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Assessment of a Novel, High-Resolution, Color, AMLCD for Diagnostic Medical Image Display: Luminance Performance and DICOM Calibration

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This article documents the results of the first in a series of experiments designed to evaluate the suitability of a novel, high resolution, color, digital, liquid crystal display (LCD) panel for diagnostic quality, gray scale image display. The goal of this experiment was to measure the performance of the display, especially with respect to luminance. The panel evaluated was the IBM T221 22.2" backlit active matrix liquid crystal display (AMLCD) with native resolution of 3840 × 2400 pixels. Taking advantage of the color capabilities of the workstation, we were able to create a 256-entry grayscale calibration look-up table derived from a palette of 1786 nearly gray luminance values. We also constructed a 256-entry grayscale calibration look-up table derived from a palette of 256 true gray values for which the red, green, and blue values were equal. These calibrations will now be used in our evaluation of human contrast-detail perception on this LCD panel.

KEY WORDS: PACS, image display, AMLCD evaluation, DICOM Part 14 calibration

IMAGE DISPLAY IS A CORE FUNCTION of picture archiving and communication systems (PACS). Typically, a PACS workstation consists of a powerful personal computer, a frame buffer (video card) designed to display images rapidly, and one or more high-resolution displays. The number and type of displays used in PACS workstations vary widely with clinical setting, personal preference, and vendor options.

Until very recently, the highest fidelity electronic reproduction of digital medical images was obtained using high resolution, high brightness, monochrome, cathode-ray tube (CRT) displays. More recently, flat panel displays (FPD) have entered the market. As lower resolution, color FPD have begun to dominate the consumer mass markets, higher resolution, monochrome FPD are now seeing clinical use for diagnostic image display. As the total cost of ownership of these new devices approaches that of the CRT, they promise to eventually replace the traditional CRT, offering substantially brighter and lighter digital systems.

This article discusses the luminance performance and DICOM calibration of a color flat panel display for primary grayscale diagnostic image presentation. In particular, new, color FPD are available, which may provide the opportunity to support not only the display of diagnostic quality digital images, but also the simultaneous integration of other imaging modalities (e.g., magnetic resonance imaging, ultrasound, etc.) that contain color information, more sophisticated graphical user interfaces, as well as widely available computer notification, communication, and collaboration tools. Many of these new display technologies are oriented to the mass market, and if their properties can be validated for use in diagnostic

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imaging, then there exists at least the potential to lower the cost of these image display systems.

LCD DISPLAY TECHNOLOGY

Some advantages of FPD include low spatial noise and high dynamic range, as well as the fine spatial resolution required for medical imaging.[1,2] Additional advantages have to do with the ergonomics of the design, and the dimensions and brightness of the display. A lighter and brighter display system provides for a significantly more comfortable environment in the reading room, as it is much easier to position and allows for more ambient light. The American Association of Physicists in Medicine (AAPM) Task Group 18 recommends keeping the ambient lighting level below the minimum display luminance "to minimize artifacts and loss of image quality associated with reflections from the display surface."

There are many different types of FPD now available, the most popular of which is the liquid crystal display (LCD). This technology is based on the ability of liquid crystal molecules to polarize light depending on the supplied voltage levels. The more twisted the molecules, the better the contrast and the viewing angle that can be achieved. Available LCD(s) are divided into "passive" and "active" displays. All active electronics (transistors) are outside the display screen in passive matrix displays. Active matrix displays (also called thin film transistor [TFT] LCD) have a transistor built into every pixel, which provides brighter and sharper display but is generally more expensive to manufacture.[2]

A limited viewing angle is a serious drawback that comes with LCD technology, although new technologies such as twisted nematic with film, in-plane switching, and multi-domain vertical alignment have matured and enable LCDs with much greater viewing angles. The twisted nematic (TN), the Super Twisted Nematic (STN), and "Dual Scan STN" modes are usually associated with passive matrix displays. They are less expensive than in-plane switching (IPS) technologies, which are frequently used in active matrix displays. While each of these technologies has its drawbacks, they all offer great improvements in achieving a wider viewing angle, higher contrast ratio, and a faster response time in LCD displays.[3]

Other drawbacks of LCDs include their inability to support multiple resolutions (unless scaling is performed on the graphics card, which often introduces distortion into the images), and the higher costs usually associated with their production. At the same time, when compared to CRT displays, LCDs have higher luminance, are capable of supporting a higher maximum resolution, and have a much smaller footprint. Notably, individual pixels of an LCD are sharply defined, whereas with a CRT pixels have a Gaussian distribution. As a consequence, a 3-megapixel LCD may have better resolution than a 5-megapixel CRT. Some other important advantages offered by LCD are lower power consumption, lower radiation, flicker-free image, and the durability of the backlights controlling the display brightness, all of which become even bigger issues with more displays being in use for longer periods of time.

Some of the other types of flat panel displays include OLED, EL, plasma, and FED. [2-4] Of these, although still in the early stages of development, OLED(s) (organic light-emitting displays) are the most promising for medical imaging applications. Because they are based on either small-molecular weight organic materials or polymer-based materials that form a single monolithic layer, they should be able to offer a very high resolution, and they can be made of light and flexible materials. The anticipated drawbacks include low durability and increased sensitivity to humidity, temperature, and oxygen level changes.[2,4]

MATERIALS AND METHODS

The IBM T221 (IBM, Armonk, NY) is a 22.2" backlit digital LCD TFT display with 16:10 aspect ratio. It has a native display resolution of 3840×2400 with 0.1245 mm dot pitch size, 204 dots-per-inch (dpi), and a nominal 170 degree viewing angle. The combined QUXGA-W (3840×2400) and UXGA-W (1920×1200) resolution support provides the ability to toggle between two resolutions. In our case it is driven in QUXGA-W mode by an ATI FireGL4 digital graphics accelerator (ATI Technologies Inc, Markham, Ontario) with 128 MB DDR SGRAM. The IBM T221 supports up to four simultaneous digital visual interface (DVI) connections. The FireGL4 has 2 DVI-I (a digital flat panel interface from the Digital Display Working Group) and digital monitor output connectors, and it can support

Table 1. A Palette of 766 Luminance Values Measured Using Two Additional Sub-sequence States for Each Major State

R	G	B
0	0	0
0	1	0
0	1	1

Table 2. A Palette of 1786 Luminance Values Measured Using Six Additional Sub-sequence States for Each Major State

R	G	B
0	0	0
0	0	1
1	0	0
1	0	1
0	1	0
0	1	1
1	1	0

the color depth of 32 bits per pixel. It also has a fixed screen refresh rate of 41 Hz (above the 30 Hz flicker-fusion frequency necessary to present static images), and a data frame rate of 25 Hz. Although problems may exist with respect to flicker-free display of moving images because of issues associated with pixel refresh time on this display, such discussion is beyond the scope of this paper. The monitor was not calibrated for DICOM (digital imaging and communication in medicine) 3.14[5] conformance prior to our experiments.

To measure the luminance response, we followed AAPM[2] and VESA FPDM[6] guidelines. We used software and spreadsheets developed at Henry Ford Health Systems to create DICOM calibration look-up tables based on the measured luminance response of the monitor.[7,8] The luminance measurements were made with an IL1700 research radiometer (International Light, Inc., Newburyport, MA) with an SHD033 High Grain Silicon detector with a Y-photopic filter, a 62.5-mm long ×42-mm diameter barrel hood, and a 9-mm aperture cone.[9] Additional measurements were made with a Minolta LS-100 (Minolta Co., Ltd., Radiometric Instruments Operations, Osaka, Japan) luminance meter.

The luminance response was measured using graphic software to display a test pattern conforming to DICOM part 14 with a target region that could be set to any luminance and color by specifying appropriate red-green-blue (RGB) values. Target colors were automatically sequenced with the luminance recorded using the serial line interface of the IL1700 meter. Using major steps of 1, the 256 measurements with R, G, and B values equal were obtained. For each major step, the R, G, and B values were selectively perturbed by 1 according to defined sub-sequence tables. A palette of 766 luminance values was measured using two additional sub-sequence states for each major state (Table 1). A palette of 1786 luminance values was measured using six additional sub-sequence states for each major state (Table 2). Because all luminance values were measured in total darkness, a target gray scale was determined by subtracting a nominal value of ambient luminance from the DICOM gray scale display function. Calibration look-up tables were then created by selecting a set of 256 sequentially increasing luminance states that most closely followed the target gray scale display function between a specified maximum and minimum luminance.

The uncalibrated luminance responses for palettes of 256, 766, and 1786 were measured by using ramp functions in the display controller that did not modify the specified RGB color values. Calibration look-up tables generated from the uncalibrated luminance response were loaded to the graphic card where requested RGB values are transformed according to the installed table. The calibrated luminance response was then finely measured for 256 gray values (R = G = B) in steps of 1 and coarsely measured for 18 gray values in steps of 15. Using a spreadsheet program, the calibrated luminance response was compared to the DICOM gray scale display function by relating the measured relative luminance change between each measured value to that of the DICOM standard.

The programmable electronics built into IBM T221 also allow 10-bit–based color calibration. This is achieved by loading a 10-bit look-up table (LUT) directly into the display frame buffer memory. A special Color Management Utility then directs all system gamma ramp calls to this LUT, and a 2 × 2 spatial dithering is performed to obtain precise color definition. In the future, we intend to build a 1024 DICOM compliant RGB LUT based on the 1786 pseudo-gray palette in an attempt to increase the number of available distinct gray-scale levels.

RESULTS

The relative luminance from green, red, and blue pixels typically is weighted as 4-2-1 (the contributions of R, G and B recommended by digital component video standard CCIR-601 are $Y = 0.299R + 0.587G + 0.114B$, and may vary slightly depending on the monitor). Figure 1 illustrates the response of R, G, and B pixels for the T221 monitor evaluated hi this work. R, G, and B are specifically weighted in the amounts of 2r, 1b, 4g at lower luminance levels, and 3r, 2b, 8g at higher luminance levels. The sub-sequences used to build the 1786 and the 766 pseudo grayscales[5] were built to reflect these relative contributions.

Figures 2(a, b, c), 3(a, b, c), 4(a, b, c), and 5(a, b, c) represent the pre- and post-calibration measurements of the luminance and contrast response, respectively, of the IBM T221 as related to the expected response associated with DICOM 3.14 standard. The calibrations were

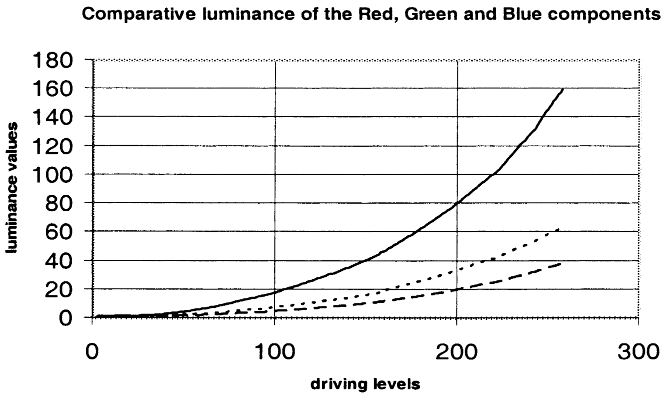

Fig 1. Luminance response for the red, green, and blue components in isolation. Solid line: green; dotted line: red; dashed line: blue.

done using tables built from a palette of 256, 766, and 1786 (Figures 3, 4, and 5, respectively). Figures 2a, 3a, 4a, and 5a represent coarsely measured luminance in cd/m^2 vs. the just noticeable difference (JND) index value as defined by the DICOM 3.14 standard display response specifications. Figures 2b, 3b, 4b, and 5b represent the relationship between DICOM specified expected contrast response from coarse measurements with a 10% tolerance limit as recommended by AAPM[2] and the observed contrast response expressed as L(n + 1) - L(n)/(n + 1) + L(n)/2 (where L(n) represents a single luminance step) normalized through dividing by the JND index difference associated with each point relation to the average JND index expressed as (JND(n + 1) + JND(n))/2 (where JND(n) represents a single JND step as defined by DICOM Part 14). Figures 2c, 3c, 4c, and 5c also represent the observed contrast response, but this time it was finely measured for all 256 grayscale values. The zero values here correspond to redundant gray states with no contrast between sequential driving levels. For primary class display devices, AAPM TG18[2] recommends that "< .JND/.p > should not be greater than 3.0 to prevent visible discontinuities in luminance from appearing in regions with slowly varying image values. The maximum deviation of the observed JNDs per luminance interval should not deviate from < .JND/.p > by more than 2.0. The root mean square deviation relative to < .JNP/.p > should not be larger than 1.0." The mean JND per luminance interval was approximately 2, for the calibrated pallets. The root mean square error (RMSE) deviation for the 1786 pallet was 0.33 (16%), as opposed to the 32% standard deviation measured with the 766 pallet, and the 60% standard deviation measured with the grayscale palette. The largest deviations from the average delta JND for the 1786 palette occurred between 19 cd/m^2 and 20 cd/m^2 where it reached the value of 0.85, while the average deviation from for < .JNP/.p > this calibration was approximately −0.01. The measurements taken at each of the four display quadrants indicate that calibration holds constant across the entire area of the monitor. The overall DICOM compliance achieved with the 1786 pseudo grayscale demonstrates the value of RGB calibration possible with the color displays.

We found that the luminance (L) range of the monitor varied for different brightness settings. Figure 6(a, b, c) shows the bright and the dark states at different brightness levels, as well as the L_{max}/L_{min} in relation to the changes in brightness settings. The minimum luminance of the panel measured at the highest brightness setting is 0.8 cd/m^2. The maximum luminance of the panel is 266 cd/m^2. This results in a luminance range of about 332. The dynamic range, assumed when creating the calibrated LUT, was 200. These luminance values varied at different brightness settings of the panel, the lowest setting rendering the dark state at 20 and the bright state at 58, resulting in a slightly lower contrast ratio of about 290. According to the manufacturer, these measurements are affected by a phantom image that persists after

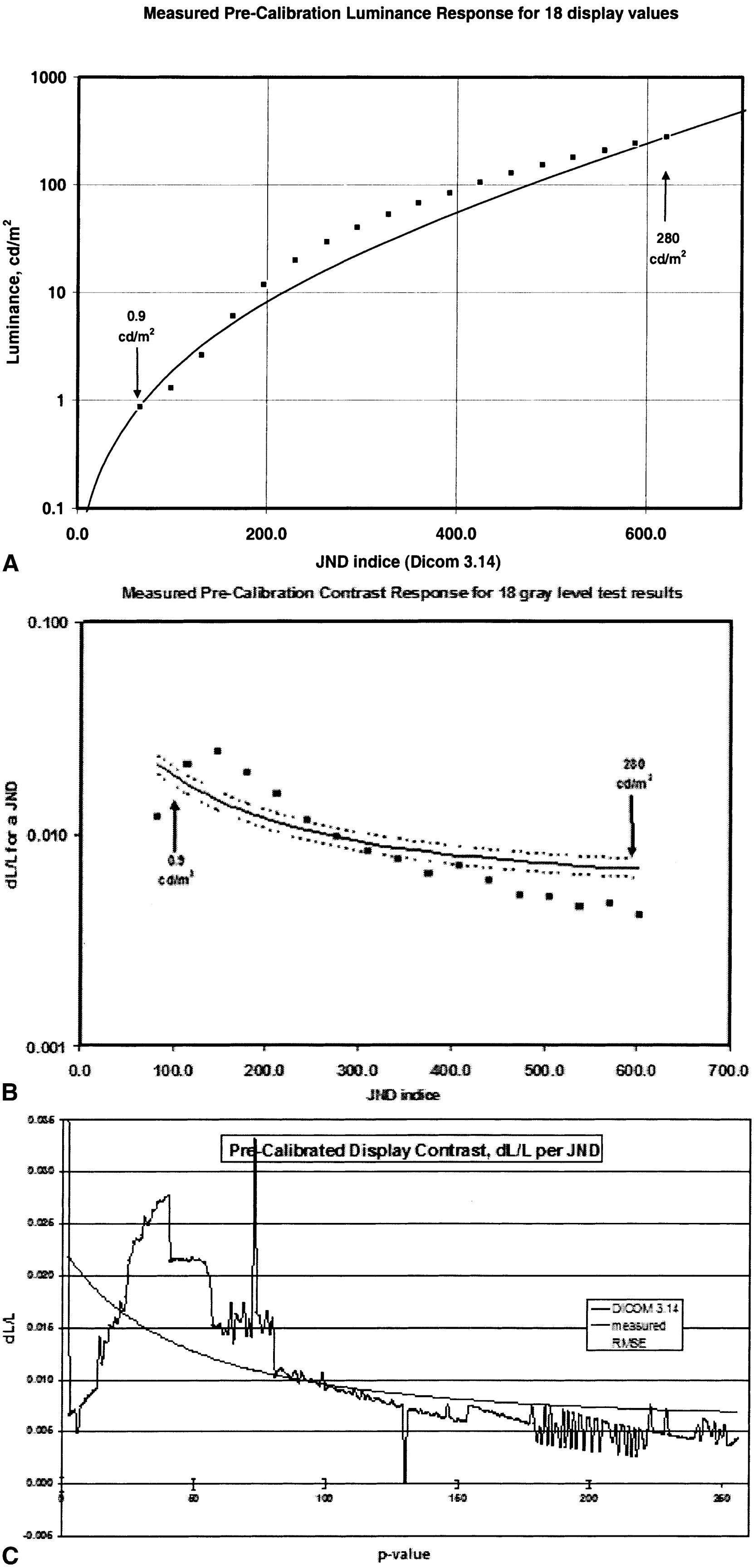

Fig 2. a. The measured luminance for 18 display levels is plotted in relation to the Dicom 3.14 standard luminance response function. b. The measured contrast response computed from 18 gray levels is related to the expected response associated with the Dicom 3.14 standard luminance response with 10%; tolerance limits indicated. c. The measured contrast response computed from 256 gray levels is related to the expected response associated with the Dicom 3.14 standard luminance response.

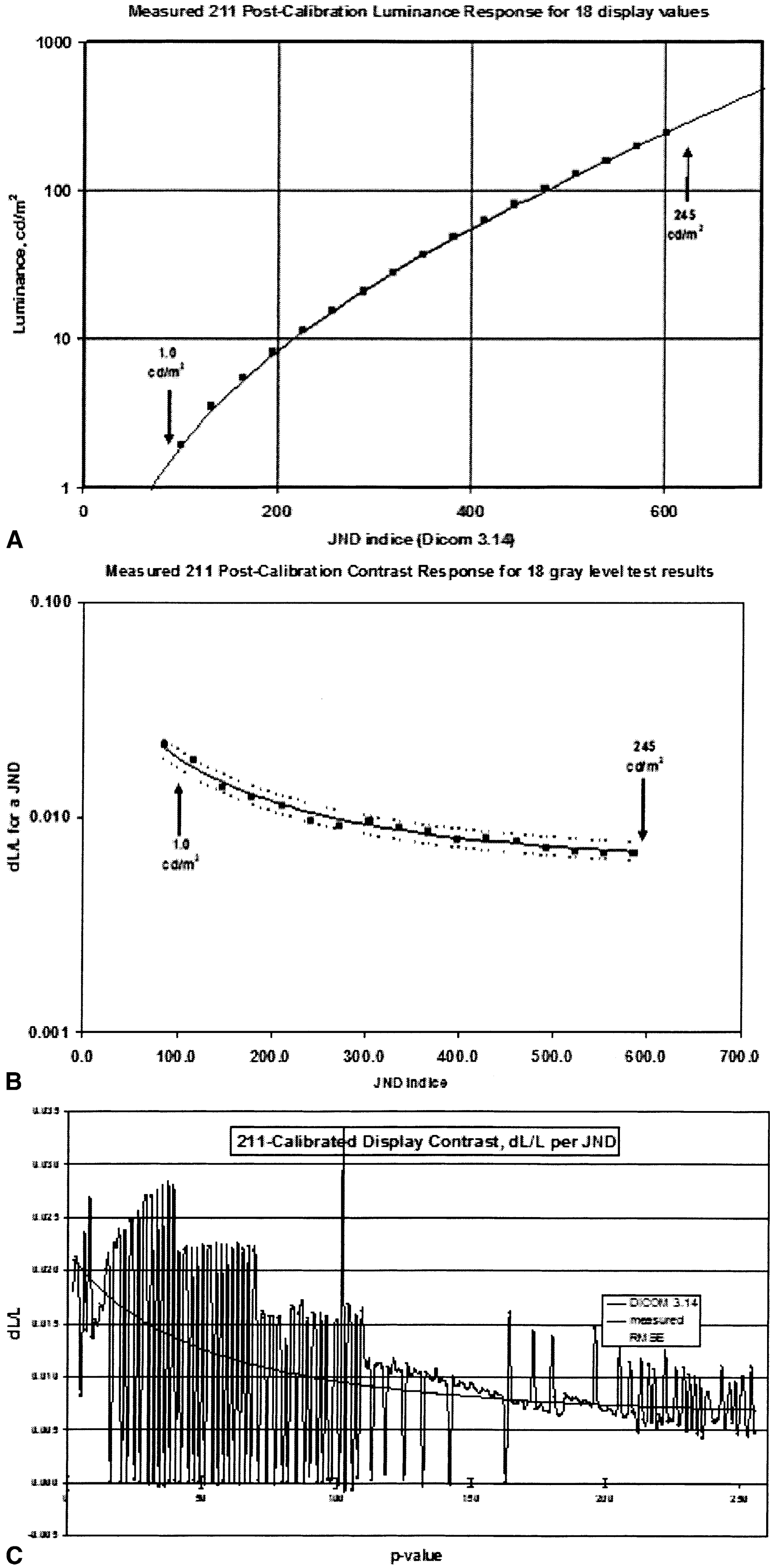

Fig 3. a. The measured luminance for 18 display levels is plotted in relation to the Dicom 3.14 standard luminance response function. b. The measured contrast response computed from 18 gray levels is related to the expected response associated with the Dicom 3.14 standard luminance response with 10%; tolerance limits indicated. c. The measured contrast response computed from 256 gray levels is related to the expected response associated with the Dicom 3.14 standard luminance response.

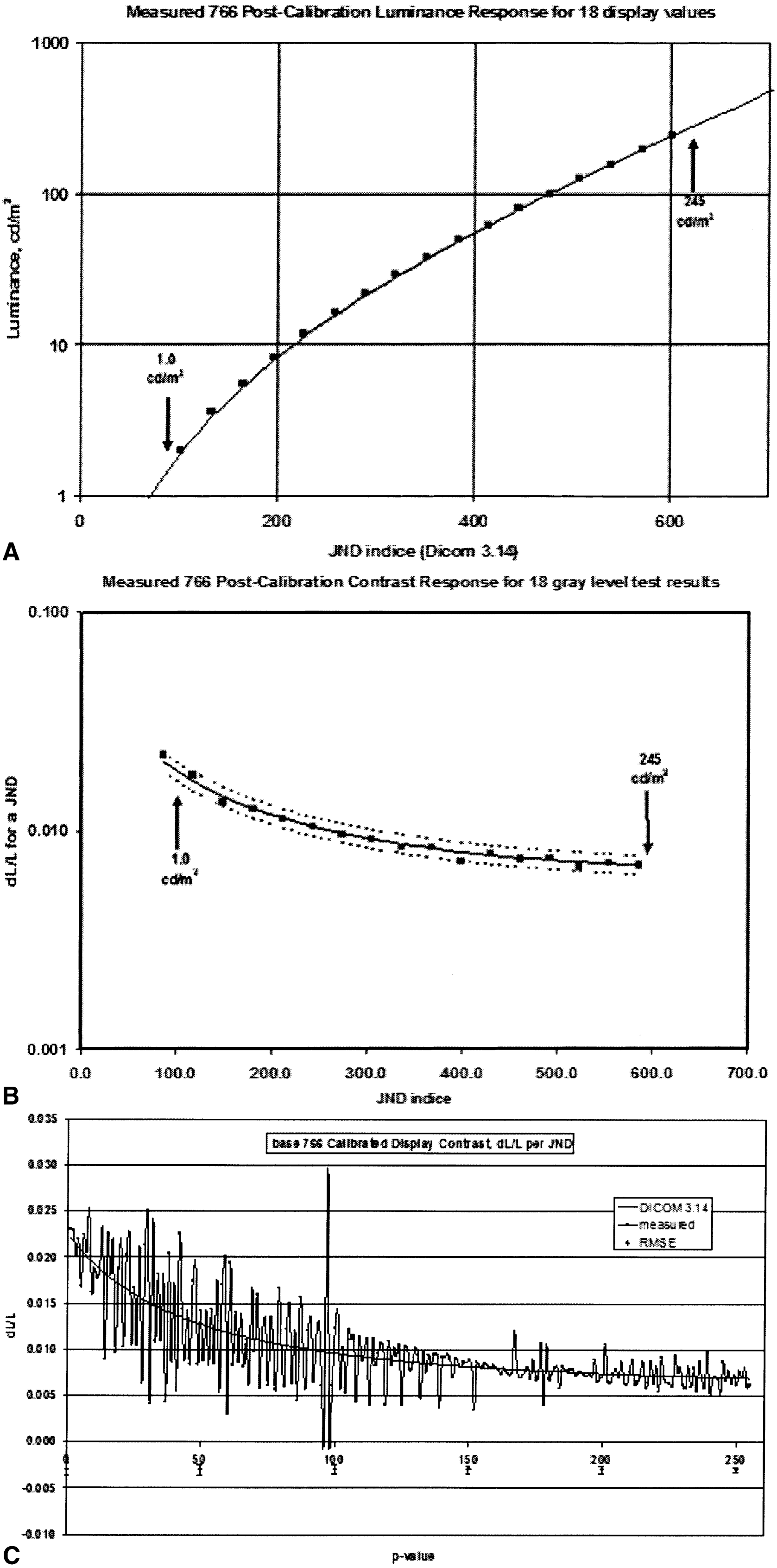

Fig 4. a. The measured luminance for 18 display levels is plotted in relation to the Dicom 3.14 standard luminance response function. b. The measured contrast response computed from 18 gray levels is related to the expected response associated with the Dicom 3.14 standard luminance response with 10%; tolerance limits indicated. c. The measured contrast response computed from 256 gray levels is related to the expected response associated with the Dicom 3.14 standard luminance response.

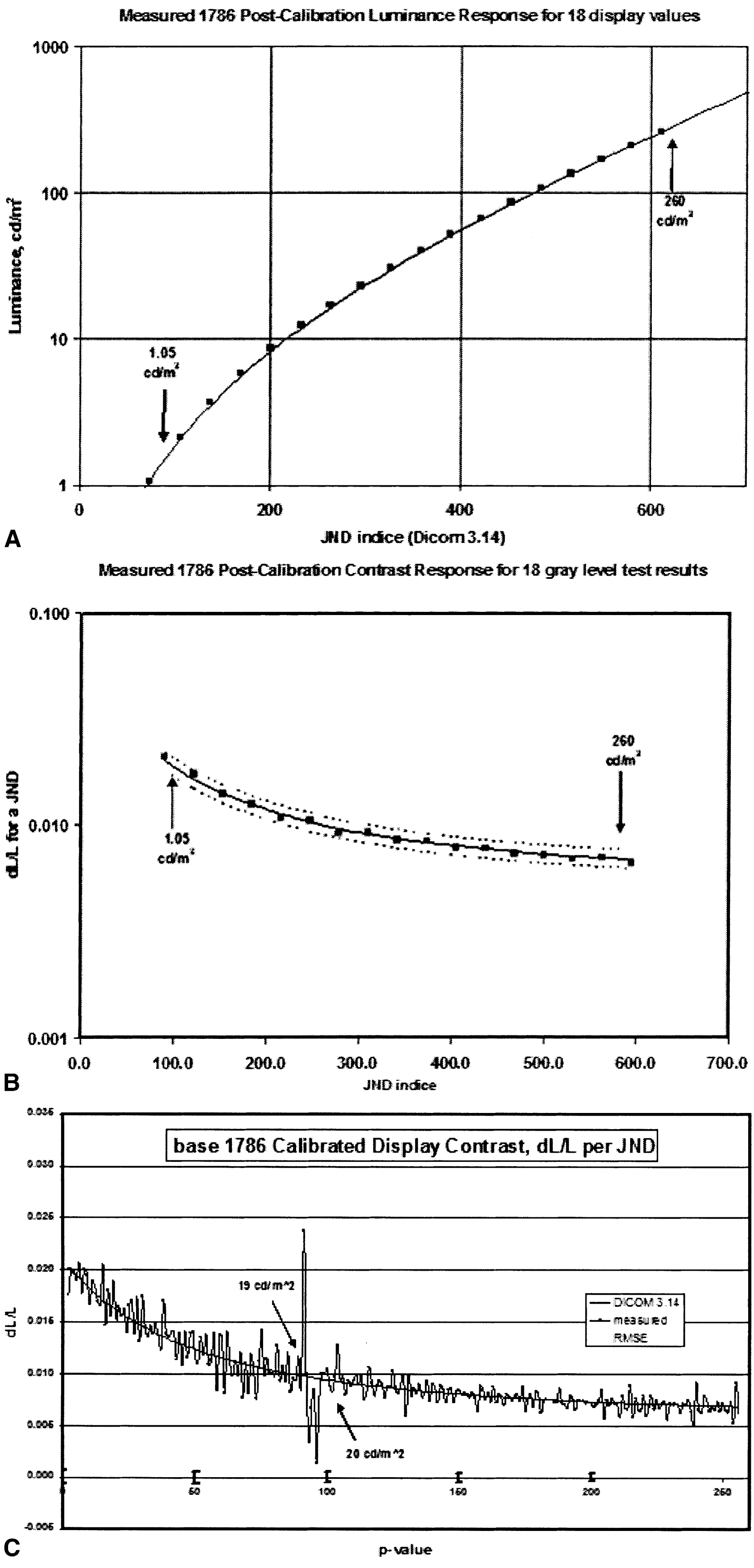

Fig 5. a. The measured luminance for 18 display levels is plotted in relation to the Dicom 3.14 standard luminance response function. b. The measured contrast response computed from 18 gray levels is related to the expected response associated with the Dicom 3.14 standard luminance response with 10%; tolerance limits indicated. c. The measured contrast response computed from 256 gray levels is related to the expected response associated with the Dicom 3.14 standard luminance response.

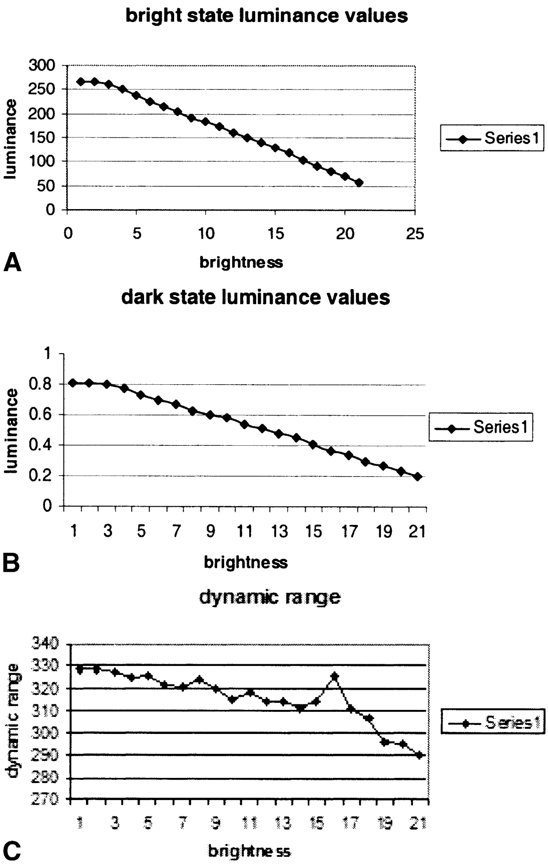

Fig 6. a,b,c. An illustration of the bright and the dark states at different brightness levels as well as the L_{max}/L_{min} in relation to the changes in brightness settings.

the actual driving levels have been changed. The phenomenon is more prevalent at lower brightness settings as it intensifies with decreases in temperature. This phenomenon, which is present in the evaluated unit, is supposed to disappear completely in subsequent production devices. All luminance measurements were taken in total darkness using the DICOM test pattern with 10% area and 20% surrounding luminance.

DISCUSSION

We used software written at Northwestern University to update gamma correction tables with the specified LUT to measure calibrated response. The downside to correcting the look-up tables in hardware is a minor loss of color because certain driving levels are not going to be achievable based on the modified LUTs. Creating look-up tables and manipulating *P* values directly in software may be preferable when color integrity is very important, but it introduces a high degree of complexity. This complexity can be avoided at a relatively small price in color quality, especially where grayscale response is of primary importance.

Taking advantage of the human eye is sensitivity for small differences in luminance, as opposed to differences in color,[10,11] creating a greater number of DICOM compliant gray levels should improve contrast resolution without going to 10-bit output displays. Commercial 10-bit displays are not only much more costly but may also require longer delays in transmitting each pixel. Other techniques such as dithering, error diffusion, and sub-pixel scaling can be employed to manipulate the 8-bit output systems to display 10-bit signals without much distortion, effectively emulating 10-bit output displays. The color-management capabilities built into IBM T221 displays, which enable the 10-bit color correction mechanism through spatial dithering, could offer a middle of the road solution.

CONCLUSION

The initial measurements produced on the IBM T221 9-MPixel color LCD monitor put it well within the range for diagnostic quality work stations and warrant further investigation. The color capabilities of the panel enable RBG calibration that closely follows the DICOM gray scale display function. Although the maximum luminance of the monitor is a little below 300 cd/m^2 which is lower than that of some other diagnostic quality work stations now in use, its dynamic range is about 300 and thus falls within the range recommended by AAPM. Other vendors are starting to manufacture monitors with similar specifications; the cost of such panels is expected to drop rendering them even more desirable for use in diagnostic imaging. As the next step, we intend to conduct a contrast-detail study and a clinical evaluation of the monitor. A host of opportunities for exploiting the color features of this display will open up if this novel color flat panel can adequately present diagnostic quality grayscale images.

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