represent the viewing angle coordinates.

Table 3 shows the comparison of the standard deviation of the difference between the desired contrast and the measured contrast at each of the JND indices reported. The results show that the standard deviation for every viewing direction, except the horizontal-negative, is smaller for 9MP display. The largest standard deviation for 5MP display is 0.011 and occurs in one of the diagonal viewing directions, whereas the largest standard deviation for the 9MP is 0.0076 and occurs in one of the diagonal viewing directions.

Table 1. Comparison of Luminance Ratio (LR) Characteristics for the 5MP Display

Axis	θLR = 0.5(.)	θLR = 0.2(.)	θLR = 0.1(.)
HP	31	—	—
HN	32	—	—
VP	42	—	—
VN	38	—	—
D1P	20	31	39
D1N	25	37	46
D2P	25	36	44
D2N	21	30	40

Note: The data represent the angle (θ) along every axis needed to achieve a particular drop in the luminance ratio. The maximum luminance ratio is 782.HP: horizontal positive; HN: horizontal negative;VP: vertical positive; VN: vertical negative.

Table 2. Comparison of Luminance Ratio (LR) Characterisitics for the 9MP Display

Axis	θLR = 0.5(.)	θLR = 0.2(.)	θLR = 0.1(.)
HP	45	—	—
HN	41	—	—
VP	48	—	—
VN	45	—	—
D1P	22	39	51
D1N	30	49	60
D2P	36	49	60
D2N	34	45	58

Note: The data represent the angle along every axis to achieve a particular drop in the luminance ratio. The maximum luminance ratio is 367.

DISCUSSION

In this article, we report results obtained with two commonly used methods for measuring the angular luminance and contrast responses: the goniometric and the Fourier-optics methods. The Fourier-optics method is commonly used in display industry laboratories because it can fully characterize the viewing angle performance of a display device in minutes. The goniometric method, considered more laborious, is also more accurate, especially in the low luminance range.[4] The results described here are not affected strongly by the differences between the two experimental methods. To ensure this, the goniometric method was used to measure all data presented in the luminance and contrast response plots (see Figs. 1–4), while the

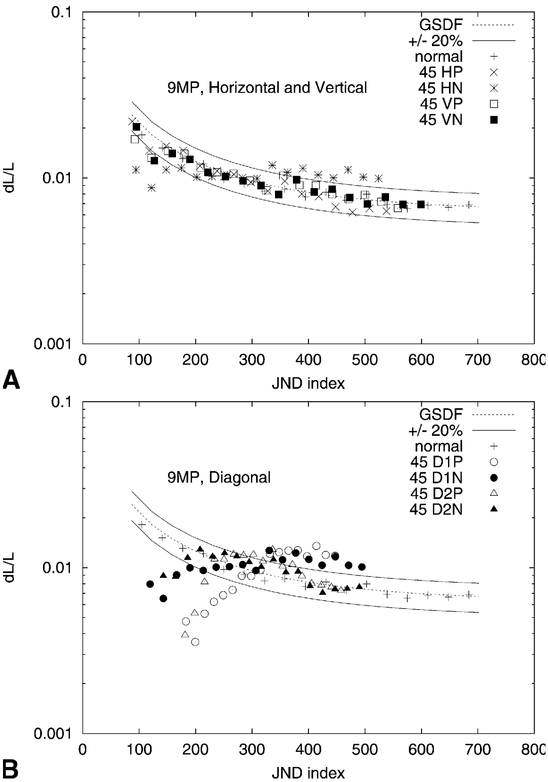

Fig 4. Contrast response as a function of viewing angle for the 9MP display in the horizontal and vertical (a) and diagonal axes (b).

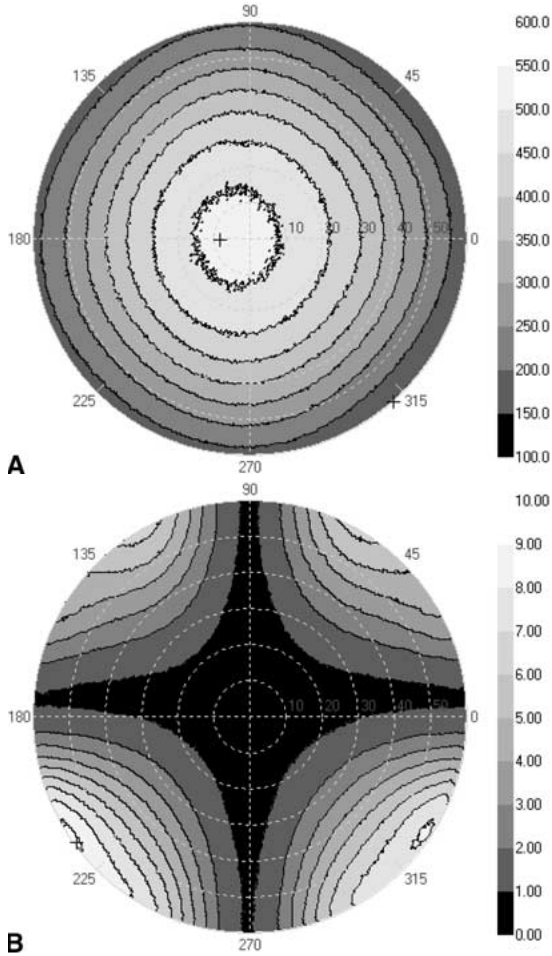

Fig 5. Luminance response for the 5MP display at the highest measured gray level (a) and the lowest measured gray level (b). The angles around the border correspond to the values for ï†, whereas the angles on the horizontal axis correspond to values for θ. The luminance at (0,0) is 509 cd/m^2 for (a) and 0.67 cd/m^2 for (b).

Fourier-optics method was used only to obtain the angular response polar plots for the 5MP display (see Figs. 5 and 6) and the luminance ratio characteristics data presented in Tables 1 and 2.

Our comparison suggests that there are differences in the viewing angle characteristics of the 5MP and 9MP displays. However, we note that the luminance range of both systems as used in the experiments were not the same. A change in the luminance range of an AMLCD can result in improved viewing angle performance, as has been shown elsewhere.[3] Our study was focused on comparing the monitors, following the directions of the manufacturers with respect to perpendicular calibration. Therefore, our results do not provide a general comparison of the two devices under any calibration and luminance range presentation strategy.

Our results show that although the 9MP display has an overall better angular contrast response, the angular luminance response is only better for small luminance values. For higher luminance values, the 5MP display has a smaller deviation from the expected response. The results also show that along the horizontal and vertical directions, the 5MP display performs slightly better than the 9MP display, by having more of its values within the 20% tolerance limits. The opposite is true in the diagonal directions, where the 9MP display outperforms the 5MP display. The results presented in Table 3 also suggest that the changes along each of the viewing direction axes is similar for the two displays. Interestingly, the standard deviations corresponding to the 9MP

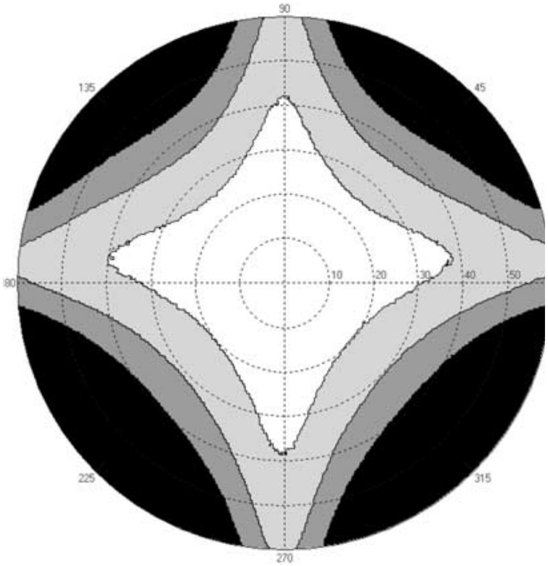

Fig 6. Full-angle luminance ratio plot for the 5MP display. The borders between gray levels correspond to a particular drop in the luminance ratio (see scale), and the concentric circles represent the polar angle of the viewing direction.

Table 3. Comparison of the Standard Deviation of the Difference between Desired and Measured Contrast at Different Viewing Directions for the 5MP and 9MP Displays

Axis	5MP	9MP
N	0.0028	0.0009
HP	0.0042	0.0020
HN	0.0042	0.0049
VP	0.0060	0.0027
VN	0.0035	0.0022
D1P	0.0101	0.0076
D1N	0.0089	0.0060
D2P	0.0079	0.0064
D2N	0.0110	0.0048

N: perpendicular direction

display are most often smaller than for the 5MP. This finding contradicts some of the previous rankings of the systems based on luminance ratio values, and it suggests that a single scalar does not capture all of the luminance and contrast changes associated with different viewing directions.

CONCLUSIONS

We measured the angular emission characteristics of two AMLCDs of potential use in medical imaging. Our findings indicate that the differences between the 5MP and 9MP AMLCDs are small. The angular emission characteristics of the two systems are similar, with differences in the order of less than 10°, for the angles at which the luminance ratio drops to 10%, 20%, and 50% of the maximum. This comparison relates only to angular emission profiles and was not designed to evaluate overall image quality of the display systems. We cannot determine without further clinical trials whether these differences have a significant impact on radiologist performance in a clinical image feature detection tasks. The advantages in terms of economics and potential use of color merit the further investigation of new AMLCD devices.

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