Image Presentation in Digital Radiology: Perspectives on the Emerging DICOM Display Function Standard and Its Application[1]

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DICOM (Digital Imaging and Communications in Medicine) Working Group XI, formerly called ACR/NEMA (American College of Radiology/National Electrical Manufacturers' Association) Working Group XI, is currently developing a display function standard. The main objective of the standard is to define mathematically a display function for all image presentation systems. As a secondary objective, the standard aims at providing similarity in gray-scale perception for a given image between display systems of different luminance and at facilitating efficient utilization of the available digital input levels of a display system. The design of the display function incorporates the concept of perceptual linearization. The proposed standard applies to monochrome image presentation devices such as cathode ray tube monitor–display controller systems and digital laser image printers. The standard does not eliminate the use of application-specific display functions but rather ensures their effectiveness. Neither does the standard guarantee equal information transfer between image presentation devices with different physical properties; it does, however, form the basis for applying image processing to compensate for such differences.

■ INTRODUCTION

In today's radiology practice, hard-copy films of computed tomographic (CT), magnetic resonance (MR) imaging, or computed radiographic examinations are routinely produced by a laser image printer with satisfactory gray-scale rendition and without much interaction by technologists. This seemingly transparent process is the result of negotiations between imaging equipment manufacturers and printer manufacturers, who have jointly established a certain gray-scale response function for a given class of images. If the images were to be sent to a different printer, the gray-scale rendition would likely change and would no longer satisfy clinicians' needs.

Abbreviations: ACR = American College of Radiology, CRT = cathode ray tube, DICOM = Digital Imaging and Communications in Medicine, JND = just noticeable difference, NEMA = National Electrical Manufacturers' Association, SMPTE = Society of Motion Picture and Television Engineers

Index terms: Digital Imaging and Communications in Medicine (DICOM) • Images, display • Images, transmission

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When the gray-scale renditions produced by different display systems are compared, many inconsistencies become apparent because neither hard-copy printers nor soft-copy display systems adhere to a standard display function. The following examples illustrate some of these inconsistencies.

1. As part of the print service communication, the Digital Imaging and Communications in Medicine (DICOM) Standard allows the definition of modality, values-of-interest, polarity, and user-preference gray-scale transformations (Fig 1). However, these transformations can be defined only after the printer gray-scale response is known, and then for only one particular printer at a time because another printer may have a different response function.

2. In teleradiology, physicians discuss patient treatment while viewing the same images at separate remote locations. At present, neither of the communicating physicians can predict how gray scale is rendered on the workstation of the other, and both may need to make gray-scale adjustments on their respective systems before they have satisfactory (although not necessarily similar) renditions of the image being viewed.

3. After performing extensive image processing, a radiology researcher produces a soft-copy image on a general-purpose workstation and sends the image to the printer in the radiology department to obtain a hard copy of the image. Typically, the gray-scale rendition produced by the laser image printer will make the hard copy look different from the soft copy on the workstation.

DICOM Working Group XI, with representatives of the American College of Radiology (ACR) and the National Electrical Manufacturers' Association (NEMA), is currently developing a display function standard (Fig 1) to help overcome these inconsistencies (1,2).

Although we are members of DICOM (formerly ACR/NEMA) Working Group XI, we are not officially representing the working group in this article. Rather, we are presenting our own perspectives on the emerging display function standard and its application to medical image display systems. In this article, within the limitations imposed by journal gray-scale printing, it is attempted to illustrate the effects the proposed DICOM standard will have on both soft-copy and hard-copy image presentation systems.

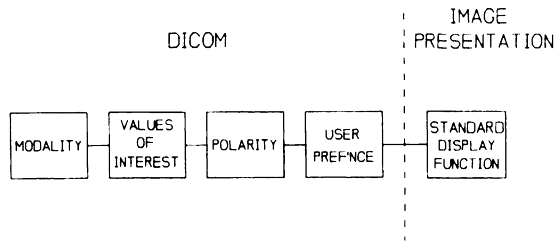
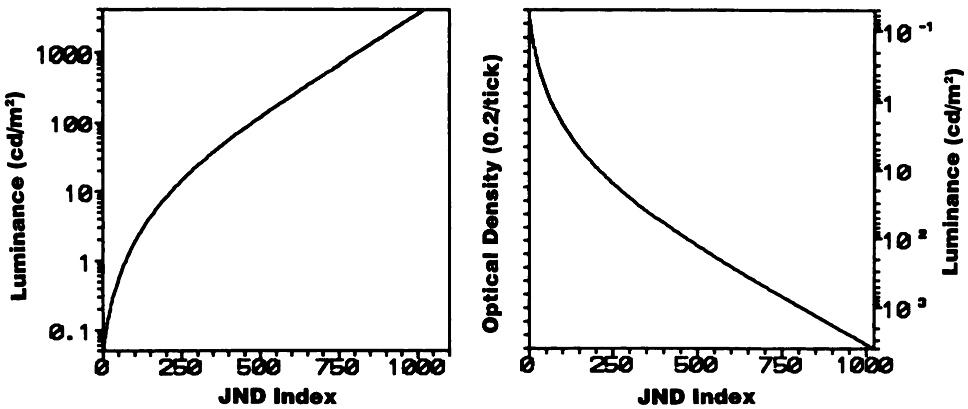


Figure 1. Schematic shows the transformations performed as part of the DICOM Standard and the additional transformation, the standard display function, proposed in the DICOM Standard. By implementing the standard display function as the last gray-scale transformation following the chain of DICOM-defined transformations, print services and future display services in DICOM gain openness and become largely independent of the characteristics of any particular image presentation device. Depending on system configuration, the DICOM transformations may be executed in part in the image presentation device.

■ PROPOSAL FOR A STANDARD: SOLUTION TO THE PROBLEM

The proposed DICOM standard defines mathematically the monochrome gray-scale response of image presentation systems, which facilitates predictable and reproducible gray-scale rendition of monochrome images. From the vast number of conceivable mathematical functions, a function was selected based on human contrast sensitivity (3-18).

An image presentation device is said to be perceptually linear when equal increments in digital input produce equally perceived differences in luminance throughout the entire range of digital input values. (Luminance is the measurable quantity that most closely corresponds to "brightness," a subjective attribute that humans assign to perceived luminance.) Strictly speaking, perceptual linearization is realizable only for very simple images. Although perceptual linearization of images is not an explicit objective of the proposed standard, it appears that perceptually linearized display functions support the secondary goals of the standard: similarity in perceived gray scale of complex images even when absolute luminance and luminance range differ, and efficient utilization of the available digital input levels of a display system. The standard display function represents a perceptually linearized display function for a special sinusoidal target. Equal increments in digital input produce equally perceived or a fixed number of just-noticeable differences (JNDs) in luminance for the target. A JND in luminance



a. b.

Figure 2. Graphs show the standard display function as luminance versus JND index (or digital input to the display system) **(a)** and optical density versus JND index **(b)**.

describes the threshold contrast for a specific target (eg, a circular patch in a uniform surrounding) that a human observer detects with 50% efficiency. JNDs are used as a logical construct for defining the standard display function.

Similarity between image presentation devices does not guarantee equal information content. Those devices with a wider luminance range or higher maximum luminance are capable of presenting more JNDs of a specific test pattern to an observer.

■ CONTENTS OF THE STANDARD

The proposed DICOM standard describes the standard display function, which defines the gray-scale response of image presentation devices and is based on human contrast sensitivity and perceptual linearization (Appendix A).

The standard display function is defined for the luminance range from 0.05 to 4,000 candelas per square meter (cd/m^2). The low end of the luminance range corresponds to a minimum practically useful luminance for cathode ray tube (CRT) monitors; the high end exceeds the unattenuated luminance of very bright light boxes used in the interpretation of mammograms. The standard display function explicitly includes the luminance generated by ambient light reflected diffusely by the display medium. The standard display function is represented graphically in Figure 2.

To comply with the DICOM standard, a given image presentation system should provide a display function that represents a section of the standard curve for the available luminance range of the presentation system. Two annexes to the standard illustrate how the characteristic curve of image presentation systems may be measured and describe a metric to assess how closely the display function of a given display system matches the standard display function.

The first annex describes how the characteristic curve of CRT monitor-digital controller systems may be measured with a computer-generated test pattern. The test pattern consists of a square covering 10% of the active display area, placed in the center of the display field and surrounded by a uniform background covering the rest of the display screen. The background is set to a fixed luminance of 20% of the maximum luminance of the display system. The luminance of the central square is systematically increased from minimum to maximum luminance by varying the digital input for that section of the display field. The characteristic display function is determined by measuring the luminance of the central square with a photometer, a measurement that includes the effect of ambient light, as a function of digital input.

The photometer must have a measurement range that extends beyond the minimum measured luminance by a factor of at least 50 to minimize the effect of limited digitization resolution. The precision, stability, and repeatability of the photometer (or densitometer to measure

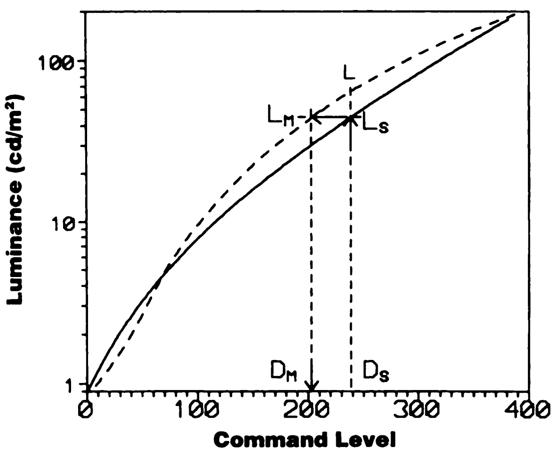


Figure 3. Graph illustrates the transformation of the display system response function so that it conforms to the display function standard. Dashed line represents the measured luminance, solid line represents the standard luminance.

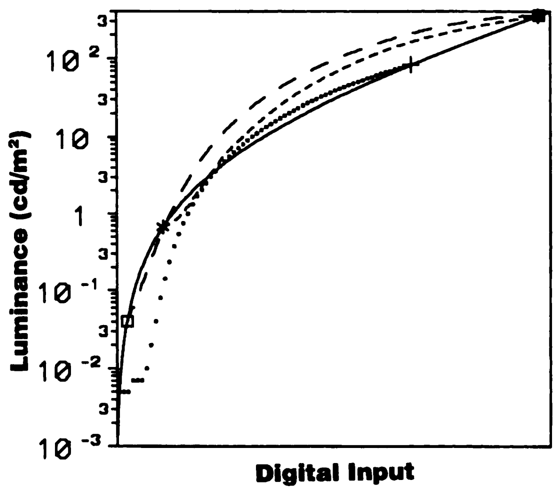


Figure 4. Graph demonstrates the characteristic curves of three CRT monitor-display controller systems (small dashed line represents monitor A; large dashed line, monitor B; dotted line, monitor C) and the corresponding section of the standard display function (solid line). The extreme luminance levels for each characteristic curve have been indicated by a pair of symbols.

the characteristic curve of a printer-film system) should be less than 2%–3% over the needed measurement range. With precise photometers and densitometers, the relative error caused by instrument noise and digitization resolution is less than 1% of the measured quantity. Errors of such magnitude fall below the perception threshold and do not adversely affect the standardization program.

Internal scatter or veiling glare in CRT monitors causes the characteristic curve to depend not only on the displayed test pattern but also on the location within the display area. Therefore, the characteristic curve as determined with the test pattern is not necessarily representative for all images and all locations within an image on a CRT monitor. With negligible ambient light, the suggested test pattern typically produces a maximum-to-minimum luminance range of 200:1 to 300:1, which is not very different from the range within a chest radiograph displayed on a CRT monitor.

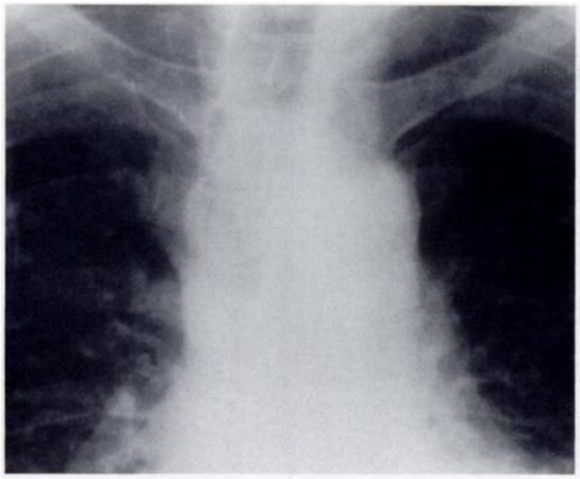
The second annex describes why the transformed display function must coincide both globally and locally with the standard display function. Specifically, the luminance intervals along the curve, defined by the given digitization resolution, should be proportional to a fixed multiple of the JNDs of the standard display function over the entire luminance range of the display system. A metric for assessing how well the transformed display function matches the standard display function is given in Annex C of the Informative Section of the standard and in reference 19.

■ IMAGE PRESENTATION WITH AND WITHOUT THE STANDARD

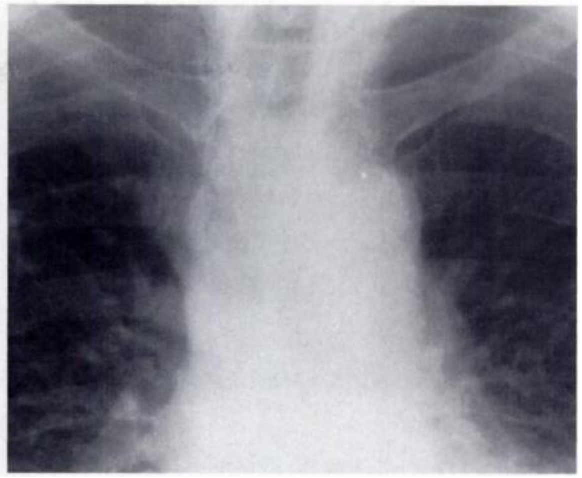
Figure 3 shows the measured characteristic curve of a CRT monitor–digital controller system and the section of the standard display function corresponding to the luminance range of the display system. To change the gray-scale response of the system so that it follows the standard display function, a transformation is calculated that assigns to every digital input level D_s a level D_m such that, instead of luminance L, the desired luminance L_m is produced that matches the standard display function.

Figure 4 shows the characteristic curves of three CRT monitor–display controller systems from workstations used in today's radiology departments. The display curves, although they are moderately different from each other and from the corresponding section of the standard display function, are typical characteristic curves.

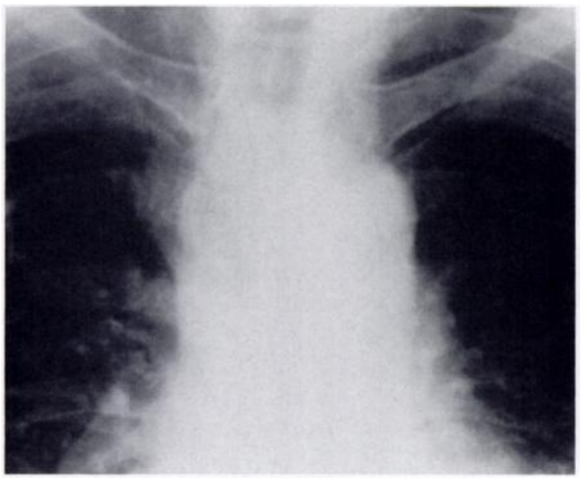
Figures 5 and 6 illustrate the effect of the different display functions on gray-scale rendition before and after implementing the standard display function. Figure 5 shows photographs of the same section of a computed chest radiograph as it appears on the three CRT display systems with the default characteristic curves presented in Figure 4. Figure 6 shows the chest image on the same three display systems after system-specific gray-scale transformations have been applied so that the display functions all conform to the standard. Although the CRT



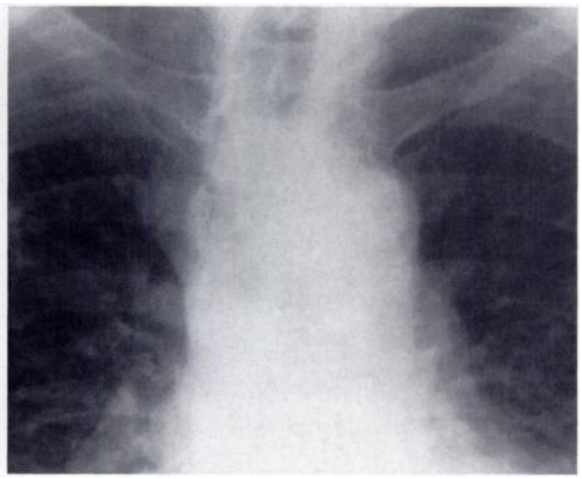
5a.



6a.



5b.



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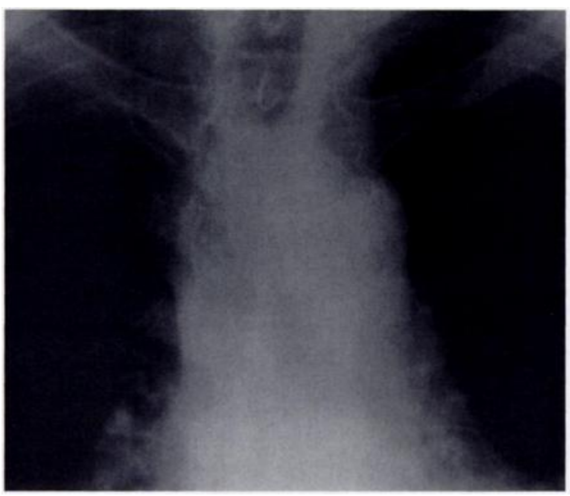
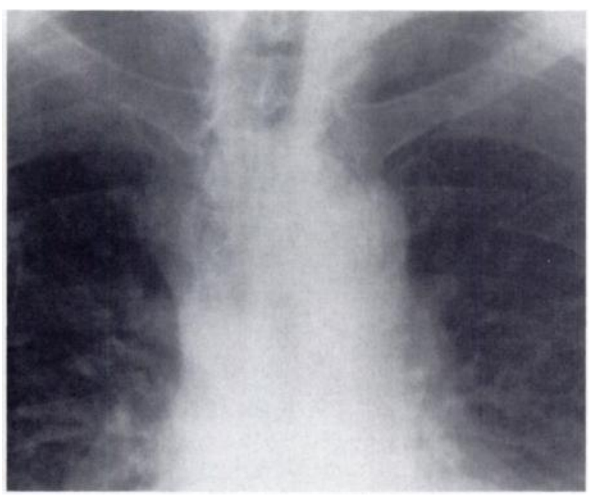
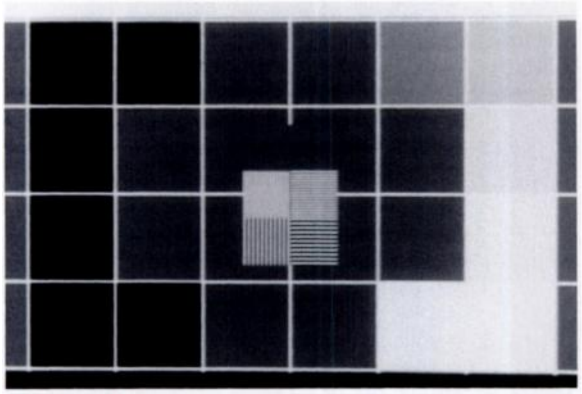


5c.

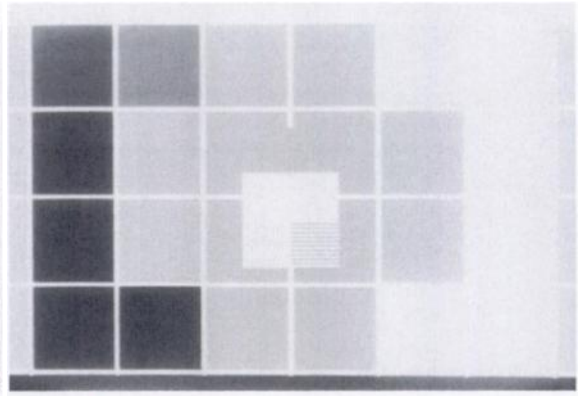


6c.

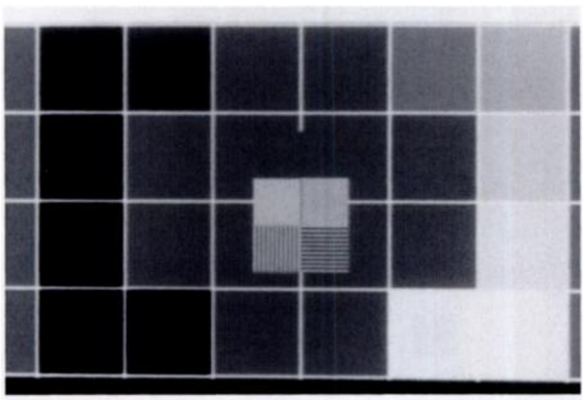
Figures 5, 6. **(5)** Effect of different display functions of three CRT monitor–display controller systems before a gray-scale transformation is applied to the image data to make the systems comply with the standard display function. Photographs showing detail of a computed chest radiograph near the heart-lung border were taken under identical conditions except that the exposure for each photograph was adjusted proportional to the maximum luminance of the monitor for the corresponding CRT monitor–display controller system. **(6)** Effect of system-specific gray-scale transformations to make the display systems comply with the standard display function. Photographs of the same detail of the computed chest radiograph and produced with the same three display systems as in Figure 5 but after standardization to the display function standard now have a very similar appearance. These photographs and those in Figure 5 were processed identically (Appendix B).



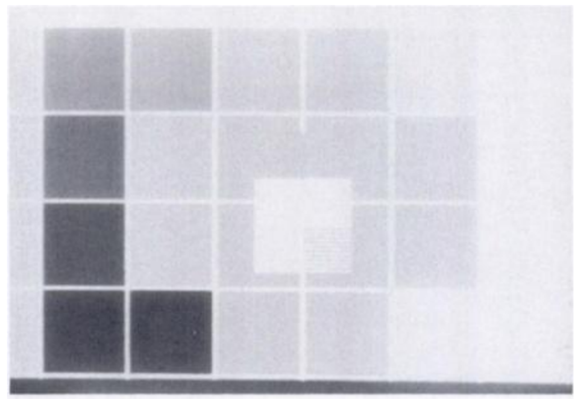
7a.



7b.



8a.



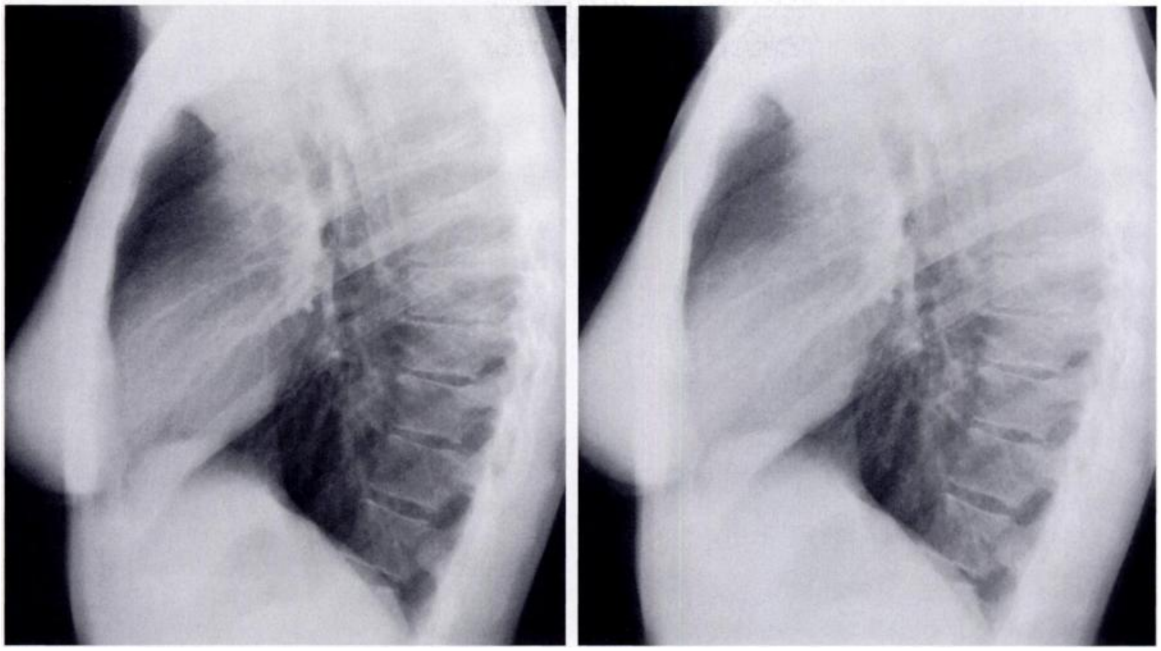
8b.

Figures 7, 8. **(7)** Center sections of the SMPTE pattern containing the 95% **(a)** (bottom row, second square from right) and 5% **(b)** (bottom row, second square from left) fields (ie, the 95% target square inside the 100% surround square and the 5% target square in the 0% surround square) displayed with the default characteristic curve of monitor C (see Fig 4). The 95% field in **a** is just barely visible; the 5% field in **b** is not visible at all because, as often happens, too few digitization values were assigned to the high-luminance range and too many to the low-luminance range. **(8)** Same sections of the SMPTE pattern as shown in Figure 7 after application of a gray-scale transformation that makes the display system conform to the display function standard. Both the 95% **(a)** and 5% **(b)** fields are now more equal in contrast. Figures 7a and 8a were photographed and processed identically, as were Figures 7b and 8b. The two portions of the SMPTE pattern were processed separately because the print medium was unable to reproduce the contrast visible in the soft copy on the CRT monitor.

monitors have different luminance levels and luminance ranges within the chest radiograph, the images now appear similar to each other, which was not true for the nonlinearized images.

Similarly, Figures 7 and 8 demonstrate display function standardization with images of the Society of Motion Picture and Television Engineers (SMPTE) test pattern. Figure 7 shows two sections of the SMPTE pattern on display system monitor C with the default characteristic curve (shown in Fig 4). Figure 8 shows the same image sections after standardization of the display system.

Figures 9 and 10 demonstrate the effects of the display funtions of different laser image printers. As indicated earlier, the characteristic curve of laser image printers is typically well controlled and is mathematically defined, although it is often not known to users of the system. In this hypothetical situation, Figure 9a shows a printed detail from a computed chest radiograph with gray-scale rendition as expected. The printer had been configured such that its optical density was a linear function of the digital input data. The designer of the computed radiography system knew this and applied a sigmoidal display function transformation (Fig 10) to the image data before sending them to the printer. On this day, the printer failed to work and the radiology technologist



a. b.

Figure 9. **(a)** "Proper" gray-scale rendition of the detail of a computed radiograph printed by a laser image recorder defined jointly by the manufacturers of the computed radiography system and the printer system. The printer was configured to produce an optical density scale linearly proportional to the digital output of the computed radiography system. The computed radiography system mapped the spatially filtered image data to a sigmoidal gray-scale curve. (The hard copy was displayed on a typical light box.) **(b)** Hard copy of the detail of the computed radiograph in **a** made with a printer that reproduces the standard display function and a sigmoidal "modality" look-up table designed for a printer with a "linear" (ie, optical density proportional to digital input) characteristic curve. The photograph was taken under the same exposure conditions as in **a**.

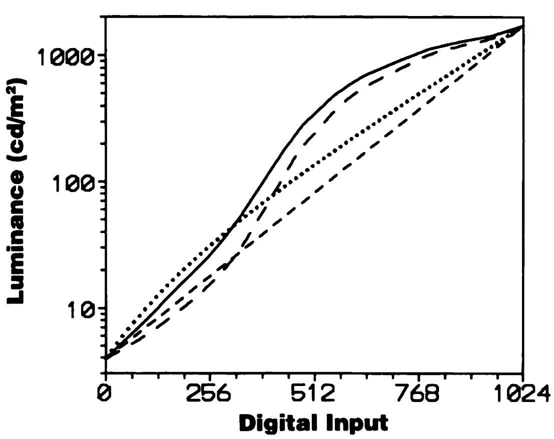


Figure 10. Graph shows the display functions used to print the computed chest radiograph shown in Figure 9. The display functions are computed by cascading the linear or standard display function with the sigmoidal display function for the radiograph. Small dashed line = assumed response of printer, dotted line = actual response of standard display function, large dashed line = desired display function, solid line = resultant display function.

routed the computed radiograph to another high-performance laser image printer. This second printer was configured to comply with the display function standard; however, the technologist did not modify the data transformation in the computed radiography system. The resultant display function and image rendition are shown in Figures 9b and 10. Once more we see how important it is that display devices on a network abide by the display function standard.

For most image printer systems, the boundary between the DICOM domain and the image presentation domain is not as distinct as portrayed in Figure 1. In the future, however, separation of the two domains may become predominant, leading to greater transparency for the printer user and simpler interfaces with image presentation devices.

■ CONCLUSIONS

The proposed DICOM standard has two objectives: (*a*) It defines a mathematical function for the relation between the luminance and digital input of an image display system, thereby providing an objective method for generating a predictable and reproducible gray-scale rendition of monochrome images; and (*b*) it aims at providing similarity in gray-scale renditions among different display devices independent of their luminance, thereby facilitating efficient utilization of the available digital input levels of a display system.

Even though further testing is needed to determine the optimal standard display function for the second objective, the members of the DICOM Working Group sensed an urgency to proceed with the development of the standard. Side-by-side deployment of hard- and soft-copy medical imaging systems and exchange and communication of images between very different image presentation systems will become much more acceptable, even with only limited perceived gray-scale similarity but objectively predictable display system behavior.

It is crucial that the DICOM Display Function Standard be adhered to if image telecommunication as envisioned in the DICOM Standard is to work properly. Future extensions of the DICOM Standard will refer explicitly to the proposed display function standard.

The proposed standard is not a visualization standard. Because the standard display function is mathematically defined, the standard facilitates pseudo-standard visualizations in combination with application-specific display functions. Soft-copy display devices potentially differ from each other in maximum luminance and luminance range and usually offer lower maximum luminance and a smaller luminance range than do hard-copy display systems. Even when all image presentation devices conform to the display function standard, the differences in maximum luminance and luminance range will generally require different degrees of spatial filtering or local contrast equalization to maximize perceived information transfer.

Establishment of the DICOM Display Function Standard is the first step toward standardizing the image quality of display systems. More standardization may become necessary, especially when one considers the following: (*a*) in critical diagnostic tasks such as mammography, the ACR has adapted standards that define system properties such as minimum spatial resolution and noise; and (*b*) the ACR, the American College of Cardiology, and the Food and Drug Administration have been very careful about accepting lossy data compression for primary diagnosis in routine practice. However, current soft-copy display systems vary widely in terms of spatial resolution and noise, as well as gray-scale characteristic curve. As a result, they may not always meet minimum image quality requirements and may perform the equivalent of lossy data compression when displaying an image. Consequently, standard classification of image presentation systems concerning spatial modulation transfer and noise properties may need to be developed to maintain not only predictable gray-scale rendition, which the proposed standard addresses, but overall image quality in image communication.

Public review of the standard has been completed. Once the final revisions have been implemented, the standard can be obtained in printed form from the NEMA, 1300 N 17th St, Suite 1847, Rosslyn, VA 22209, telephone number (703)841-3300. The standard will also be accessible via the Internet under a NEMA http (hypertext transfer protocol) address (contact David Snavely of the NEMA).

Acknowledgment: The DICOM Display Function Standard resulted from the collaborative effort of many individuals from industry, academia, the ACR, and the NEMA.

Appendix A

Contrast sensitivity is derived from Barten's model of the human visual system (20–22). Specifically, the DICOM standard refers to contrast sensitivity for a standard target consisting of a square subtending a visual angle of two degrees by two degrees with a horizontal or vertical grating and a sinusoidal modulation of four cycles per degree, which is near the peak contrast sensitivity of the human visual system. (When viewed from a distance of 50 cm, the dimensions of the square are 1.75×1.75 cm, and the grating modulation has a frequency of 4.6 line pairs per centimeter.) The square is placed on a uniform background with a luminance equal to the mean luminance of the target. Contrast sensitivity is defined by the threshold modulation at which the grating becomes just visible to the average human observer. Luminance modulation represents the JND for the target at the given luminance. The standard display function is calculated by computing the threshold modulation as a function of mean grating luminance and where the mean luminance values of successive JNDs are separated by the peak-to-peak modulation of the JNDs.

The standard lists the JNDs in luminance for the standard test target as a function of luminance over the entire luminance range described earlier and provides an interpolation formula for these values that represents the mathematical definition of the standard display function (2).

Appendix B

Both the soft- and hard-copy images were photographed on 35-mm T-Max film (Eastman Kodak, Rochester, NY) at 50 ASA. The film was processed in T-Max developer (Eastman Kodak) for 5 minutes at 75° F (24° C) and fixed and washed under standard conditions prescribed by the manufacturer. The film images were printed on Multigrade IV RC-Deluxe paper (Ilford, Paramus, NJ) and developed with a 2150 RC automatic processor (Ilford).

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