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Liquid-crystal displays for medical imaging: a discussion of monochrome versus color

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ABSTRACT

A common view is that color displays cannot match the performance of monochrome displays, normally used for diagnostic x-ray imaging. This view is based largely on historical experience with cathode-ray tube (CRT) displays, and does not apply in the same way to liquid-crystal displays (LCDs). Recent advances in color LCD technology have considerably narrowed performance differences with monochrome LCDs for medical applications. The most significant performance advantage of monochrome LCDs is higher luminance, a concern for use under bright ambient conditions. LCD luminance is limited primarily by backlight design, yet to be optimized for color LCDs for medical applications. Monochrome LCDs have inherently higher contrast than color LCDs, but this is not a major advantage under most conditions. There is no practical difference in luminance precision between color and monochrome LCDs, with a slight theoretical advantage for color. Color LCDs can provide visualization and productivity enhancement for medical applications, using digital drive from standard commercial graphics cards. The desktop computer market for color LCDs far exceeds the medical monitor market, with an economy of scale. The performance-to-price ratio for color LCDs is much higher than monochrome, and warrants re-evaluation for medical applications.

Keywords: Liquid crystal displays, LCD, medical imaging, color, monochrome, calibration, viewing angle, DICOM.

1. INTRODUCTION

Unlike the image-acquisition portion of the medical imaging process, the image processing and presentation portions of the process utilize what should be considered standard computer and display technology. Recently, there has been a proliferation of monochrome liquid-crystal displays (LCDs) for medical applications, displacing monochrome cathode-ray tube (CRT) displays. Some advantages of LCDs over CRTs include sharp pixel definition with high local-area contrast, high brightness, digital drive, calibration stability, low power, small footprint, and long lifetime. LCD disadvantages, such as variation of characteristics with viewing angle, have not significantly inhibited the acceptance of this technology by the medical community. In part because of customer expectations and experience with monochrome CRTs, monochrome LCDs have been targeted as replacement units. However, the performance of color LCD technology has grown considerably, and there is a need for re-evaluation. Presently, the highest resolution LCD available on the market is color, not monochrome. Color LCD monitors, driven by standard digital graphics cards, have large potential utility in a workflow environment involving both medical image and office applications. A practical evaluation of display performance should include how this performance relates to the imaging system, applications, and user environment. Considerations should include issues such as flexible use, multi-monitor versus single monitor operation, portrait versus landscape mode, open off-the-shelf versus custom proprietary solutions, and total cost-of-ownership.

Most medical imaging applications utilize grayscale images, requiring only monochromatic display. However, there is a growing number of medical modalities which either require color display or can be enhanced through the judicious use of color. Some examples of the use of color to enhance grayscale imaging applications include annotation and highlighting, pseudo-color coding for different parameters or conditions, and computer-aided detection. The information bandwidth of the human visual system is enormous, and taking advantage of color to enhance perception and cognition should be part of an overall strategy to improve performance and utility of medical imaging systems. Another important consideration for color is that for at least some of the time, radiologists and other users are performing tasks on medical monitors which do not involve image analysis- such as locating and editing patient records, filing or distributing images, analysis, administrative tasks, word processing, spreadsheet, and browser applications. For these standard applications, performance and utility are clearly enhanced with the use of color.

There are fundamental reasons why LCD characteristics such as maximum luminance and contrast ratio, are more difficult to achieve with color than with monochrome versions of the same array glass module. These characteristics should be put in perspective with others. For example, LCDs can have very high pixel density and local area contrast, which can have a stronger impact on image quality than many other display characteristics. Theoretically, color pixels offer fundamentally finer control of luminance than monochrome pixels due to the different luminance of color RGB subpixels. This paper discusses technical features and tradeoffs between color and monochrome LCDs, and relates these to human visual system characteristics and practical operational environments.

2. RESOLUTION, PIXEL FORMAT, AND SCREEN SIZE

Displays with high information content are needed for medical imaging because many modalities utilize images with a large number of pixels. With a well-designed application and user interface, the image information content is proportional to the number of pixels. The term "resolution" for displays should refer to the resolvable pixel density in a rendered image on the display screen, in terms such as pixels per inch (ppi), pixel pitch (mm), or line pairs per millimeter. Pixel count refers to the total number of pixels on the screen, but the term "resolution" is often used in place of pixel count. For LCDs, the number of addressable pixels is essentially the same as the number of resolvable pixels. For CRT displays, the number of resolvable pixels can be much lower than the number of addressable pixels, especially when the image contrast is low. Pixel format describes the screen aspect ratio and orientation (landscape or portrait).

Increased display pixel density can have a very positive impact on image quality, if the capture, data processing and rendering are designed to take advantage of the capabilities of the display. The perceived image data may be limited by the combination of pixel density, observer visual acuity, and viewing distance. Normal Snellen 20/20 visual acuity corresponds to the ability to discriminate high-contrast image features which span one arc minute of subtended angle. 20/20 acuity is an average over the population; eyeglasses typically correct vision to this acuity or better. Vernier acuity refers to the ability to discriminate small kinks in otherwise straight lines, much more sensitive than normal visual acuity- kinks as small as a few arc seconds can be discerned. Most natural images do not require vernier acuity for interpretation. However, pixel "block" artifacts in natural images and text letter "jaggies" are noticeable when the viewing angle subtended by each pixel is above that which can be resolved by the user. Most monochrome LCDs use the same stripe geometry subpixels as color LCDs, with one square pixel comprised of three rectangular subpixels arranged in vertical stripes. For natural images, the block artifacts for color and monochrome LCDs are about the same, however for text and line art images, color displays can exhibit color fringing artifacts. These effects diminish with increasing pixel density.

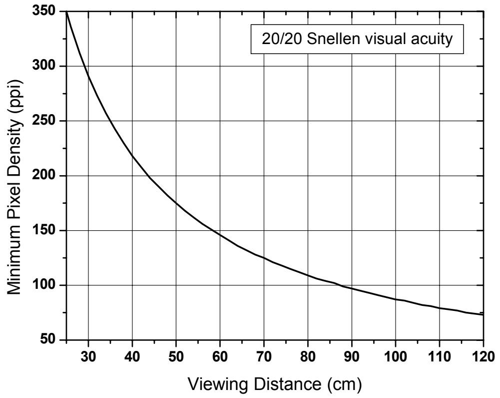

Fig. 1. Required pixel density and viewing distance.

Viewing distance is an important consideration for LCDs, which have sharp pixels. As an observer moves closer to the screen, the individual pixels become more noticeable, but at very short viewing distances, it becomes difficult to focus on the image. The minimal accommodation distance increases with subject age [1], with a typical distance of 25 cm provided by corrective eyeglasses. For reading text, the typical viewing distance is between 40 and 50 cm. In diagnostic reading, viewing distances can vary as the radiologist determines the image "gestalt", or perhaps uses a hand-held magnifier to closely examine film on a light box. Fig. 1 shows the minimum pixel density versus viewing distance to avoid visible pixel block artifacts for a normal visual acuity of 20/20. Displays with pixel densities less than about 175 ppi are compromising image quality when viewed at normal reading distances, if the image contains high local contrast pixel data. For a display pixel density of 100 ppi, there is no incentive for an observer to view the display at distances closer than about 80 cm, because there is no increase in perceived image quality or information content. This is an important ergonomic factor. For viewing film or other high-quality image print media, the normal experience is that as the user moves closer to the image, more detail can be seen. To enable this normal experience by extending the useful viewing distance downward to below 40 cm, the display pixel density should be in the range 200 to 300 ppi.

For entertainment applications, it is known that filling the horizontal visual field enhances the viewing experience, and it is natural for users to prefer as large a screen size as possible. For detailed work with images, there are ergonomic factors which limit the utility of screens sizes larger than about 35 inches in diagonal. Table 1 summarizes characteristics of typical medical-grade LCD monitors, using dual-domain In-Plane-Switching (IPS) liquid-crystal mode. The color 9 Mpixel LCD in the table is the IBM T221 display. Typical screen diagonal sizes are 20-22 inches. Often, it is desired to show images which are life-size. None of the screen sizes fully encompass the film size of chest x-rays (14x17 inches), with the closest fit for 3 and 5 Mpixel displays. For mammography with scanned 8x10 inch film, two images can be shown side-by-side on the 9 Mpixel display. Alternatively, since the image pixel count for mammograms can be as large as 6000x4800[2], a major portion of a single image can be shown on the 9 Mpixel display. For 512x512 CT or MRI images, typically an array of 3x4 images is shown on a 3 Mpixel display. For the 9 Mpixel display, a 7x4 array could be shown.

Table 1. Characteristics of "typical-best" high-resolution displays.

Property	Monochrome 5 Mpixel CRT	Monochrome 3 Mpixel LCD	Monochrome 5 Mpixel LCD	Color 9 Mpixel LCD
Pixel format	2560x2048	2048x1536	2560x2048	3840x2400
Addressable pixel density (pixels per inch)	170	123	154	204
Resolvable pixel density (pixels per inch)	~ 85 (horiz) ~ 170 (vert)	123	154	204
Screen diagonal (in)	19.2	20.1	21.3	22.2
Screen area (in)	15.0 x 12.0	16.7 x 12.5	16.6 x 13.3	18.8 x 11.8
Screen area (mm)	38.2 x 30.6	49.3 x 31.7	42.2 x 33.8	47.8 x 29.9
Large-area contrast ratio	~ 600	600-700	600-700	400
Small-area contrast ratio	~ 2	~ 650	~ 650	~ 400
Viewing angle range for contrast > 100:1 (deg)	170 ?	~ 90	~ 90	~ 80
Max luminance (cd/m^2)	600-800	700	700	280
Practical maximum luminance (cd/m^2)	300-500	400-600	400-600	235
Intrinsic drive bit-depth	≤ 10	8	8	8
Luminance precision (bit-depth with dither)	-	> 11	> 11	> 14
Calibration stability	poor	excellent	excellent	excellent
Graphics card support	proprietary	proprietary	proprietary	open
Lifetime (years)	~ 2-3	~ 3-5	~ 3-5	~ 3-5
Relative price	high	high	high	moderate

The screen aspect ratio is important for large-bone and chest x-ray images, where portrait-mode operation may be preferred. Physical rotation of displays is straightforward, however, rotation of the image data can be an issue. For good graphics performance with large images, rotation of the image data must be done in the graphics card hardware, because software rotation is too slow. Hardware rotation is a feature with medical monochrome graphics cards, and emerging as standard with commercial color graphics cards.

Multiple monitors can portray different sets of image data, such as "current" and "previous" images, those taken before and after treatment, or different views within a modality. However, multi-monitors increase system cost and complexity, footprint and power. A single, 9 Mpixel color display in landscape mode can show two smaller, portrait-mode images side-by-side. Showing images side-by-side on a single monitor has two potential benefits over the use of two monitors.. The images can be adjacent, potentially facilitating interpretation. Also, less calibration is needed to closely match two separate monitor characteristics. A key issue is radiologist acceptance of smaller images which may require shorter viewing distances than that typically used with lower resolution displays.

3. CONTRAST

3.1 Contrast Sensitivity Function

The Human Visual System (HVS) can respond over a luminance range spanning over 10 orders of magnitude [1]. However, the useful luminance dynamic range for a single adaptive state of the human visual system is much smaller. The appearance of color and luminance depend upon the HVS adaptive state and the presence of complex stimuli [3,4,5]. Color and luminance appearance is well-understood in print and graphics arts industries, perhaps less so by medical imaging system designers. If fully adapted to the monitor white state, the HVS has limited ability to discern small color or luminance differences between two small adjacent dark regions of an image, and even lesser ability to discern differences between two separated regions of an image. Under some conditions, the useful dynamic range may be as high as 1000:1, while under others can be as low as about 100:1 [6]. One complicating factor is that, dependent upon light scattering into the fovea, the eye can have partial "local adaptation" to features in an image to increase sensitivity.

The Contrast Sensitivity Function (CSF) of the HVS is a measure of the ability of the eye to discriminate small luminance changes in a sine wave pattern target on a uniform background. Very roughly, the contrast sensitivity follows a Weber-law with a just-noticeable luminance ratio ΔL/L fraction of about 1%. Detailed measures of HVS contrast sensitivity over a range of stimuli reveal dependencies on absolute luminance, spatial frequency, target size, wavelength, and other factors. A large body of CSF data was modeled [7], and chosen as the basis for the DICOM calibration standard [8,9]. A log-log plot of the modeled CSF is shown in Fig. 2. There is a rapid falloff of contrast sensitivity at high spatial frequencies, and saturation at high luminance levels. In Fig. 3, a linear plot of CSF is shown, illustrating that at low luminance levels, both contrast and spatial sensitivity are low.

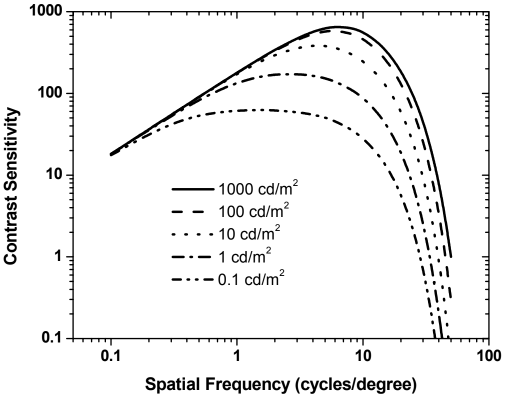

Fig. 2. Log-log plot of HVS CSF.

The intent of calibration is to "perceptually linearize" the monitor luminance versus drive level, through the use of a Grayscale Standard Display Function (GSDF), using a just-noticeable difference (JND) for luminance that can be perceived for a standard stimulus condition. Given the wide range of factors which influence HVS perception in a diagnostic setting, and the restricted range of experimental conditions used for CSF measurements, it can be argued that "perceptual linearization" can be achieved only in an artificial sense [10]. Nevertheless, it is important to have a standard for calibration, and calibration is now clearly recognized by the medical community as necessary for consistent presentation of medical imagery.

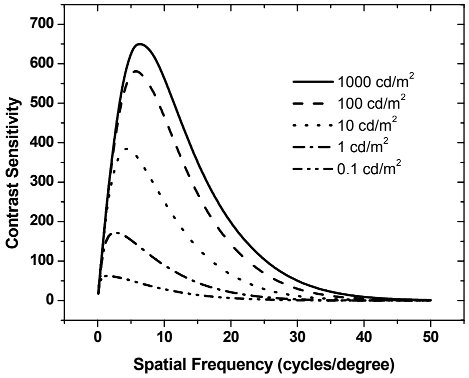

Fig. 3. Linear plot of HVS CSF.

3.2 Contrast in Print and Film

Luminance is a physical term for light areal intensity, or luminous flux from a surface. The perceived HVS absolute psychophysical quantity is termed brightness and the relative perceptual quantity is lightness [3,5]. Very roughly, brightness follows the log of the luminance, as expected from a Weber-law relationship. The CIE definition for lightness (L*), follows a 1/3 power law with luminance, similar to a log relationship over a limited range. L* has a maximum value of 100. Perceptual differences between colors (ΔE), are defined as the Euclidian distance between points in the chosen color space, with a just-noticeable difference defined as ΔE = 1. In the absence of hue and chroma differences, this reduces to ΔE = ΔL* = 1. When fully adapted to the white state luminance, lightness values below 1 cannot be discerned from each other; all appear black. Under this condition, the CIE lightness scale predicts a maximum useful contrast of 100:1, roughly matching the maximum contrast ratio of reflective paper prints, with which most psychophysical experiments have been done. Recent experiments with different stimuli have refined the definition of ΔE downward by about a factor of 3 [11]. In this way, the maximum useful dynamic range predicted by the CIE lightness scale is increasing from 100 to 300, but still below that typically exhibited by displays.

The contrast in halftone prints has a dependence on area, and the resolution in "dots per inch" can be misleading. Although a 1200 or 2400 dpi printer can nicely render small letter features in text, full grayscale capability depends on the size of the dither dot matrix, or "spot" size. The resolution at which full grayscale print capability can be achieved is described as a screen ruling in line pairs per inch (lpi). Typical prints can utilize screens with a range from 85 lpi to perhaps 200-400 lpi, depending upon halftone algorithm and printer technology. For displays and halftone print, the display pixel density should be compared to the print screen ruling or "spot" size.

The dynamic range of x-ray film can be quite large, with a maximum optical density (OD) of about 3.5 [12] and minimum OD between 0.13 [12] and 0.25 [2], a difference of about 3.1 to 3.4 OD units. However, a number of practical considerations can limit the maximum useful OD in the range 2.5 to 2.8 [6,12]. For standard light boxes, the maximum luminance of fully exposed film is about 2400 cd/m^2 [2,12] with a typical dynamic range of about 320:1. The local area contrast of film depends upon the film speed, with grains sizes of about one micron or larger. Grains are either exposed or not exposed, and the area over which the full dynamic range can be developed is larger than a grain. Assuming that 10,000 grains are needed for a 12-bit scan (4096 levels), with 1 μm grains distributed with a 5% fill factor in a 20 μm thick film, the effective film pixel density would be about 250 ppi.

3.3 CRT Contrast

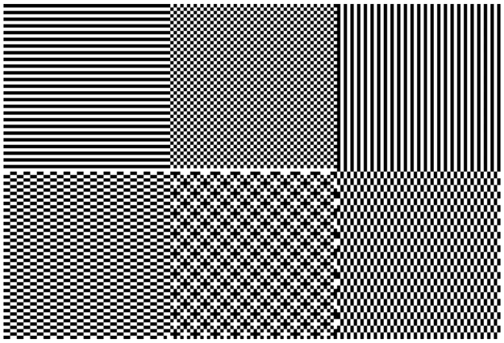

Fig. 4. CRT test patterns.

For some time, CRTs have been the mainstream medical imaging electronic display. CRT large-area contrast ratios as large as 10,000:1 have been reported. However, typical lab measures of large-area contrast with a baffled spot photometer yield contrast values of about 600:1. In use, veiling glare and other factors can reduce the large area contrast to a few hundred or less, and the local area contrast for individual pixels is very low. A CRT "pixel" is the convolution of several components and conditions, including phosphor dot, electron beam shape, cathode and optics, deflection amplifier design, charging effects, and graphics card analog drive circuit. It is difficult to simultaneously achieve a very small electron beam spot size and high beam current. CRT pixels are effectively larger than the phosphor dots on the screen, and thus appear "fuzzy". CRTs have been extensively characterized, including pixel Modulation Transfer Function (MTF), spatial, and temporal noise [13,14]. A simple measure of the effect of CRT local area contrast can be made with a spot photometer and target bitmap image patterns, such as those shown in Fig. 4. Each of the patterns contains equal densities of bright and dark pixels, with different spatial frequencies. Other patterns can be constructed with different ratios of bright and dark pixels. A limitation of CRT technology is the ability to resolve individual pixels in the horizontal direction, due to bandwidth limitations of the graphics card electronics and amplifiers used in the electron optics [13,14]. While it is clear that this implies that fine image detail cannot be rendered at an individual pixel level, it is often assumed that the *average* luminance over a detailed region is not affected by this low-pass filtering.

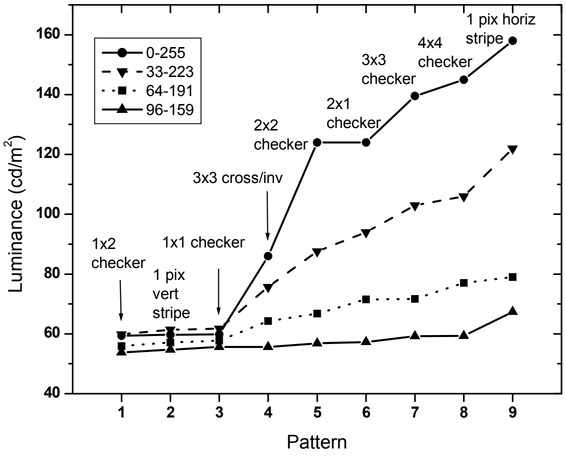

Fig. 5. Average luminance of CRT test patterns.

Fig. 5 shows the results of luminance measures on test patterns of the type shown in Fig. 4, using a typical 5Mpixel medical monochrome CRT. The topmost curve shows results for test patterns with maximum modulation of the input signal, with test patterns containing only black or white pixels (levels 0 and 255). The average luminance increases with the size of the checkerboard features, with maximum average luminance for a pattern in which there is no horizontal modulation of the pixel values. Presumably, the average luminance is not maintained due to a difference in rise and fall times for the electron beam. Other curves show results for patterns with lesser modulation between levels, 33-223, 64-191, and 96-159. If the display accurately rendered this data, the average luminance should be the same for all test patterns in a series, regardless of modulation. The average luminance closely approaches the average of the bright and dark pixel luminance for only the horizontal stripe pattern. For patterns with horizontal single pixel modulation between black and white, the average luminance was only about 30% of the ideal value! For the weakest modulation tested (96-159), about a factor of 3x in luminance, the average luminance was nearly the same for all patterns, except for the horizontal stripe pattern. While a detailed analysis of the luminance data was not done, it can be inferred that a luminance modulation of about 2:1 is the largest that can be achieved between adjacent horizontal pixels, in very rough agreement with rigorous measures of CRT spot profiles and MTF [13,14]. A reasonable expectation is that a medical imaging system should reproduce the noise in the source image data without artifacts, and maintain the correct average luminance, regardless of the modulation of adjacent pixel data.

3.4 LCD Contrast

In LCDs, there is little difference between large area contrast and small area contrast, i.e., the addressable and resolvable pixel densities are very similar. While in some cases, the MTF of LCD pixels is very sharp and difficult to measure [15,16,17], the local area contrast and luminance are not perfect. For example, there are a number of crosstalk effects which can take place in LCDs for certain kinds of image patterns [18], due to pixel array Thin-Film-Transistor (TFT) photoleakage or other photo-induced capacitive effects While the pixel array is accurate to within a few parts per million over the entire screen, the individual LCD subpixels are not perfectly defined by lithography, electrode electric field configuration, and alignment layer establishing the liquid crystal director configuration. Recent measurements suggest that the spatial noise characteristics of LCD pixels are comparable to CRTs [2,19].

Current monochrome LCD product contrast ratios are in the range of 600:1 to 700:1. Lab measurements of contrast of prototype monochrome panels have been as high as 800:1 to 900:1, over a very narrow range of viewing angles near perpendicular incidence. High LCD contrast ratio is achieved by reduction of the dark state luminance, through better extinction of the polarized light in the crossed state. It is difficult to further increase the contrast ratio, due in part to inherent limitations of polarizers. Typical, high-quality polarizers measured on-axis have an extinction ratio of about 800:1 to 1000:1, with significant off-axis light leakage [20]. Color LCDs have somewhat lower on-axis contrast ratio than monochrome due to the presence of the color filter layer in the glass module, which slightly scatters and de-polarizes transmitted light. Currently, on-axis contrast ratios measured for the best color wide-viewing-angle LCD liquid crystal modes are about 400:1. In the future, contrast increases may be possible through the use of improved color filter materials or alternative designs to achieve color. As discussed later, since contrast depends on viewing angle, the on-axis LCD contrast ratio is only one indicator of overall contrast characteristics.

3.5 Contrast Requirements

The utility of high display contrast ratio can be limited. For most images and viewing conditions, as the display contrast ratio is increased from values under 10 to values above 100, there is clear improvement in perceived quality. However, for very high contrast ratios, there may be little or no additional benefit. High LCD contrast ratio is achieved by reduction of the dark state luminance, but dark image features may or may not be discerned, dependent upon viewing conditions and calibration. For examination of image fine detail, the local small-area contrast of the display is more important than the large-area contrast Although there are a large number of JNDs at the lowest luminance range (Table 2), the darkest features of an image can be discerned only with poor spatial resolution, and only if the HVS is well dark-adapted (Fig. 3).

Table 2. JNDs per GSDF luminance interval.

Luminance interval (cd/m^2)	JNDs in luminance interval
0.05 – 1	72
1-200	500
200 - 400	101
400 - 600	60
600 – 800	44
800 – 1000	34

The bit-depth of medical images is typically 10-12 bits, within a 16-bit format. If each bit increment corresponded to a JND luminance step, the luminance range of these images would be very large. Windowing and leveling techniques are often applied to the image data, so that only a portion of the image dynamic range is utilized at any one time. Currently practiced digital image visualization can have a luminance dynamic range of about 600:1, but a display dynamic range as low as 100:1 may be acceptable for primary interpretation, with a minimum display luminance of 1 cd/m^2 [6]. Current Task Group 18 recommendations of the American Association of Physicists in Medicine (AAPM) call for a minimum target JND step value of 2.0. For a display with 8-bit drive, and a minimum luminance of 1 cd/m^2, this recommendation would require a display contrast ratio of 220:1 to implement (360:1 for Lmin = 0.5 cd/m^2).

Monochrome LCDs have inherently higher contrast than color. For dual-domain IPS mode color panels, the maximum on-axis contrast ratio is about 400:1, but material advances may be able to increase the contrast ratios to about 600:1. Higher contrast is beneficial, but a display with double the contrast ratio should not be viewed as having twice the performance. Higher contrast will allow more digital image levels to be shown, but the number of levels itself is not necessarily an important factor. Far more important, is the precision of the display luminance output.

4. LUMINANCE

American College of Radiology recommendations call for a minimum display brightness of 50 ft-L (171 cd/m^2) for diagnostic use. This specification was appropriate for CRTs a number of years ago. As discussed previously, typical light boxes with a film overlay at the minimum optical density have a maximum luminance of about 1000-2400 cd/m^2, and customers today have similar expectations for electronic displays. When comparing displays positioned side-by-side, it is common for users to gravitate toward the brighter of the two displays. This occurs even when initially the brighter display is judged as being "too bright"- as the human visual system gradually adapts to the brightest display, the other displays are then judged as being "too dim".

The maximum luminance of CRTs is often specified as the peak achievable luminance. It is difficult to maintain this luminance over large portions of the screen, and the luminance for complex image patterns will be pattern-dependent. LCDs utilize a transmissive liquid crystal optical "switch" and a backlight, where maximum luminance is not pattern-dependent. Medical monochrome LCD monitors offer maximum luminance in the range 600 to 700 cd/m^2, with recommended maximum calibrated luminance of 400 to 500 cd/m^2. The lower calibration luminance allows automatic gain control of the backlight luminance over the lifetime of the backlight lamps, and extends the lifetime. The maximum brightness specification for the 9 Mpixel color LCD is 235 cd/m^2, guaranteed over three years.

High brightness itself has only a minor contribution to increased sensitivity. Although the best visual acuity is achieved at a luminance of about 3200 cd/m^2, the contrast sensitivity begins to saturate at luminance levels well below 1000 cd/m^2 (Fig. 2). In particular, the increase in contrast sensitivity between 100 and 1000 cd/m^2 is much smaller than the increase between 10 and 100 cd/m^2. The HVS has a limited number of JNDs which can be perceived for a single adaptation state. Most of the DICOM JND steps are contained in the low- to mid-luminance range, as shown in Table 2 and Fig. 7. A doubling of display brightness from 300 cd/m^2 to 600 cd/m^2 increases the number of JND steps by only about 18%.

The most important benefit of very high brightness is the ability to use the displays under high ambient lighting conditions. This is very important for environments which do not allow dimming of ambient light or which require good legibility of paper documents or visibility of equipment controls. For low luminance displays, full adaptation to a dark ambient over a long working session may not be a difficulty. However, for short reading sessions, it is stressful and inefficient to ask users to repeatedly adapt their HVS to new conditions. For the same liquid-crystal array design and backlight, a monochrome LCD panel will have higher luminance than an otherwise equivalent color LCD panel. Monochrome panels will be brighter than otherwise equivalent color panels because there are no color filters to absorb transmitted light. By separation of the white light into three separate colors by the subpixels, at a maximum, color filters transmit approximately 1/3 of the incident light, assuming no overlap of spectral filters. In actual practice, the brightness of otherwise equivalent monochrome and color panels differs by factor somewhat higher than three, as shown in Table 1. For LCDs, the maximum luminance is limited by the aperture ratio of the pixel array, the fraction of the array area that transmits light. The aperture ratio depends on the detailed pixel array design, and decreases with increasing pixel density.

For LCDs used in avionic applications, very bright backlights are used with high dimming ratios. For medical LCDs, a sensor and feedback circuit are often used to maintain a constant output luminance. The efficiency and lifetime of the cold-cathode fluorescent lamps used in LCD backlights depends upon lamp temperature. A challenge for medical LCD designers is to provide an efficient backlight and cooling system that minimizes temperature fluctuations. For medical monochrome LCDs, and color notebook computer LCDs, efforts continue to optimize backlight design. However, much less effort has been made concerning backlights for color monitor LCDs intended for use in medical applications. There is an opportunity to close the inherent gap in brightness of color and monochrome panels, by incorporating a brighter backlight into color displays. Measurements on prototype color monitor LCD panels in our laboratory indicate that the luminance can be increased by at least a factor of two without significant degradation of other display characteristics. In the future, light-emitting diodes and new optics technology may be used to increase backlight luminance and efficiency.

5. LUMINANCE PRECISION AND CALIBRATION

One of the most important issues for display of high-quality imagery is precision and calibration of the monitor luminance [8,21]. Calibration is important for consistent image presentation and interpretation, and ensures that different monitors have the same characteristics. Re-calibration should be required infrequently or not at all. CRTs can be accurately calibrated, but suffer from drift. In some cases for the pre-press industry, CRTs require weekly or even daily color re-calibration. Liquid crystal displays can also be precisely calibrated (at least for one viewing direction), and are much more stable than CRTs. The largest contribution to LCD drift is the gradual degradation of the backlight luminance over time. The cold-cathode fluorescent lamp (CCFL) design and backlight cooling configuration affect backlight lifetime. Currently, typical backlight lifetime specifications are 30,000 to 50,000 hours to half brightness. Improvements in CCFL backlight design [22-24], and the emergence of backlights using light-emitting-diodes are expected to improve the backlight lifetime.

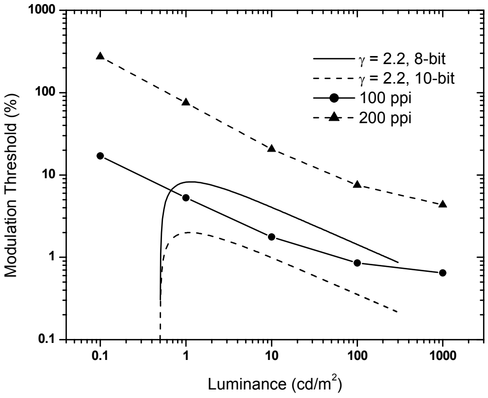

Fig. 6. Dither suitability of LSB.

An important aspect of the CSF characteristics shown in Fig. 2 is the sharp falloff in contrast sensitivity at high spatial frequencies. For LCDs with high pixel density, this aspect can be put to good advantage for calibration and luminance precision. A 100 ppi display viewed at normal reading distance corresponds to a spatial frequency of about 16 cycles/deg, with a corresponding just-noticeable relative luminance difference ΔL/L of about 0.9%. For a 200 ppi display, the corresponding just-noticeable ΔL/L is about 3.5%. Since 8-bit drive of a display with gamma ~ 2.2 results in relative luminance differences typically about 1% or less over most of the dynamic range, this pixel density "reserve" can be put to good use to increase luminance precision by dither of the Least Significant Bits (LSB) of input data. In Fig. 6, the CSF is plotted as luminance modulation threshold versus luminance. Superimposed on this plot are curves for 8-bit and 10-bit drive for a display with a gamma of 2.2, and luminance range of 0.5 to 300 cd/m^2. The LSB for 8-bit drive can be dithered for a 200 ppi display to increase average luminance precision, without individual pixel artifacts. For a 100 ppi display, similar LSB dither for 8-bit drive would result in perceived pixel artifacts. For monochrome displays, the subpixel density in the horizontal direction is 3 times larger than the pixel density in the vertical direction, providing a large safety margin for dither.

For the DICOM GSDF, a JND step of unity corresponds to that luminance difference which can just be perceived for a standard stimulus condition. For a display with wide dynamic luminance range, with a large number of GSDF JND steps, a very large bit-depth would be required to maintain a one-to-one relationship between digital drive level and JND step. However, to ensure perceptibility, each increment in rendered image level (presentation value) should have a luminance increment exceeding the minimum ΔJND of 1. A reasonable target for average ΔJND per step is 2.0, and current AAPM TG-18 recommendations [25] call for maximum average ΔJND per step of 3.0 to "prevent visible discontinuities in luminance from appearing in (image) regions with slowly varying image values", i.e. luminance banding. For calibration as close as possible to the DICOM GSDF, each digital level increase should have a corresponding ΔJND with as little variation as possible over the entire dynamic range. For many display systems, this can only be achieved by allowing the possible number of presentation levels to be less than the inherent bit-depth of the graphics card. For example, out of 256 possible drive levels, only 200 or so could be used to render the image. By utilizing spatial and temporal dither, the luminance precision can be increased to allow all digital levels to be used for presentation. Dithering techniques can also be used to increase the intrinsic drive bit-depth to 10-bits and beyond, using standard 8-bit drive signals. This can be accomplished through a suitable graphics card driver to implement the dither.

For the DICOM GSDF, the number of JND steps per luminance interval is not constant, and depends on absolute luminance (Table 2 and Fig. 7). At low luminance, there is a strong increase in JND value, but at high luminance JND values have a slow increase. For precise calibration, this requires that LCDs be re-calibrated if the backlight luminance changes, and it is not sufficient to simply "shift" the calibration curve to accommodate changes in backlight luminance.

Any automatic calibration technique which relies solely on a measure of backlight luminance must change the shape of the calibration curve to achieve the best results.

A distinction should be made between the number of possible levels of the graphics card output, and the precision of the display luminance levels. Typically, LCD calibration is achieved by measuring the native luminance response versus input digital signal level, and adjusting Look-Up Table (LUT) entries in the graphics card adapter, also referred to as the gamma ramp. For 24-bit color graphics cards, the LUT consists of 256 entries each for red, green, and blue. Each entry is a 16-bit value, spanning a range of 0 to 65535, but sometimes extending only to 65280. The LUT is implemented with 8-bit precision. Although some graphics card drivers refer to 32-bit color, this is the bit-depth of pixel data handled internally in the graphics card, not output data bit-depth. Default LUT entries increase linearly, and the default monitor luminance response is generally designed to follow a "gamma" curve relationship, with the luminance increasing as a power of the digital input level. For Windows systems, the typical target gamma is 2.2 and for Mac systems the typical target gamma is 1.8. LUT changes for Mac systems are retained upon reboot; however, Windows systems reset the LUT to default during boot up, and a startup program is required to set the LUT to the desired calibrated values after boot up.

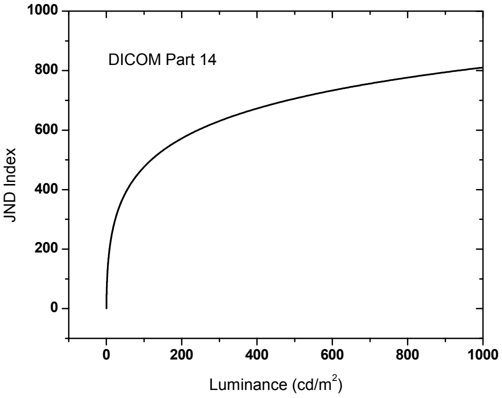

Fig. 7. DICOM GSDF.

The IBM T221 color LCD has a built-in LUT, accessed via a USB connection, with a color management utility software program [26]. The monitor LUT can be utilized to achieve very precise luminance calibration, independent of the graphics card. The monitor drive electronics compares the 8-bit digital input values with the monitor LUT values, implemented with 10-bit precision in the pixel array using a standard spatial dither technique, with a 2x2 block of full RBG pixels [26]. The least significant 8-bit values are dithered to achieve 10-bit precision over the 2x2 block. As discussed previously, dithering of these least significant bits cannot be perceived for the individual pixels, but the 10-bit average luminance precision is easily confirmed with a photometer.

Preliminary T221 calibration results using the VeriLUM® calibration product [27] have been reported [26]. Several methods of data analysis have been utilized, but only the average and standard deviation ΔJND values are discussed here. Typical calibration results with an 8-bit/color graphics card LUT yield an average ΔJND=2.0±1.1 for 256 measurements. Current AAPM TG-18 recommendations call for a maximum ΔJND standard deviation of 1.0. The calibration can be improved by simply loading the same LUT determined through standard calibration procedures into the 10-bit monitor LUT instead of the graphics card LUT. Typical 10-bit calibration results yield an average ΔJND=2.0±0.33.

A further improvement in IBM T221 calibration accuracy can be achieved by implementing subpixel dither. Medical monochrome LCDs typically employ both spatial subpixel dither and temporal modulation to achieve high luminance precision. For IBM T221, spatial dither alone is sufficient. For pseudo-gray luminance precision, color subpixel dithering relaxes the constraint that R=G=B by a small amount. Initial work showed that a ΔJND standard deviation of ~0.3 could be achieved by subpixel dithering by a few 8-bit values, similar to that achieved with the 10-bit monitor LUT without subpixel dither. A generic 8-bit subpixel dithering algorithm was developed by Image-Smiths [27], called Optigrayscale. A subsequent, 10-bit version of Optigrayscale was also developed, taking full advantage of the 10-bit monitor LUT precision. For 10-bit Optigrayscale, R and B subpixel values are allowed to deviate from G subpixel values by as much as ± 3 10-bit levels. There is a total of 50,176 choices, roughly corresponding to a grayscale luminance

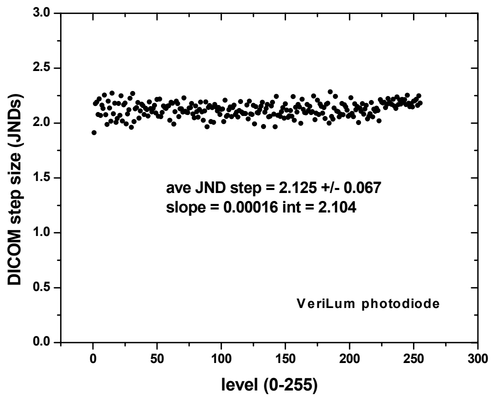

Fig. 8. Calibration results of color IBM T221, using 10-bit monitor LUT and subpixel dither.

precision of 15.6 bits. The theoretical precision is actually higher than this, due to the fact that red and blue subpixels have lower luminance than green subpixels, with different luminance increments. An additional constraint was made in the dither scheme, in which all LUT entries for each primary are required to be monotonically increasing with index value. In this way it is guaranteed that under no circumstances is there a differential contrast reversal between increasing levels of any primary color. The dithering of red and blue relative to green introduces a very slight color shift, from the native chromaticity of the grays. However, by restricting the 10-bit dither range to at most 3 levels, the difference between red and green or blue and green never reaches one 8-bit step, and the color shift is very small.

The calibration accuracy is not limited by the dithering technique, but by the precision and repeatability of luminance measurement apparatus, noise, thermal drift, etc. Calibration results using the 10-bit Optigrayscale dither and 10-bit T221 monitor LUT are shown in Fig. 8. From the VeriLUM® photosensor data, the average ΔJND = 2.1±0.067. Data obtained with a standalone Minolta LS100 photometer produced similar results, with average ΔJND=2.1±0.075. These results are for a single set of 256 measurements, with no averaging techniques employed. Further optimization is possible by making special adjustment for the endpoints. These standard deviation results are slightly better than those recently reported for monochrome medical LCD calibration, ΔJND=2.7±0.15 [15, 16], and ΔJND=2.7±0.09 [17].

6. VIEWING ANGLE CHARACTERISTICS

Unlike CRTs, LCD characteristics can have a strong dependence on viewing angle. For typical notebook computer displays with twisted-nematic liquid crystal mode, there is image contrast reversal as the display is tilted. Other liquid crystal modes, such as dual-domain IPS or Multiple Vertical Alignment (MVA) have been developed which greatly improve the viewing angle characteristics. However, even the best liquid crystal modes have non-Lambertian transmission characteristics, and LCD manufacturer specifications tend to de-emphasize viewing angle imperfections. Typically, the specified viewing angle range is determined as that range over which the contrast exceeds a ratio of 10:1, for IPS panels about 170 degrees. Newsprint can have a contrast ratio as low as about 8:1, so this specification is meaningful only for legibility of black and white print, hardly appropriate for viewing medical images. Viewing at angles ± 85^{o} from normal cannot be expected for critical use, for a single observer 40 cm from a 22" diagonal display, the center-to-corner angles are ± 54^{o}. A more meaningful specification would be that viewing angle cone over which the average contrast ratio exceeds 100:1, using an appropriate average - for liquid-crystal modes such as IPS, the iso-contrast regions have large lobes extending in particular directions.

The viewing angle dependencies of LCDs raise the question of utility of highly accurate luminance calibration, performed solely on-axis [21,28]. Consider a case where one monitor has very precise luminance precision for on-axis viewing, but poor viewing angle characteristics; and another monitor with somewhat poorer on-axis luminance precision but very uniform viewing angle characteristics. Which calibration is better? For MVA liquid crystal mode, the contrast ratio is highly peaked on-axis, but falls sharply with viewing angle, whereas IPS mode has a less-sharply peaked dependence of contrast on viewing angle. Does on-axis contrast ratio provide an accurate portrayal of display contrast?

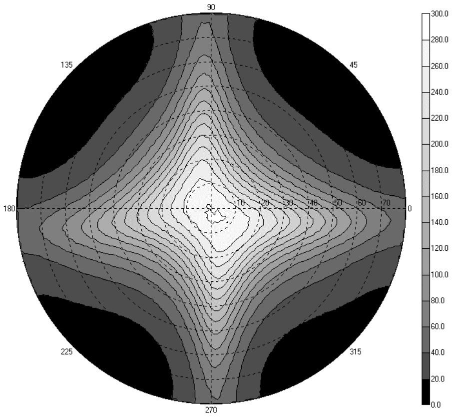

Fig. 9. Contrast versus viewing angle for a dual-domain IPS color LCD.

Typical contrast ratio versus viewing angle for an IBM T221 color LCD are shown in Fig. 9. These data were obtained with a Fourier-optic conoscopic colorimeter system (Eldim EZContrast160). The characteristics of monochrome dual-domain IPS mode LCD panels are similar, except the contrast ratio for monochrome is more peaked than for color, with a stronger falloff with polar viewing angle (Fig. 10). The color filter slightly scatters and depolarized light, increasing the light leakage for on-axis light and primary azimuths. However, the color filter layer decreases the light leakage for large polar angles and diagonal viewing azimuths, where the contrast for color falls off more gradually with polar angle than for monochrome. Although the monochrome on-axis contrast ratio is about a factor of 2 larger than color, the increase in viewing cone is small. The viewing cone over which the average contrast along the annulus exceeds 100:1 is about ± 45^{o} for monochrome and ± 40^{o} for color. At a viewing azimuth of 135^{o}, the contrast for color is within 20% that of monochrome at a polar angles larger than about ± 30^{o}.

The viewing angle distribution of the white state luminance for monochrome and color panels is about the same, roughly a Lambertian dependence, similar to CRTs. In contrast, the dark state luminance (and color) varies strongly with viewing angle. However with HVS adaptation to the white state luminance, the variation of dark state characteristics with viewing angle is difficult to discern. The inability to perceive viewing angle variations of dark pixels, relative to bright pixels in an image, is the basis for a low-cost technique proposed to improve the viewing angle characteristics of high resolution LCDs [29]. The image data is processed to spatially dither the most significant bits of the image data, while maintaining the correct local luminance. When applied to high-resolution TN-mode LCDs, the improvement in vertical viewing angle characteristics is about 18^o, with some concurrent loss of resolution. This same technique could be applied to medical monitor IPS-mode LCDs to improve the quality of DICOM calibration versus viewing angle, at the sacrifice of some spatial resolution.

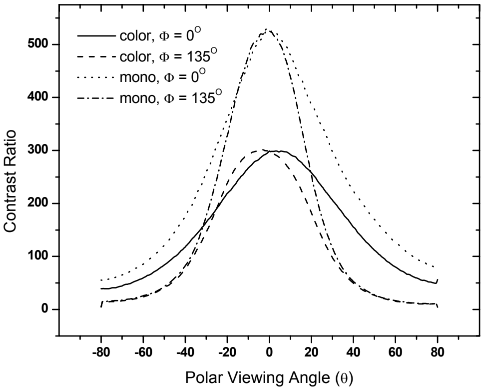

Fig. 10. Contrast versus viewing angle for monochrome and color dual-domain IPS LCDs.

7. SYSTEM ISSUES

Digital drive of LCDs at their native resolution is required for optimal image quality. Digital drive is very stable, and enables interchange of graphics cards and displays with self-contained calibration. The graphics card standard for color digital output is the Digital Video Interface (DVI), now widely available. For a 9 Mpixel color LCD, the data rates can be large. The current maximum DVI clock rate is 165 MHz, with 24 bit data for one RGB pixel transmitted each clock, for a maximum transmission rate per channel of about 4 Gbit/sec. Driving 9 Mpixels at 41 to 48 frames/sec requires data rates of about 10 Gbit/sec, so multiple DVI channels are required. There are many graphics cards with multiple DVI outputs, providing a good drive solution for a single panel. While drive of two 9 Mpixel panels can be done with a single AGP bus graphics card, or a combination of AGP and PCI cards, the best solutions for medical applications use two PCI bus graphics cards. Suitable multi-head PCI bus cards have recently emerged in the market, and it is likely that further development of these cards will continue, along with the emergence of a new bus, PCI-Express. It is interesting to note that the highest performance 3D color graphics cards on the market today are still priced lower than medical 2D monochrome graphics cards. For monochrome medical LCDs, the data bandwidth requirements are lower than color by a factor of three. This has allowed the development of custom PCI bus cards for medical applications with minimal graphics chipset performance or 3D capability. There is no established standard for monochrome DVI, and most medical monitor manufacturers have chosen to bundle monitors with custom graphics cards, using proprietary interfaces. While this allows for good, controlled solutions and product differentiation, it does not allow interchange of system components or foster price reduction through standardization.

8. PERFORMANCE AND PRICE

There are fundamental reasons why medical monochrome LCDs are more difficult and expensive to manufacture than computer monitor color LCDs. The technical challenges are primarily an issue for the LCD glass module manufacturers, somewhat less so for monitor manufacturers and medical imaging system integrators. For glass module manufacturers, to achieve the best optical performance and screen uniformity for monochrome panels, the liquid crystal cell gap must be tightly controlled and be made very uniform. The absence of a color filter, combined with high contrast ratio, reveals any cell gap imperfections. Additional quality control is also required to meet other medical monitor manufacturer specifications for pixel defects, chromaticity, unit-to-unit variation, etc. and there may be special requirements for use in operating rooms or other environments, or systems requiring FDA approval.

The main non-medical application for monochrome LCDs is for intelligence image analysis. Altogether, the market for monochrome LCDs is much smaller than for color LCDs. The small market size and high performance requirements have a strong upward pressure on monochrome display price. Presently, monochrome LCD prices are roughly in the range \$2,000 to \$4,000 per megapixel. In contrast, the market size for color LCD monitors is very large and growing.

There is a gap in performance between medical-grade LCDs and most computer LCDs, nonetheless, it is interesting to note that typical prices for color desktop LCD monitors are in the range of $500 to $1000 per megapixel, roughly a factor of four lower than monochrome LCDs. Some of this difference can be attributed to special features offered with medical monochrome monitors, such as automatic brightness control, auto-calibration, and certification.

9. CONCLUSIONS

The display and graphics card portion of medical imaging systems are rapidly becoming what should be viewed as "standard" computer hardware. The drive bandwidth requirements for monochrome are a factor of 3 lower than for color, but this advantage is largely offset by the use of specialized monochrome graphics cards. With digital drive and dithering, there is no significant difference in luminance precision between monochrome and color LCDs. The high brightness of monochrome LCDs is advantageous, but the brightness of color LCDs can be increased with relatively small additional cost, *provided* there is acceptance of color displays for medical applications. The high contrast ratio of monochrome is not highly advantageous in most practical settings. The high performance to cost ratio for commercial high-end color LCDs warrants a re-evaluation of this technology for medical applications.

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