Evaluation of video gray-scale display

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Setting up and maintaining video display monitors properly will help to reduce display variation and improve overall presentation of the radiological image. Display monitor gray-scale characteristics were examined using the SMPTE test pattern. This test pattern may be used as a standard for adjusting brightness and contrast. The controls should be adjusted to display the full dynamic range so that the 5% and 95% signal levels in the pattern are visible. Measured luminance on a laboratory workstation used for radiological perceptual experiments, and on the Siemens CT gray-scale monitor was determined to range from 0.17 to 76.0 nit, and 0.17 to 24.66 nit, respectively. These were compared with the range of approximately 17 to 514 nit for a typical film–viewbox combination. Characteristic curves were determined for both monitors, and CRT gammas were 3.34 and 2.48 for the perceptual workstation and CT console, respectively. The display gamma was determined from fitting luminance data to a log–log plot of luminance versus input gray level. The usefulness of the SMPTE test pattern for visual presentation as well as photometric measurement is demonstrated.

Key words: display monitor, gray scale, SMPTE test pattern, luminance, characteristic curve

I. INTRODUCTION

Protocols for the setup and periodic evaluation of video display devices will become part of the standard quality control program in modern radiology departments, because the viewing of digital images on these devices is becoming an essential activity. Evaluation of the video monitor is important to insure that important image information is not lost during the visual presentation. The testing of performance characteristics such as linearity, distortion, high and low contrast resolution, and gray scale provides a means for proper adjustment and maintenance of the display. Linearity (i.e., alignment of vertical and horizontal lines) and distortion can usually be observed through visual inspection of the image, while resolution and gray-scale evaluation may require the use of test patterns for more quantitative information.

The SMPTE (Society of Motion Picture and Television Engineers) test pattern was designed for use in standard practice for setup and evaluation of video and hard copy displays.[1–5] It can be used for both visual inspection and measurement of performance characteristics of the display device (see Fig. 1).

The proper setup of the display monitor requires appropriate settings of the brightness and contrast controls in order to display the full dynamic range of the image. This is important because with improper settings, image information may be lost. The SMPTE test pattern can be used as a means of checking the brightness and contrast controls of a video display monitor. Gray *et al.*[2] suggested adjusting the brightness and contrast so as to display the full range of gray, while at the same time keeping the brightness at a level that is pleasing to the viewer. This is accomplished on the test pattern by adjusting the controls so that the 5% signal level steps at both ends of the gray scale are visible. Similarly, Roehrig *et al.*[3] used the SMPTE test pattern for monitor adjustment in their evaluation of CRT displays. The importance of physical performance of CRTs in comparison to the film–viewbox combination was discussed by Blume, Roehrig *et al.*,[4,6] and some easy tests were presented that can be utilized for this performance evaluation.

In most cases, for clinical application, a visual inspection of the test pattern displayed on the monitor is sufficient. More quantitative information regarding the effect of brightness and contrast may be obtained from luminance measurements of the step wedge presented in the center of the SMPTE test pattern. Bronskill[5] used this test pattern to investigate how observers used brightness and contrast controls to set up the gray-scale display on an MR imaging system. From the luminance data, he found that the observers chose similar gray scales when using the 5% and 95% signal levels in the SMPTE pattern to set up the display. Also, there was good repeatability for a particular observer, i.e., observers set up the display in much the same way when asked to repeat the procedure 10 days later.

The gray-scale characteristics of two display monitors have been evaluated. Each monitor has its own luminance-response curve, indicating how image information is displayed across the full dynamic range. It is the purpose of this study to show how the SMPTE test pattern may be used to set up and maintain video displays. It may also be used to characterize the mapping between digital gray level and luminance so as to determine what part of the gray scale may need to be modified in order to display perceptually useful information. For a discussion of physical performance of CRTs, refer to Blume *et al.*,[4] who use this test pattern to make a direct comparison of performance characteristics between CRT and hard copy displays, and recommend a CRT display function standard. They also de-

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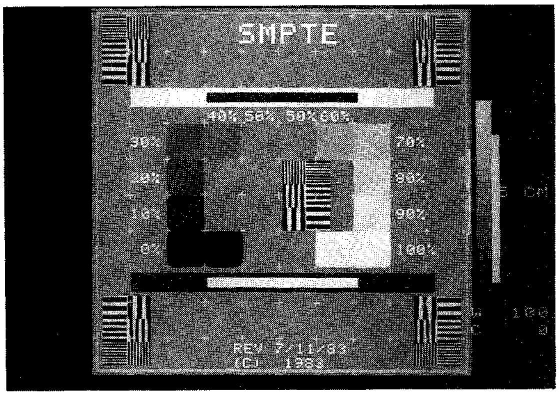

FIG. 1. 1983 version of SMPTE test pattern (7/11/83). Gray-scale step wedge in the center of pattern was used for luminance measurements.

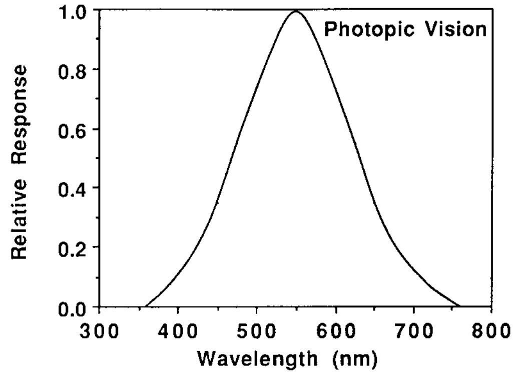

FIG. 2. C.I.E. luminosity curve, illustrating relative sensitivity of human eye as a function of wavelength.

scribe spatial resolution, and information content that is present in the CRT displayed image.[7]

A. Radiometry, photometry, and units

When measuring the brightness of a display device, it is important to identify the particular quantities that are used. Radiometry is defined as the measurement of radiant energy, i.e., radiation from the entire electromagnetic spectrum (10^{-9} to 10^{15} nm). Photometry is defined as the measurement of light energy, that is, energy from the visible portion of the spectrum with wavelengths from approximately 380 to 760 nm.[8]

The brightness from the surface of a display may be described in terms of the amount of energy or radiance. When the radiant energy is modified by the response of the human eye, it is then known as luminance. Light and related photometric quantities are defined through measurements which take into account the physiological response of the human eye, and thus are not considered basic physical quantities.

The primary quantity in both systems is power; the amount of energy/time. The watt, a radiometric unit, specifies the amount of energy, whereas the lumen, a photometric unit, describes that energy's ability to elicit a visual response.

The lumen is the unit of luminous flux, or the light energy per unit time emitted from a source. The candela (cd) is the S.I. unit of luminous intensity, or the number of lumens/steradian. Luminance is defined as the luminous intensity per unit area, and may be expressed in units of footlamberts (fL), or cd/m^2, where 1 fL = 3.426 cd/m^2. The S.I. unit of luminance is the cd/m^2, or nit. Thus luminance is the amount of light energy per unit time, per unit solid angle, per unit area, emanating from a surface such that, when incident on a detector such as the eye, a response is produced that is proportional to the amount of this energy.

The photometric quantities as identified above are relevant only when describing the visual response to a stimulus. Radiant energy from any other part of the nonvisible spectrum cannot be described in terms of luminance.

The ratio between the photometric quantity and the radiometric quantity is called the relative luminosity or visual response factor. This function is described by the C.I.E. (Commission Internationale de l'Eclairage) photopic or luminosity curve.[9] This curve (Fig. 2) specifies the photopic sensitivity of the visual system to a particular wavelength of light. This sensitivity is then the weighting factor that converts radiant energy to luminance. It is the difference between perceived luminance of displayed gray levels that is important when considering characteristic curves and proper monitor setup.

B. Gray-scale transformation and Weber's law

Our goal for the display transformation used in our perceptual experiments was to assure that equal discriminability between gray levels, is provided across the full dynamic range. This can be achieved by (1) using a linear transformation between log-luminance and input gray level and (2) displaying a sufficiently bright image.

The eye's response to changes in luminance is nonlinear and is described by Weber's law which is given by

$$\Delta B/B = K, \tag{1}$$

where B is the brightness, K is the Weber ratio, and ΔB is the just noticeable difference in brightness.[10] This law remains valid in the luminance range where the Weber ratio is constant; from approximately 3.4 to 3400 nit.[11] Thus if one assumes that the range of luminance displayed on the monitor satisfies Weber's law, then a linear transformation between log-luminance and input gray level makes all displayed gray levels equally discriminable.[12]

Another goal of our investigation was to understand the technical factors that determine the transformation between gray level and pixel luminance. CRT luminance is due to electrons striking a phosphor screen. The luminance is proportional to the amount of energy deposited in the phosphor (see Fig. 3). Assuming that the energy of each electron is constant, i.e., the voltage between the screen and cathode is constant, the brightness is proportional to the electron beam current I_b which is given by[13]

$$I_b = k(V_S + V_g)^n,$$

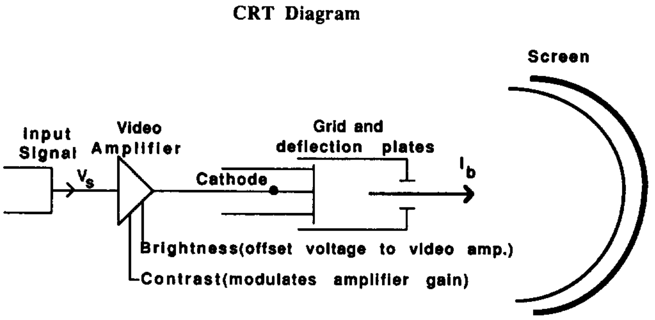

FIG. 3. Diagram of CRT parameters showing input signal, beam current, and monitor controls.[13]

where k is a proportionality constant, V_S is the input signal corresponding to the digital gray-level value, V_g is the offset voltage, and n is the gamma of the monitor. Consequently, the luminance is a nonlinear function of input voltage:

$$L = k'(V_S + V_g)^n. \tag{2}$$

From a log–log plot of luminance versus input signal, the gamma of the display can be determined from the slope of the curve, using Eq. (2), i.e.,

$$\log L = K' + n \log(V_S + V_g), \tag{3}$$

where $K' = \log k'$.

By adjusting the brightness and contrast controls, and thus changing I_b, the luminance transformation of the CRT can be manipulated.[13] The brightness control sets the offset voltage of the video amplifier by adjusting the cathode potential of the CRT, and the contrast control is used to change the amplifier gain of the video signal. These controls determine the range of the gray-scale display (minimum and maximum brightness), and also the path from minimum to maximum brightness.

Equation (3) can be used to describe characteristic curves determined from luminance measurements of several monitors. As shown in Fig. 4 the shape of the curve is a result of the mapping between input gray level and output luminance of the monitor. For a particular brightness and contrast setting, each pixel in the image represents a given input signal. It is the distribution of these values across the range of gray from black to white, and the manipulation of I_b via the control settings, that determine the characteristic curve of the display. As brightness is increased and contrast is held fixed, the response curve is shifted to higher luminance levels. When only contrast is adjusted, the slope of the response curve is changed due to greater difference in luminance between successive gray levels.

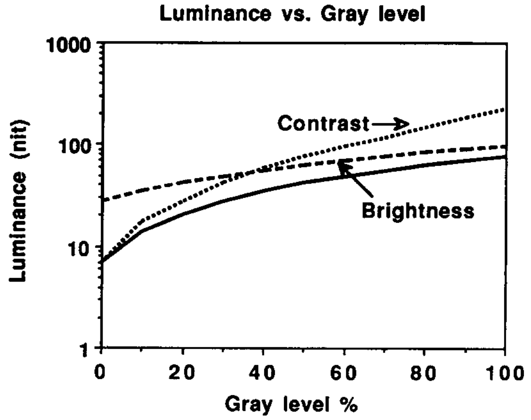

FIG. 4. Brightness and contrast manipulation. When brightness is adjusted and contrast remains fixed (solid arrow), luminance curve shifts to different level. Contrast adjustment (open arrow) changes shape of curve.

Thus from a set of input values corresponding to the image data, which are converted to an analog input signal, a look-up table (LUT) may be established from luminance measurements on a selected set of gray levels. The look-up table is the mapping between input signal and output brightness of the monitor.

II. METHODS

The perceptual workstation monitor used was a SUN 2064M series gray-scale CRT display with a 1152×900 pixel resolution manufactured by Philips Ltd. (see the Appendix for equipment specifications). This monitor is used to display images used as stimuli for radiological perceptual experiments. Test patterns are displayed in the center of the monitor in a 512×512 format with a surrounding dark region.

A Quantum Instruments PHOTO-METER 1 photometer with a 3-mm aperture fiber optic probe (accuracy 7% of full scale) was used to measure luminance. This photometer was provided by Nuclear Associates (Carle Place, New York). The photometer probe was positioned on the monitor at the center of the patch being measured. This was done to minimize the contribution of reflections from the region surrounding the measurement area. Ambient light was kept to a minimum by turning off room lights.

The SMPTE test pattern provided a quick test to check the visibility at the two extremes of the gray scale, that otherwise may have gone unnoticed. Brightness and contrast controls were set at the maximum and kept fixed for all measurements. These settings seemed to provide the best visibility of all gray levels even though the 95% signal was visible while the 5% was not. The 5% signal was not visible at any setting of the controls using the look-up table provided by SUN. The location of the gray scale in the test pattern was chosen to avoid problems with reduced brightness at the periphery of the monitor.

A. Luminance measurements

The SMPTE test pattern was linearly transformed to the SUN raster format such that the 0% and 100% levels in the pattern corresponded to gray level 0 and gray level 255, respectively. Since the low end of this range was not visible, the display transformation also was modified so that level 0% was mapped into gray level 55. This display transformation was used in the experimental evaluation. The pattern's physical size as measured on the perceptual monitor was 15.2×15.2 cm, with individual patches 1.5 ×1.5 cm or 51×51 pixels.

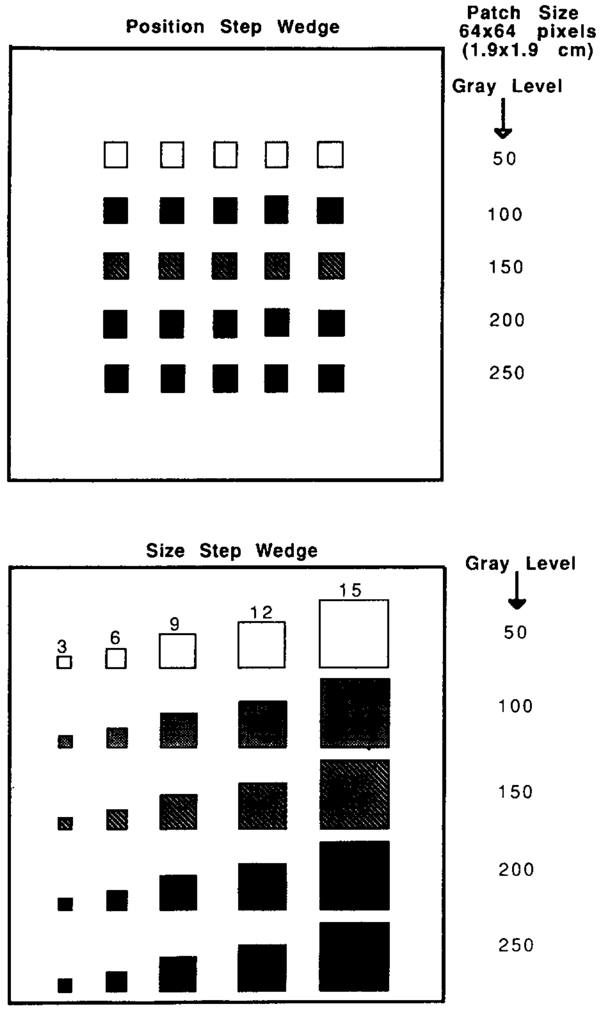

FIG. 5. Position and size step wedges are displayed on the perceptual workstation monitor. Position wedge consists of five gray-level patches displayed horizontally and vertically on the screen. Horizontal wedge is shown. Size wedge consists of five gray-level patches of different sizes displayed on the screen.

Luminance measurements were also made across the gray scale or the SMPTE pattern displayed on the Siemens SOMATOM PLUS CT monitor in the radiology department (see the Appendix for specifications). The pattern's physical size as measured on the Siemens monitor was 19 ×19 cm, with individual patches 1.9×1.9 cm or 39×39 pixels. Ambient lights were dimmed to simulate a typical clinical reading environment.

Simple step-wedge patterns were created and displayed with a constant surround in order to minimize background influence on the individual gray-level patch considered. In this manner it was possible to control the environment surrounding the patch. The position wedge pattern was created to investigate any changes in luminance at different positions on the perceptual workstation monitor. This wedge consists of five gray-level patches (0, 50, 100, 150, 200) that were displayed both horizontally and vertically on the screen (see Fig. 5). Each patch was separated 0.95 cm from its neighbor by a dark surround. The size of each patch in the wedge was 64×64 pixels or 1.9×1.9 cm. Luminance was measured across each wedge horizontally, and vertically for each of the five different gray levels.

The size wedge pattern was created to determine the smallest size patch that could be measured accurately with this instrument. Knowing this limit, one can determine whether the SMPTE test pattern contains gray-level patches large enough to be measured accurately with a particular instrument on a particular monitor. This pattern consists of a series of five step wedges, each containing five square patches. The patch sizes were 3, 6, 9, 12, and 15 mm on edge so that the ratio of patch size to aperture diameter was 1, 2, 3, 4, and 5, respectively. As shown in Fig. 5, the five wedges were displayed horizontally across the screen of the perceptual monitor. A dark region of surround separated the wedges. Luminance values were recorded for each of the sizes at each of the five gray levels. These values are plotted as a function of size ratio.

III. RESULTS

All gray-level patches in the SMPTE test pattern did not contain the same gray-level value surrounding the patch. The step-wedge patterns provided a means of evaluating luminance as a function of position and size of patch within a constant background.

There was very little variation in luminance at the different positions across the perceptual workstation monitor. As shown in Fig. 6, the luminance remained relatively constant vertically and horizontally for each of the five levels. Since the SMPTE pattern contains patches at different positions, it is instructive to know that the measured luminance of an object will not be affected by its position. It is important to establish this fact since many medical images contain the same structures displayed at different positions on the screen.

In Fig. 7, the luminance is plotted against the ratio of patch size (length of edge) to aperture diameter for each of five different gray levels as displayed on the perceptual monitor. Each curve indicates how large the patch must be relative to aperture size in order to achieve a measurement of luminance that remains constant. At the higher gray levels (150, 200, 250), where there is a greater difference between gray level of patch and gray level of background (i.e., increased contrast), the change in luminance between the three smallest sizes was much greater than the change at the lower gray levels. The luminance remained constant at the three highest gray levels for an object larger than three times the aperture diameter. At the two lowest gray levels, the contrast between patch and background is not large enough for the instrument to distinguish between the two. The low value of the background gray level contributes significantly to the measurement, and thus a lower value of luminance is recorded. In order to achieve stability, an object should be at least three times larger than the aperture diameter. Thus the gray-level steps in the SMPTE test pattern, which are 15 mm on edge, should present no difficulty.

Measurements of luminance were made on each of the 11 steps of the SMPTE pattern displayed on the perceptual workstation monitor. Figure 8 shows results for the trans-

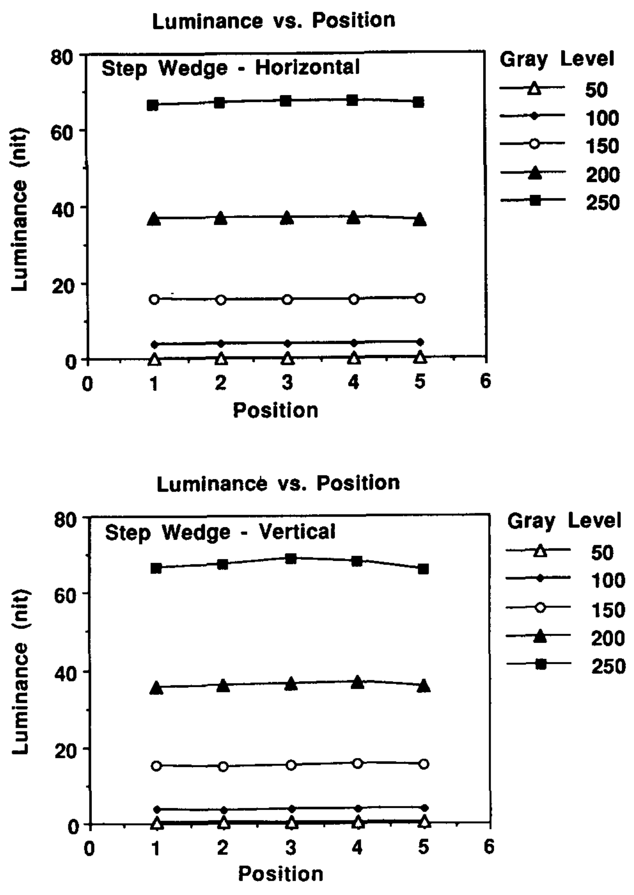

FIG. 6. Luminance of five different gray levels as a function of position in both horizontal and vertical direction on the perceptual workstation monitor.

formation both before and after it was modified. The gray-level steps were all distinguishable. The 5% and 95% signals were visible when the 55 to 255 gray-level transformation was used. The range of measured luminance across the full SMPTE gray scale (0 to 255) was 0.17 to about 76.0 nit, compared with 17 to 514 nit for a typical film–viewbox combination. The images of the SMPTE pattern on film were photographed using a laser multiformat camera with a linear conversion LUT. The luminance data on the film–viewbox combination was obtained using the same photometer and probe.

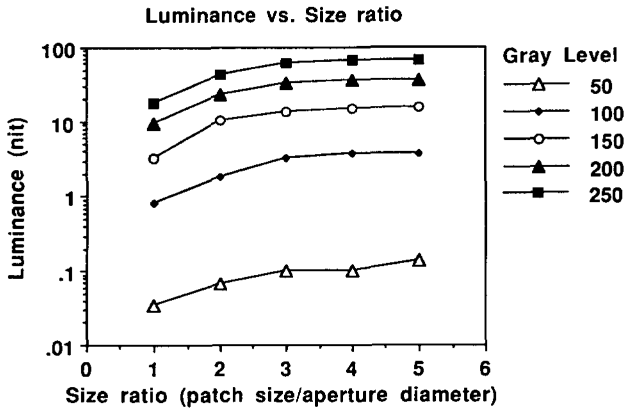

FIG. 7. Luminance of five different gray levels as a function of patch size.

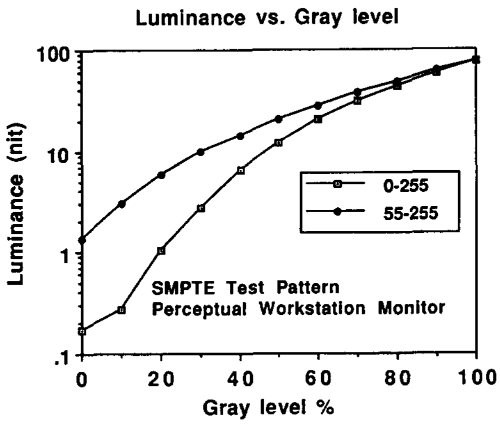

FIG. 8. Luminance versus gray level of SMPTE test pattern for two different LUT transformations on perceptual workstation monitor.

On the perceptual monitor, the low end of the curve for the 0 to 255 transformation where the measurement was less accurate, represents the portion of the gray scale near the photometer's lower limit of sensitivity (i.e., less than 0.34 nit). The change in luminance with gray level for the dark steps is greater than at the high end, but the low value of luminance here corresponds to a region where differentiation between gray levels, both visually and through measurement, is poor. Using the 55 to 255 transformation, the 5% gray level was visible. A much flatter curve is produced, but there is much more discriminability at the low end.

The curve shown in Fig. 8 for the (0–255) transformation is very similar to the data presented by Roehrig.[6] He generated the two characteristic curves by measuring the same 11 gray-level steps in the SMPTE pattern using different photodetectors, and obtained a maximum luminance of 147 nit, about a factor of 2 greater than the maximum, 76.0 nit, indicated in Fig. 8. The two curves he presented, show a deviation in measured luminance between gray level 0 and 25. At gray level 0, the response from one detector was 0.034 nit, while the measurement from the other detector was approximately an order of magnitude higher, 0.51 nit. This flattening out at the darker steps, much like the behavior of the perceptual monitor, was presumably due to veiling glare resulting from internal light scatter within the CRT.

In Fig. 9, response curves are presented for both the perceptual monitor (gamma = 3.34) and Siemens CT monitor (gamma = 2.48) over the range of 255 gray levels. The gammas were determined from the data in representing the linear portion curve (i.e., gray levels above 25), by using linear regression and applying Eq. (3). In the middle to upper range of the gray scale the perceptual monitor was brighter by approximately a factor of 3, and also shows a greater change in log-luminance and presumably a greater perceived difference in this region. There is similar behavior of the two monitors at the dark end; however, both 5%

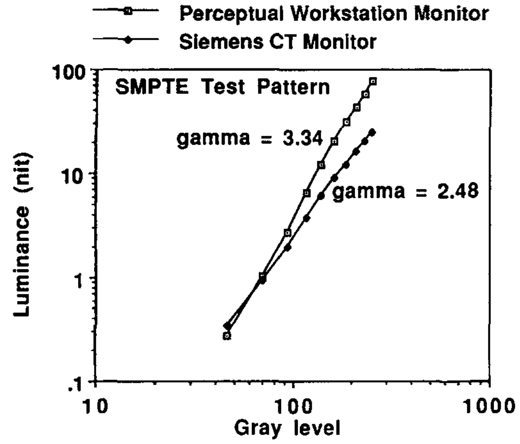

FIG. 9. Luminance versus gray level on both perceptual and Siemens CT monitors. Gammas of displays were determined from fitting this data to Eq. (3).

and 95% signals were visible on the CT monitor during measurement.

A comparison of measurements from the CT monitor and film transparency is presented in Fig. 10. The linearity of the film–viewbox curve was due to the chosen LUT for the particular film that was used. This will equalize the discriminability between gray levels, given that Weber's law remains applicable.

IV. DISCUSSION

The luminance data obtained for the lowest portion of the gray scale on the perceptual monitor, indicated a lower limit of sensitivity of the photometer. The photometer was adequate for qualitative assessment such as measuring the luminance at several positions on the monitor. At the low end of the gray scale (less than ~0.34 nit), only two data points are presented as shown in Fig. 8, and this was a limitation of the SMPTE test pattern. With data obtained from a more sophisticated and sensitive instrument, the monotonic decrease down to 0.034 nit may characterize the display more accurately. This disadvantage of CRT displays is discussed in more detail by Blume *et al.* in their comparison of hard versus soft copy displays.[4]

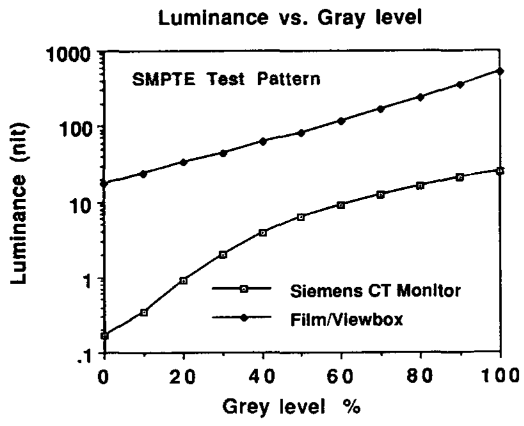

FIG. 10. Luminance versus gray level of SMPTE test pattern for film–viewbox combination and for Siemens CT monitor display.

The relative difference in brightness between a typical CT display monitor and film–viewbox combination is apparent in Fig. 10. At the low end of the gray scale, this difference is approximately two orders of magnitude, while at the high end the difference is about one order of magnitude. The amount of ambient light was not accounted for when considering the luminance output of the CT display, however, it would appear that due to this effect of ambient light, the CT monitor should be used at 10 to 100 times lower ambient light levels to obtain similar visibility.[4]

The response curve for the CT monitor shows similar behavior to that of the perceptual workstation monitor, even though the perceptual monitor display was brighter. The overall brightness of the monitor is important when trying to perceive low luminance levels. At the dark end of the gray scale on the perceptual monitor, differences in measured luminance were observed; however, discriminability was poor since these gray levels were outside the range (i.e., less than 3.4 nit) in which Weber's law remains valid.[11] The luminance measured at the 0% signal on the perceptual monitor for the 0–255 transformation, and on the CT monitor, was approximately the same (0.17 nit); however, the curve for the CT monitor does not show the same flattening out between the 0% and 10% signals. This may have been due to differences in ambient light conditions, and also the effect of internal reflections from the monitor. Using a test pattern that contained a greater number of signal levels between 0 and 20% would allow a more detailed display characterization for the low luminance levels. For radiological images, it will be important to determine how useful this low luminance information is for the observer.

The SMPTE pattern may be used for routine examination of CRT displays according to the setup procedure described by Gray.[2] When adjusting the brightness control, the offset voltage of the CRT is increased to a level so that the image is just observable. This is important when considering the effect of ambient light levels on visual interpretation or photometric measurement. Having established this "just perceptible" level, the contrast can now be adjusted thus manipulating the beam intensity, so as to produce the desired change in luminance between gray levels, i.e., one that allows visibility of the 5% and 95% signal levels. Once the brightness and contrast have been adjusted, they should remain fixed for a particular viewing environment.

This test pattern was useful for understanding display issues such as luminance and contrast, and for gray-scale evaluation of the display monitors through visual inspection and photometric measurement. It may be incorporated into the radiology department's quality control program to insure proper setup of display devices. Eventually, it can become a standard to be used on various imaging systems throughout the department, in order to minimize variation in displayed information, either from one monitor to another, or between different viewing environments.

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APPENDIX

This appendix describes the specifications for the SUN 3 perceptual workstation monitor, the Siemens CT monitor, and the Quantum Instruments PHOTO-METER 1 photometer.

The SUN 3 monitor is a 2064-M series monochrome CRT display manufactured by Philips Subsystems and Peripherals.

Specifications:

Diagonal-48.26 cm (19 in.)

Displayed video picture size—33.0×26.4 cm (1152×900 pixels).

Horizontal frequency—61.8 kHz

Vertical frequency—66 Hz (noninterlaced) Linearity—10%

%Maximum pixel format—1280×1024 pixels.

The Siemens monitor is a 1249 line monochrome CRT display.

Specifications:

Diagonal-38 cm (14.96 in.)

1024×1024 pixel display

30 frames/s

The PHOTO-METER 1 is a digital footcandle/footlambert meter.

Specifications: (Quantum Instruments Operating Manual)

Capabilities—illuminance, luminance

Readout—three digit LED display

Range—in footcandles or footlamberts, 0.01 to 99,900

Accuracy—within 7% of full scale

Sensor—silicon photodiode with photometric filter

Spectral response—close match to the C.I.E. photopic response curve.

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