AAPM ON-LINE REPORT NO. 03

ASSESSMENT OF DISPLAY PERFORMANCE FOR MEDICAL IMAGING SYSTEMS

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CONTENTS

PREFACE

The adoption of digital detector technology and picture archiving and communication systems (PACSs) have provided health care institutions an effective means to electronically archive and retrieve radiological images. Medical display workstations (also termed soft-copy displays), an integral part of PACS, are used to display these images for clinical diagnostic interpretation. Considering the fundamental importance of display image quality to the overall effectiveness of a diagnostic imaging practice, it is vitally important to assure that electronic display devices do not compromise image quality as a number of studies have suggested (Ackerman et al. 1993; Scott et al.1993, 1995).

According to the American Association of Physicists in Medicine (AAPM) professional guidelines (AAPM 1994), the performance assessment of electronic display devices in healthcare institutions falls within the professional responsibilities of medical physicists. However, there are currently no guidelines available to perform this function in a clinical setting. Prior literature has focused mostly on design aspects or on the fundamental physics of the display technology (Muka et al. 1995, 1997; Senol and Muka 1995; Kelley et al. 1995). A number of investigations have begun to address the quality control aspects of electronic displays (Roehrig et al. 1990a; Gray 1992; Nawfel et al. 1992; Reimann et al. 1995; Eckert and Chakraborty 1995; Kato 1995), and the Digital Information and Communications in Medicine (DICOM) standard, through its Grayscale Standard Display Function (GSDF) Working Group 3.14, has recently provided recommendations for grayscale standardization of soft-copy displays (NEMA 2000). However, prior efforts have fallen short of providing a systematic approach for testing the performance of display devices. In order to be useful, the approach should cover all aspects of display performance, be specific to medical displays, and be relatively easy to implement in a clinical setting.

The intent of this report is to provide standard guidelines to practicing medical physicists, engineers, researchers, and radiologists for the performance evaluation of electronic display devices intended for medical use. Radiology administrative staff, as well as manufacturers of medical displays, may also find this reference helpful. The scope of this report is limited to display devices that are used to display monochromatic medical images. Since cathode-ray tubes (CRTs) and liquid crystal displays (LCDs) are currently the dominant display technologies in medical imaging, significant attention is paid to CRTs and LCDs. However, many of the tests and concepts could be adapted to other display technologies that might find their place in medical imaging in the future. It is hoped that this report will help educate medical physicists and other health care professionals on this subject, enable inter- and intra-institutional comparisons, and facilitate communication between industry and medical physicists.

HOW TO USE THIS REPORT

This report is divided into six sections and three appendices:

- **Section 1** summarizes prior standardization efforts in the performance evaluation of medical display devices.
- **Section 2** is a tutorial on the current and emerging medical display technologies. The section focuses on CRT and flat-panel LCD display devices. The section also defines photometric quantities pertaining to displays and outlines current engineering specifications of display devices. Finally, the section offers a definition for the two classes of display devices, primary and secondary devices, used in medicine and addressed in this report.
- **Section 3** sets forth prerequisites for the assessment of the display performance and includes a description of required instrumentation and TG18 test patterns. In addition, the initial prerequisite steps for testing a display device are described.
- **Section 4** is the main body of this report. The section includes the description and the general quantification methods for each key display characteristic. The section provides detailed methodology for testing each characteristic at three different levels: visual, quantitative, and advanced. The two former levels are more applicable to clinical display devices, while the latter provides guidelines and general direction for individuals interested in more advanced characterization. The section further provides guidelines and criteria for acceptable performance of the device at each of the three levels of evaluation for both the primary and secondary display devices.
- **Sections 5** and **6** outline procedures for acceptance testing and quality control of display devices. The sections include two detailed tables (Tables 7 and 8) that summarize the tests that should be performed as a part of acceptance testing or quality control, the details of which are fully described in the preceding sections 3 and 4. Sections 5 and 6 can be used as the starting point for evaluating the performance of a medical display device for medical physicists who must learn in a short time the tests that need to be performed.
- **Appendix I** provides guidelines for evaluating the performance of "closed" display systems, the systems on which the TG18 test pattern cannot be easily displayed.
- **Appendix II** is a tutorial on the requirements for equivalent appearance of images on monochrome image displays.
- **Appendix III** provides a full tabular description of TG18 test patterns.

The report is largely organized as a detailed tutorial on the evaluation of medical display devices. However, it does not need to be read or utilized in the order in which it is presented. Individuals unfamiliar with the subject might want to go through the report sequentially. However, those who are familiar with the subject or have limited time may start from sections 5 and 6 and identify the exact tests that they want to perform and the required instrumentation and patterns. The details of the tests and the tools can then be sought in sections 3 and 4.

1 INTRODUCTION

1.1 Background

The medical image display is typically the last stage of a medical imaging chain. Medical images are initially created by imaging modalities such as x-ray, ultrasound (US), magnetic resonance imaging (MRI), computed tomography (CT), or nuclear medicine scans that measure physical or functional attributes of the patient in the form of multidimensional data sets. Images vary widely in their characteristics such as size, spatial resolution, and data depth. Data from different modalities also vary in the way that they are meant to be viewed and comprehended.

Historically, most medical imaging instruments recorded images directly on films that were viewed by transillumination on a light box. The response of the film defined the relationship between the physical attribute being imaged (such as x-ray absorption) and the image characteristics (film density). The advent of digital modalities led to the generation of intrinsically electronic images. In the early implementations, these images were sent to digital printers. Many of these connections were initially direct, with a printer serving only one image source or several image sources with similar characteristics. The appearance of the printed image was controlled by calibrating each image source together with the printer to give acceptable results. It was not necessary to standardize either the source or the output device, since they were adjusted together. Later, network capabilities were added to digital printers so that several imaging devices could access a single printer. Printers were designed to accept a command code from the modality that would select the appropriate modality-specific response of the imager to the incoming data. In this case, it was necessary only for the printer to respond appropriately to the proper code, and no standardization was required.

As display workstations were introduced, medical images could be viewed on a video display device with the ability to alter the appearance of the image. These devices were used primarily for receiving and displaying digital images from a few similar imaging instruments, and the image appearance was adjusted using the "brightness" and "contrast" controls of the display device. The "fluidity" of soft-copy presentation raised concerns about the consistency of image appearance. The cross-utilization of both soft-copy and hard-copy images brought new challenges in that respect to diagnosticians, raising the need for acceptance testing and quality control of electronic medical displays.

Before the 1970s, few electronic medical imaging users gave thought to acceptance testing and quality control, relying instead on the modality manufacturer for quality control and setup of the electronics, and the cathode-ray tube (CRT) manufacturer for providing uniform CRT performance. In the 1970s, medical CRTs progressively implemented more advanced designs to enhance performance via adding variations in signal characteristics using interlaced and progressive scanning methods to achieve increased matrix sizes and different display aspect ratios. In addition, phosphors with characteristics (e.g., spectral composition, persistence) optimized for human observers started to be employed in medical CRTs. With these new advancements and variables, users became increasingly aware of the need for, and benefits of, quality control. The recent advent of liquid crystal displays (LCDs) for radiological applications has further raised the need for uniformity of image quality across different display technologies.

In a modern picture archiving and communications system (PACS) environment, images from a number of instruments of varying type may be viewed or printed in a variety of locations by different individuals. Various clinicians at different locations may read an examination on different display workstations; referring physicians may review an examination as a part of a clinic visit; a surgeon may print images for use in the operating room. In such cases, standards are essential to successful integration of these components. Standardization must include not only the communications protocols and data formats, but also capabilities for ensuring the consistency of image display and presentation among the modalities, printers, and workstations where images will be displayed.

1.2 Existing Display Performance Evaluation Standards

In this section, we summarize some prior efforts to standardize the evaluation of soft-copy electronic medical display devices. This summary is not meant to be comprehensive and is limited to those initiatives that were directly related to the objectives of this task group. For a more comprehensive description, readers are encouraged to consult the work by Nier (1996) and Nier and Courtot (1991).

1.2.1 SMPTE RP 133-1991

The need for user evaluation was addressed by the Society of Motion Picture and Television Engineers (SMPTE) in the early 1980s and resulted in the approval and publication of a recommended practice, SMPTE RP 133-1991, *Specifications for Medical Diagnostic Imaging Test Pattern for Television Monitors and Hard-Copy Recording Cameras* (SMPTE 1991). SMPTE RP 133 described the format, dimensions, and contrast required of a pattern to make measurements of the resolution of display systems for both analog and digital signal sources. The recommended practice provided users with a single comprehensive test pattern for initial setup, and for day-to-day operational checks and adjustments of display focus, luminance, contrast, spatial resolution, mid-band streaking, uniformity, and linearity for both soft-copy displays and hard-copy film recordings. However, while the recommended practice specified both a test pattern and a methodology, no performance specification standards were proposed.

One feature of the recommended practice was a popular test pattern that has become known as simply “the SMPTE pattern” (pronounced SIMP-tee). One the most valuable and frequent uses of the pattern was the rough luminance adjustment of display systems, via its 5% and 95% inset patches. This ensured that inappropriate adjustment of display brightness and contrast controls or printer settings was not rendering the extremes of signal amplitudes undetectable (see sections 3.4.5 and 4.3 for details). It should be noted that even though the SMPTE pattern provided a means to visualize the entire range of grayscale values in an image, it did not guarantee that all grayscale values were distinctly presented. Furthermore, the pattern did not ensure equivalent presentation of an image with different display systems, which could vary in their maximum and minimum luminance capabilities and/or luminance transfer characteristics.

1.2.2 NEMA-DICOM Standard (PS 3)

In 1984, the American College of Radiology (ACR) and the National Electrical Manufacturers Association (NEMA) formed a committee that produced and currently maintains the Digital Imaging and Communications in Medicine (DICOM) standard. The committee produced a document, *Grayscale Standard Display Function* (NEMA 2000), which specified a standardized display function known as the Grayscale Standard Display Function (GSDF) for grayscale images. The intent of the standard was to allow images transferred using the DICOM standard to be displayed on any DICOM-compatible display device with a consistent grayscale appearance. The consistent appearance of images was approached through perceptual linearization, where equal changes in digital values cause equal changes in perceived brightness (Hemminger et al. 1994). See section 4.3 and appendix II for further discussion of consistency of image appearance. The standard distinguished the standardization of display devices from the optimization of image display occurring during image processing of the image supported in DICOM via lookup table (LUT) functions (e.g., Modality LUT, Value of Interest LUT, and Presentation LUT, defined in the next paragraph); see Figure 1.

To understand this standard it is necessary to clearly distinguish between pixel values, grayscale values, p-values, digital driving levels (DDLs), and the monitor characteristic function. After image acquisition and certain corrections (e.g., flat-field and gain corrections), the application saves the image to disk—the digital image is basically an array of *pixel values* (also termed *grayscale values*), often with 12 to 16 bits per pixel. When requested to display the image, the application may apply additional image processing (e.g., edge enhancement) and software- or hardware-implemented window/level adjustments. The pixel-dependent digital values sent to the display hardware are termed p-values, for presentation values. The display hardware (specifically the display adapter) provides a digital LUT (see Figure 2) that converts the p-values to *digital driving levels,* which are converted to luminance values by the display hardware. A digital-to-analog converter (DAC) and analog electronics are generally involved in the conversion from DDLs to luminance levels, although all-digital monitors are now available in LCD technology. Note that the DDL to luminance transformation, termed the monitor *characteristic function,* is generally not adjustable. The DICOM standard allowed the calculation of a function that maps the p-values to DDLs, such that the displayed luminance levels have the desirable property that equal changes in perceived brightness correspond to equal changes in p-values. In practice, the characteristic function is determined by initially applying a unit transformation at the LUT, which allows software manipulation of the DDLs and direct measurement of the monitor characteristic function. This function is used to calculate the necessary LUT entries such that the *net* transformation from p-values to luminance follows the DICOM standard. Note that

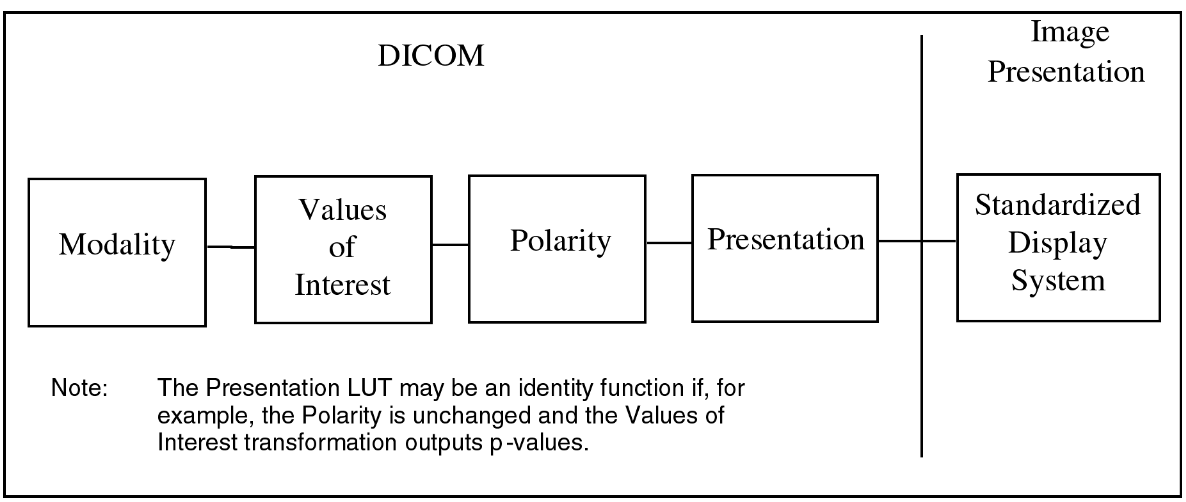

Figure 1. The Grayscale Standard Display Function (GSDF) is an element of the image presentation after several modifications to the image have been completed by other elements of the image acquisition and presentation chain. Adapted, with permission, from NEMA PS 3.14-2000 (NEMA 2000).

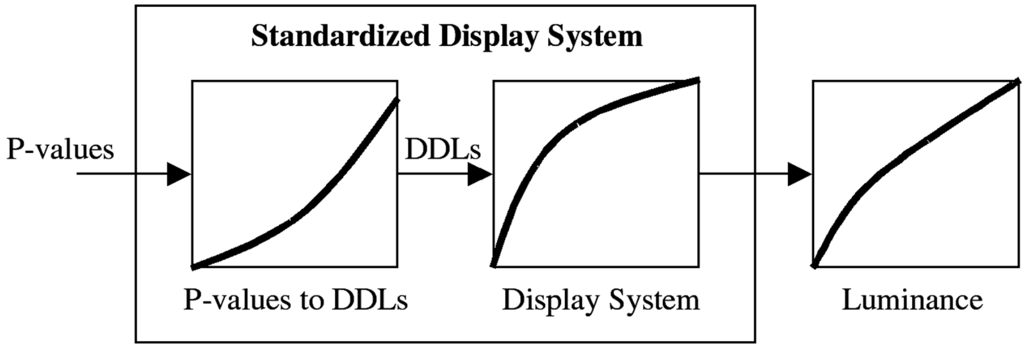

Figure 2. The conceptual model of a standardized display system maps p-values to luminance via an intermediate transformation to digital driving levels (DDLs) of an unstandardized display system. Adapted, with permission, from NEMA PS 3.14-2000 (NEMA 2000).

DICOM specified the exchange and presentation of images, but left the implementation considerations to the vendors. Thus, image processing or standardization could occur on the computer, in the graphics/video card, or on the display itself.

1.2.3 DIN V 6868-57

Acceptance testing and quality control is mandated in Germany. The German standards institution, Deutsches Institut für Normung e.V. (DIN), standard 6868 part 57, *Image Quality Assurance in X-Ray Diagnostics, Acceptance Testing for Image Display Devices* (DIN 2001), was developed as an acceptance testing standard addressing the requirements for display systems. The standard specified the requirements for acceptance testing of display devices, with resulting reference values used for quality control or constancy checks. The aspects of the display performance covered included: (1) viewing conditions and the effects of ambient illuminance, (2) grayscale reproduction, (3) spatial resolution, (4) contrast resolution, (5) line structure, (6) color aspects, (7) artifacts, and (8) image instabilities. Appropriate test images were specified, including the SMPTE test pattern. As with the SMPTE recommended practice, the DIN standard allowed the test patterns to be supplied either by an analog video pattern generator or by a computer via a digital file. In addition to geometric test patterns, at least one clinical reference image was also mandated for a visual assessment of the grayscale value display and for checking the absence of artifacts (especially pseudocontours).

DIN V 6868-57 called for joint assessment of both the imaging device (acquisition modality) and the display device. The standard defined three application categories of display devices: category A for digital radiographic images, category B for all other types of images, and category C for alphanumeric/graphic or control monitors. Recommendations were provided for the quality controls or constancy check according to the device's intended use, including environmental viewing conditions. It included a requirement for the ratio of the maximum to minimum luminance. The standard required that for category A and B devices, this ratio must be greater than 100 and 40, respectively. Spatial luminance uniformity, expressed as the fractional deviation between corner and center luminance, was specified not to exceed 30% for CRTs, and be within ±15% for flat-panel displays.

As for the luminance function, the DIN standard recognized two functions for uniform display presentation: the DICOM function described above and a function specified by the

International Commission on Illumination, Commission Internationale de l'Eclairage (CIE). Incorporating IEC 61223-2-5:1994 (*Evaluation and Routine Testing in Medical Imaging Departments—Part 2-5: Constancy Tests—Image Display Devices*) (IEC 1994), the standard required that luminance measurements be made with a meter with an absolute measuring uncertainty (2σ) of 10%, within a measuring range of 0.05 cd/m^2 to ≥500 cd/m^2, an angular acceptance between 1° and 5°, and photopic spectral sensitivity.

1.2.4 ISO 9241 and 13406 Series

The International Standards Organization (ISO) standard, ISO 9241-3:1992, *Ergonomic Requirements for Office Work with Visual Display Terminals (VDTs) Part 3: Visual Display Requirements* (ISO 1992), aimed to establish image quality requirements for the design and evaluation of video display terminals for text applications such as data entry, text processing, and interactive querying. The standard provided test methods and conformance requirements for geometric linearity, orthogonality, minimum display luminance, minimum contrast, luminance ratios between hard-copy and soft-copy images, glare, luminance spatial uniformity, temporal instability (flicker), spatial instability (jitter), and screen image color. While in practice ISO 9241-3 was most useful to the user as a purchase specification, annex B provided an empirical method for assessing flicker and jitter. An alternative comparative user performance test method for testing compliance was included in annex C.

The ISO 9241 standard did not address flat-panel display devices. Those devices were addressed by a newer ISO standard, ISO 13406-2:2001, *Ergonomic Requirements for Work with Visual Displays Based on Flat Panels. Part 2: Ergonomic Requirements for Flat Panel Displays* (ISO 2001). The key display issues covered by this standard were display luminance, contrast, reflection, color, luminance uniformity, color uniformity, font analysis, pixel defaults, and flicker. Under ISO 9241, ergonomic requirements for display devices were specified under parts 3, 7, and 8, while ISO 13406-2 was equivalent to those parts combined.

1.2.5 VESA Flat Panel Display Measurements (FPDM) Standard

In May 1998, the Video Electronics Standards Association (VESA) released Version 1.0 of the Flat Panel Display Measurements standard (FPDM) (VESA 1998). The purpose of this document was to specify reproducible, unambiguous, and meaningful electronic display metrology. The FPDM standard was strictly not a compliance standard, but rather a manual of procedures by which a display's conformance to a compliance standard could be verified. Accordingly, the FPDM standard complemented the requirements set forth by compliance standards bodies. It was intended to extend the standard so that it could be used for all display types. However, the standard focused on emissive or transmissive color displays that are used in the workplace, in laptop computers, or equivalent. Particular attention was paid to the measurements that would characterize the performance of flat-panel displays.

The format of the FPDM standard offered easy access to the procedures through short sections that enumerated the basic measurements. Each of these sections contained a description, setup protocol, description of the measurement procedure, analysis, reporting, and comments. The procedures were tested before inclusion, and many (identified as being in the "suite of basic measurements") were considered essential in the industry. The measurements were divided into the following categories: center measurements of full screen; detail, resolution, and artifacts; box-pattern measurements; temporal performance; uniformity; viewing-angle performance; reflection; electrical performance; and mechanical and physical characteristics.

Following all the procedures was a set of explanations of methodologies including pattern generators; light-measurement devices; diagnostics for spatial, temporal, and chromatic problems; array detector measurements; error analysis; and harsh environment testing. These specific metrology explanations were followed by textbook tutorials ranging in subject matter from photometry and colorimetry to the optical principles underlying all display measurements.

Soon after Version 1.0 of VESA FPDM was published in May 1998, the need became clear for good metrology standards for all kinds of displays, not just for flat-panel displays. Accordingly, the Display Metrology Committee (DMC) was formed to apply the concept of the FPDM standard to many other display areas served by VESA. The FPDM Version 2.0, published in June 2001 (VESA 2001), contains measurements unique to CRT and projection displays, including contributions from the National Information Display Laboratory (NIDL), such as raster pincushion and linearity, convergence, and stereo extinction ratio. The FPDM and DMC aimed to detail display measurement methods, but did not provide recommendations for performance criteria, compliance criteria, or ergonomic requirements for specific applications.

2 OVERVIEW OF ELECTRONIC DISPLAY TECHNOLOGY

In this section, we review the components of electronic display systems and the engineering concepts that are important for understanding how the performance of devices can be assessed and standardized.

2.1 Electronic Display System Components

Medical imaging workstations consist of several physical and functional components. These include the computer, operating system software, application display software, display driver, and, finally, the display device. Displaying digital images in a soft-copy display workstation is only possible by a series of manipulations of digital data in each of these components. The functions and characteristics of each affect the process of displaying, viewing, and interpreting the images. In this report, *display device* refers to the physical display component of a display system or workstation, sometimes referred to as *display monitor*.

2.1.1 General Purpose Computer

The computer is the foundational component of a display workstation. Most display workstations use a general-purpose computer, which includes a central processing unit (CPU), mathematical computation modules, input/output (I/O) controllers, and network communication hardware. The computer also includes devices for user interaction, such as keyboard, mouse, trackball or wheel, joystick, barcode scanner, or microphone; devices for storage or recording such as a hard disk, digital video disk (DVD), compact disk (CD), or tape units; and output devices such as display monitors, printers, and speakers.

Computers rely on several other hardware and software components for displaying images. These include the display controller hardware that converts digital information into analog or digital signals as appropriate for the display device, and software modules that allow programs to access the controller hardware. Finally, a user application program is needed to access image data and to send it to a display controller in the proper form. One primary difference between a standard computer system and a medical workstation is its associated display interface. The special needs of medical imaging necessitate the use of special display software, high-resolution display devices, and high-performance display controllers, which are not normally needed by general consumers.

2.1.2 Operating System Software

Basic computer hardware such as hard disks, CPUs, I/O devices, and printers require complex software to perform their functions properly and efficiently. In addition, many functions that are necessary or useful are usually not implemented in computer hardware, due to cost or inflexibility of hardware solutions. Instead, software is used to give the hardware the complex, detailed, but definite instructions to perform their functions. The operating system (OS) is a low-level specialized program that controls the resources of the computer. It provides services such as network communications, security, display management, file management, and execution of application programs. The OS also provides time-sharing resources and interrupt processing to permit multiple programs to be simultaneously active, each receiving a portion of the processing power of the central processor(s). The OS also monitors events that originate from hardware devices such as the keyboard, mouse, network, and other devices running autonomous tasks.

The OS provides interfaces for users, as well as services that can be used by application programs. OSs differ in the interaction modes supported, in the types and degree of user access controls, in the type of protection provided between applications, and in the services provided by the OS to application programs. Also, OSs provide different methods for supporting multiple applications running together such as cooperative versus preemptive multitasking. Since the OS effectively creates the robustness of the computer, different computer hardware may use the same OS, and interface to a user. The OS therefore creates an operating environment for the user and for applications programs. Hence, an operating system may be implemented on many types of computer hardware and will have the same look and feel. Alternatively, a given hardware configuration may support one or more OSs and provide multiple looks, depending upon how it is "booted." However, typically a particular OS runs on a narrow class of central processors, and most computers are set up to run only one OS.

OSs used in medical imaging workstations include UNIX, LINUX, Macintosh, and various Microsoft Windows systems. Functionally, any OS can support a medical imaging system. Practically, the choice of OS is driven by several technical and nontechnical needs: the degree of performance required for the entire system, the OSs support for particular applications or hardware, and the ability of the medical facility to support multiple computer OSs. The choice of OS limits what kinds of software can be run on the computer, and the interface and provided tools determine how the user interacts with the machine.

2.1.3 Display Processing Software

All digital images consist of an array of digital grayscale values that are transformed to image luminance values by the display device. Devices that acquire medical images will frequently store images with values specific to the modality, such as the CT numbers for CT scanners. For some acquisition devices, the values used by different devices may be different, for example, the image values generated and stored by digital radiography (DR) imaging devices of different manufacturers. To be viewable, these image values must first be converted to DDLs and finally converted to analog or digital voltages for presentation on a display device.

The conversion of image values to DDLs involves transformations at the OS level, using the OS's image processing software modules, or at the application display software level. For example, DR images are commonly processed using nonlinear transformations for data scaling, spatial transformations for equalization, and edge enhancement for resolution restoration. In CT, display software is used to provide simple linear value transformations associated with display window and level adjustments. The processing might also include colorizing the image, such as in nuclear medicine and US imaging. The software support for color is more complex, commonly needing greater efficacy that comes with processing at the OS level.

2.1.4 Display Controller

A display controller, sometimes referred to as the video card or graphics card, is a combination of hardware and software to transform DDLs to appropriate signals for the display device. The controller includes a special-purpose memory (i.e., video memory for analog displays) that accepts the output of the application program in "screen-ready" form. The digital values in this memory are transformed to signals ready for the display device. Repeated scans of the memory refresh the picture. A computer system also has driver software that provides an interface for the application to control the contents of the video memory. For example, in response to window or level adjustments, the software application program changes the display screen seen by the viewer by calling driver software that appropriately updates the image memory in response to the adjustments.

Most current display devices accept only analog video signals (VESA 2001). For these systems, the display controller performs a digital to analog (D-A) conversion as the memory is scanned. By driving the display device directly from this D-A converter, 2^n different voltages can be generated, where n is the number of bits per pixel in the video memory. For color displays, three parallel D-A converters for each pixel create the red, green, and blue signals. The number of bits per pixel in the D-A converter physically limits what is available to the display application and determines the maximum number of shades of gray, or colors, that can be provided to the display. The video memory typically has 8 or more bits per pixel. In the case of 8-bit grayscale controllers, up to 256 (0–255) digital values can be generated. When 3 bytes of storage are used for each pixel (true-color RGB), 8 bits can be used for each of the red, green, and blue components of the pixel, resulting in potential for 2^{24} colors. In color displays, 24-bit color controllers are prerequisites for 8-bit grayscale presentations.

Since individual displays respond differently to the same voltages, in order to control the appearance of an image, the display voltages should not be evenly spaced. The control of the display's light output is dependent on changing the digital values, a feature that is offered (and necessary) in high-quality display controllers manufactured specifically for medical imaging. These controllers, which are typically for monochrome displays, may have 10- or even 12-bit image memories and have an ability to store an LUT to change the DDLs stored in the memory for D-A conversion. By installing the proper LUT in the controller, the grayscale response of the display device can be made to follow a specified standard. These advanced controllers often include integrated luminance probes and calibration software to be used to compute the proper LUT. Consumer-grade graphics cards, generally limited to 8-bit memory, are not suitable for most medical display applications in that the LUT process may result in a loss of distinct luminance levels to the display. Typically, 20 luminance steps are sacrificed when correcting CRT and LCD monitors to the DICOM GSDF function.

The methods used to convert DDLs to monitor luminance are changing with new systems. For flat-panel devices, the controller sends a digital signal to the display device, and the device converts this to the appropriate signals to control luminance. As standards mature, manufacturers of computer displays are pursuing designs that accept direct digital signals from a display controller. The new product offerings provide improved performance at lower cost for several aspects of display performance. However, the basic requirement to standardize the relationship between DDL and luminance remains the same.

2.1.5 Display Device

The final hardware element of a medical imaging display workstation is the display device. The display device is the actual physical unit that generates a visible image from analog (or digital) video signals. In addition to hardware, the display device has internal software to be able to respond to commands by the controller. A workstation can have four or more display devices, but the most common configurations have only one or two. The CRT is currently the most common type of display device, but newer flat-panel technologies are rapidly gaining the market share. Section 2.3 provides descriptions of display device technologies in detail.

2.1.6 Workstation Application Software

The workstation application software program controls the application-level operation of the workstation to display a medical image. A wide variety of programs are available in the market. Basic programs permit images to be sent to the workstation for review by a referring physician or a consulting radiologist. More advanced programs include tools for image manipulation, database access, archive query/retrieve, and support for multiple high-resolution displays. Tools are provided to measure characteristics of the images such as distances, digital values, areas, histograms, and other metrics. A powerful feature of advanced programs is the ability to select (in some cases automatically) relevant images from prior examinations and present them in appropriate relation to more recent data. Often part of larger PACS installations, these advanced programs provide capabilities for logging user access, controlling workflow, load balancing among multiple systems, and setting preferences for users, groups, and departments.

The operation of display workstations in a PACS environment is greatly facilitated by complying with the DICOM standards. Current standards address data structures, object and service types, communication protocols, grayscale display, print management, and work-list management, to name but a few. Work in progress is addressing advanced methods to control the presentation of multiple images and methods to associate interpretive reports with image content. The aspects of the approved DICOM standard that relate to display image quality have been considered in this report (see section 4.3).

2.2 Photometric Quantities Pertaining To Display Devices

Two photometric quantities are of great importance in discussion of display performance or specifications: luminance and illuminance.

2.2.1 Luminance

Luminance is the photometric term used to describe the rate at which visible light is emitted from a surface—display surface in the case of displays. It refers to the energy of visible light emitted per second from a unit area on the surface into a unit solid angle (Ryer 1998, Keller 1997). The energy of visible light reflects the visibility of light quanta as a function of wavelength through a standard photometric weighting function. The SI unit for the energy of visible light is the lumen-second,[1] and therefore, the unit for luminance is 1 lumen per steradian per meter squared, commonly referred to as candela per meter squared (cd/m^2).[2]

An important characteristic of light emitted from a surface is its spatial distribution. When luminous intensity from a surface varies as the cosine of the viewing angle, the appearance of the surface brightness is constant irrespective of the viewing angle. Such surfaces are characterized as having a Lambertian distribution.

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[1]The lumen (lm) is the psychophysical equivalent of watt, or joule/second of the radiant energy, but weighted with the visibility equivalence function.

[2]The unit cd/m^2 is sometimes referred to as nit. The nit is a deprecated unit and its use is no longer encouraged. Luminance is also sometimes expressed in the traditional units of foot-lambert (1 fL = 3.426 cd/m^2). Foot-lambert is a non-SI unit, and thus its use is not encouraged by the AAPM Task Group 18.

2.2.2 Illuminance

Illuminance is the photometric term used to describe the rate at which visible light strikes a surface. It is often used to describe the amount of ambient lighting or the light striking a display surface. The unit of illuminance is lumen per meter squared (lm/m^2), or lux (lx), a unit identical to luminance except for the absence of the solid-angle dimension. Illuminance and luminance can be related for ideal reflective objects (Lambertian surfaces): an illuminance of 1 lux striking a perfectly reflective white surface will cause the emission of $1/\pi$ observed luminance in cd/m^2 (Ryer 1998).

2.3 Display Device Technologies

2.3.1 Cathode-Ray Tubes

The CRT is a common and mature display technology that has undergone numerous evolutionary changes. In 1878, Sir William Crookes, experimenting with variations on the Geisler discharge tube, developed the progenitor of the modern electron gun. But it was not until 1920 that Vladimir Zworykin developed the other components needed for the first camera and picture tubes (respectively, called the iconoscope and kinescope). All the basics elements of original CRT devices are still present in modern CRT devices. An understanding of these elements and their interactions is essential to better appreciate the factors affecting image quality and how to best implement soft-copy electronic display solutions (Keller 1997; Lippincott 1988).

2.3.1.1 CRT Structure and Principles of Operation

The basic components in a monochrome CRT are illustrated in Figure 3. A stream of electrons is produced by thermionic emission from the cathode, which is operated near ground potential and heated by a filament (F). The electrons are drawn from the cathode and through the control "grid" aperture, G_1, by a positive potential (~1000 V), on to the first anode or accelerating electrode, G_2, typically at about +25 kV. Depending on the design of the electrodes, the beam comes to a focus inside G_2 and then diverges. The anode consists of a layer of aluminum that extends back to the position of the deflection yoke. A graphite compound is applied into the neck to make the electrical connection with the gun structure. Three prongs, called snubbers, form the mechanical connection.

Although electromagnetic beam–focus coils around the tube neck are used in some CRT devices, more commonly the beam is brought back to a focus electrostatically at the position of the phosphor screen by the action of the electronic lens system (G_3, G_4, and G_5). Upon impact on the phosphor screen, the focused electron beam produces a light spot roughly 0.1 to 0.2 mm in diameter. The light distribution of the spot is commonly characterized by a two-dimensional Gaussian function. Another important characteristic of this generated light is its Lambertian distribution. As the cross-sectional area of the display's faceplate also varies with the cosine of the viewing angle, in display devices with Lambertian light emission, the apparent luminance of the display does not vary with viewing angle, to a first approximation.

In monochrome CRT displays, the visible image is formed one line at a time as the single, narrow electron beam is moved in rectilinear scan fashion across the face of the phosphor screen. Because of the need to deflect the beam through relatively large angles, electromagnetic (as opposed to electrostatic) deflection is normally employed. The horizontal deflection coils in the yoke assembly produce a vertically oriented magnetic field that sweeps the beam from left to

(a)

(b)

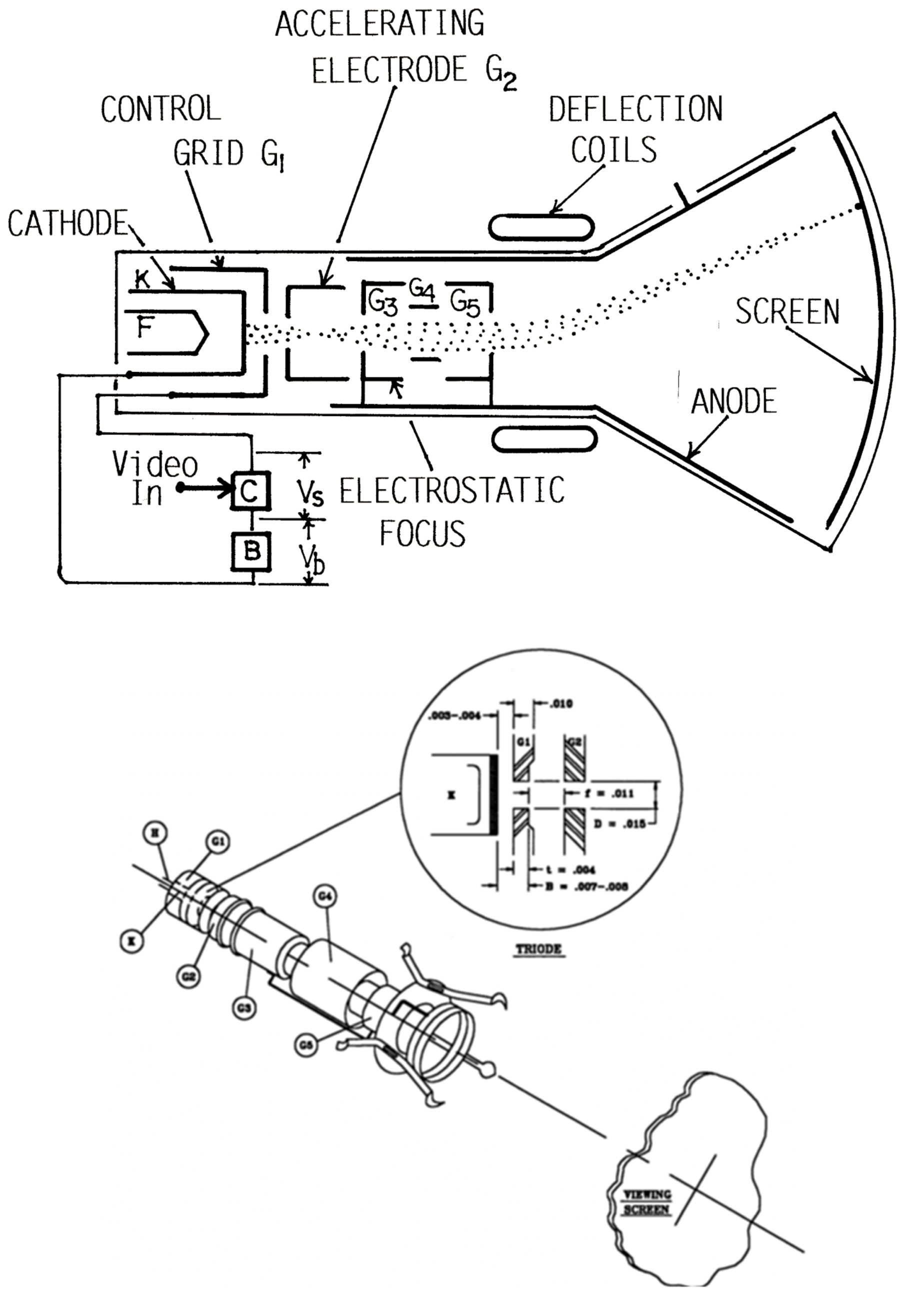


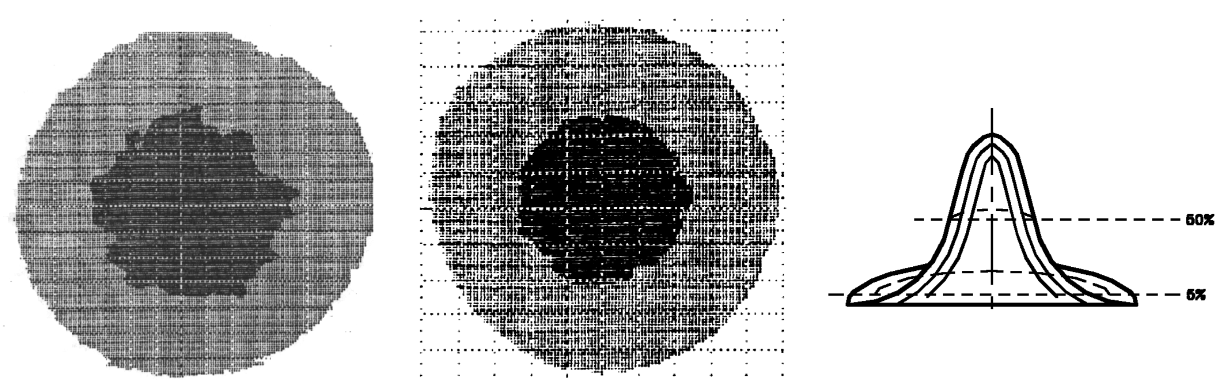
Figure 3. Two views of the CRT components.

right as each line is scanned. A ramp or sawtoothlike current waveform is applied to these coils at the line rate (e.g., 140 kHz for 2000 line–70 frame/s display operation). In like manner, vertical deflection coils move the beam downward as the frame is painted, then reposition the beam for the start of the next frame. The frame rate (e.g., 70 Hz) determines the frequency of the vertical deflection control voltage. The values of horizontal and vertical control voltage determine the beam location (i.e., the coordinates of the pixel being rendered at any instant). This information is employed in high quality display devices to accomplish a position-dependent (dynamic) focus correction, which is necessitated by the longer source-to-screen beam travel distance associated with peripheral versus central areas of the display.

Phosphor materials used in screens are identified by a P-number system maintained by the U.S. Electronics Industry Association. The type of phosphor (P4, P45, P104, etc.) employed determines the color displayed on the CRT and also influences the luminance capability of a display device, since some phosphors are more efficient than others in converting electron beam energy into visible light. For example, P104 has a higher luminance efficiency than P45, requiring less current for a given output luminance level. Monochrome display devices capable of producing maximum luminance of up to 500 cd/m^2 are currently available, with 300 cd/m^2 more common. These levels are to be compared to the luminance level of typical radiographic film illuminators, 1000 to 2000 cd/m^2, or mammography illuminators, 3000 cd/m^2. Use of larger beam current leads to greater display luminance, but this tends to enlarge the beam spot size and thus reduce image resolution. Larger beam current and image luminance also reduce the useful life of the display device by hastening the normal fall-off of phosphor efficiency and cathode depletion with time.

In addition to luminance efficiency and aging characteristics, various phosphors used in screen construction differ from each other in their persistence or decay times and phosphor noise. The persistence characterizes the rapidity of fall-off of luminescence with time after a given area of the screen is momentarily activated by the electron beam. Use of phosphors with long decay tends to reduce the perception of flicker (also known as ripple ratio) in the display, but this comes at the expense of a greater image lag or smearing, which might be unacceptable in a display device used for viewing dynamic processes. Use of a higher display frame rate also reduces flicker. Phosphor noise is attributed to its granular structure and is observed as spatial noise. P45 as a single-crystal phosphor has considerably less phosphor noise than the other phosphor types. Comparatively, the P4 and P104 phosphors exhibit more phosphor noise due to blending of multiple phosphor components with slightly different color tints. Figure 4 illustrates the differences in luminance output distribution of a single pixel using P45 and P104 phosphors. Note the distorted edge transition at the full-width-at-half-maximum (FWHM) level for P104 caused by phosphor noise.

The operation and design of color CRT display devices is similar to that for monochrome CRTs, but color devices contain three electron guns in the neck of the tube, instead of one, for the production of three scanning beams (Spekowius 1999). Each of these beams is made to



P104 Phosphor (a)

P45 Phosphor (b)

(c)

Figure 4. Pixel profiles in CRTs with P104 (a) and P45 (b) phosphors. The contour lines depict the full-width-at-half-maximum (FWHM) and full-width-at-twentieth-maximum lines (c).

strike one of three screen phosphor elements in each pixel producing red, green, and blue (i.e., RGB) light. Each beam is modulated by its own video signal, and the relative strength of the three beams determines the perceived color of the pixel being created at a given time during the image rendition process. Color CRTs also contain a shadow mask (or aperture mask) consisting of a thin plate located somewhat in front of and parallel to the phosphor screen. For a color display device capable of displaying 800 pixels per line, the mask will have 800 openings, from left to right, through which the three beams must pass. These openings are positioned precisely in front of the display pixels so that any part of a color-specific beam that might be directed toward the "wrong" phosphor element will be intercepted, or "shadowed," by the mask and thus prevented from striking the wrong phosphor. Similar to monochrome CRTs, color CRTs have a graphite-type coating inside the tube glass surface, extending into the neck of the tube.

The positioning of the three electron guns determines the appearance of the three colors in each pixel. In the dot-triad design, the axes of the three guns are positioned symmetrically around the axis of the tube neck and separated by 120°. The mask contains a matrix of round apertures in front of the pixels. Examination of the screen in this type of CRT with a hand microscope demonstrates that each pixel consists of a triad of red, green, and blue (RGB) dots located at the corners of a small triangle. Other designs employ three in-line guns used with a mask that consists of a grille of vertically oriented slit apertures. For this design, each pixel is made of three vertical bars, one for each primary color. Although a mask is important to the operation of the color CRT, its presence contributes to increased veiling glare due to electrons that scatter off of the mask and eventually strike the screen in unintended areas. This effect becomes more pronounced as the number of pixels per line is increased, which tends to limit the maximum pixel matrix sizes for color display devices. It is also more pronounced in shadow masks than in aperture grills. The mask-initiated veiling glare in color CRTs is one of the major quality issues in using color CRTs for viewing monochromatic medical images.

In principle, workstation-level CRT display devices are similar to commercial televisions, but there are important performance differences. A TV displays one frame consisting of 480 active horizontal lines (in the form of two interlaced fields of 240 lines each) every 1/30 of a second (i.e., one frame every 1/60 of a second). By contrast, displays employed for diagnostic imaging may address as many as 2000 horizontal lines on the screen in noninterlaced (i.e., progressive) mode, and the image refresh rate may exceed 70 images per second. In commercial televisions, each line is painted during a period of about 53 μs, and modulation of beam intensity sufficient to represent all needed image details as luminance variations must take place in that time period. In a high-line-rate medical imaging display, time per scan line can be as low as 5 μs, necessitating much faster modulation of the electron beam current and a much higher bandwidth requirement.

2.3.1.2 Video Signal, Brightness, and Contrast

In CRTs, the intensity of the electron beam, and hence the luminance produced at points on the screen, is controlled by varying the voltage differential between the cathode (K) and the control aperture (G_1), which is sometimes referred to as the control grid due to the analogy with older vacuum tube designs. A more positive voltage applied to G_1 allows greater beam current, whereas a sufficiently negative potential on G_1 will cut off the beam as needed during horizontal and vertical retrace. Alternatively, and more commonly, G_1 may be set to a fixed value while K is driven between different positive potential values.

The beam control voltage applied to K-G_1 typically consists of two components, as suggested in Figure 3, which are adjusted by the "contrast" and "brightness" controls of the CRT. The first of these is the output of circuit C, namely an amplified video signal, which is related to the numerical intensity value of the pixel being displayed. The effect of increasing the amplification of C (i.e., increasing the "contrast" control) is shown in Figure 5; luminance differences between various areas of the image are enhanced. The second component of K-G_1 control voltage is a bias applied by the bias circuit, B. By making this bias more positive (or less negative) via the brightness control of the CRT, all areas of an image are given an equal upward shift in luminance without a change in contrast. The brightness control is usually used to set the black level (i.e., cutoff threshold), while the contrast control adjusts the dynamic range. Although brightness and contrast controls are ideally independent of one another (i.e., a change in one control should not affect the other parameter), these controls are often correlated, and iterative "tweaking" of both of these controls is necessary to attain a desired maximum and minimum luminance.

2.3.1.3 Pixel Characteristics and Resolution

As described above, CRT image pixels are generated on a phosphor screen by a scanning electron beam that "writes" the pixels on the phosphor screen in a precisely controlled continuous manner. Since the electron beam cannot be moved in discrete steps, and the sweep movement is not completely stable, as indicated by the schematic of the video signal in Figure 6, the resulting spot size is not distinct and does not correspond to exactly one nominal pixel size. The CRT pixels usually have a pseudo-Gaussian profile that extends beyond the nominal pixel size. In contrast, in flat-panel displays such as LCDs, a matrix of discrete pixels is used to display the image. Thus, the nominal area of the display that is used in addressing a single pixel is reliably reproduced in image representation, provided the flat panel is operated in its "native resolution." In reality, in an active-matrix LCD (AMLCD) the actual pixel size is smaller than the nominal size due to the finite size of the electronic elements controlling each pixel. The ratio of active pixel area to the nominal area is known as the *aperture ratio* (so-called *fill factor* in flat-panel

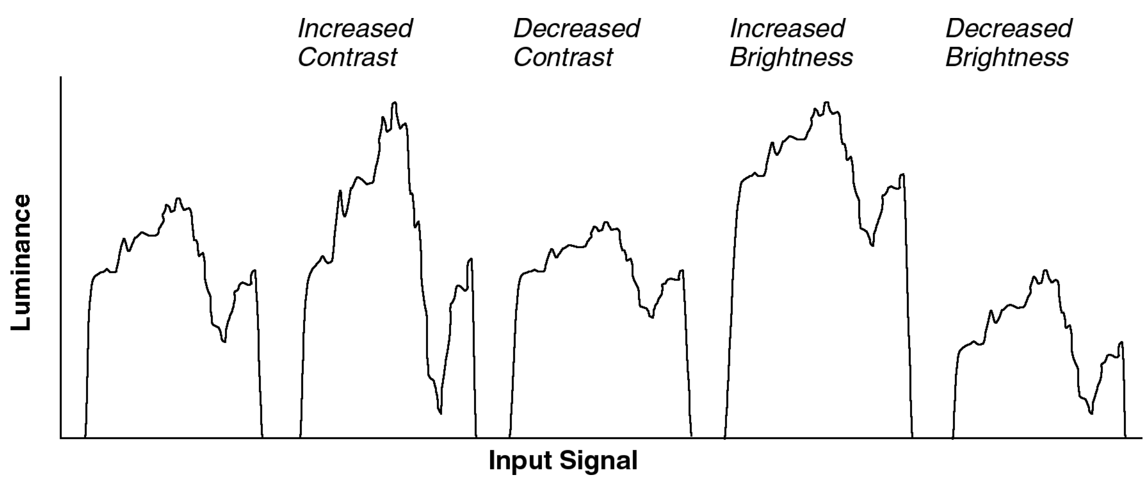


Figure 5. Effect of contrast and brightness control adjustment on image. Control grid-to-cathode voltage (which determines beam intensity and image luminance) and time (i.e., horizontal position of beam) are represented along vertical and horizontal axes, respectively.

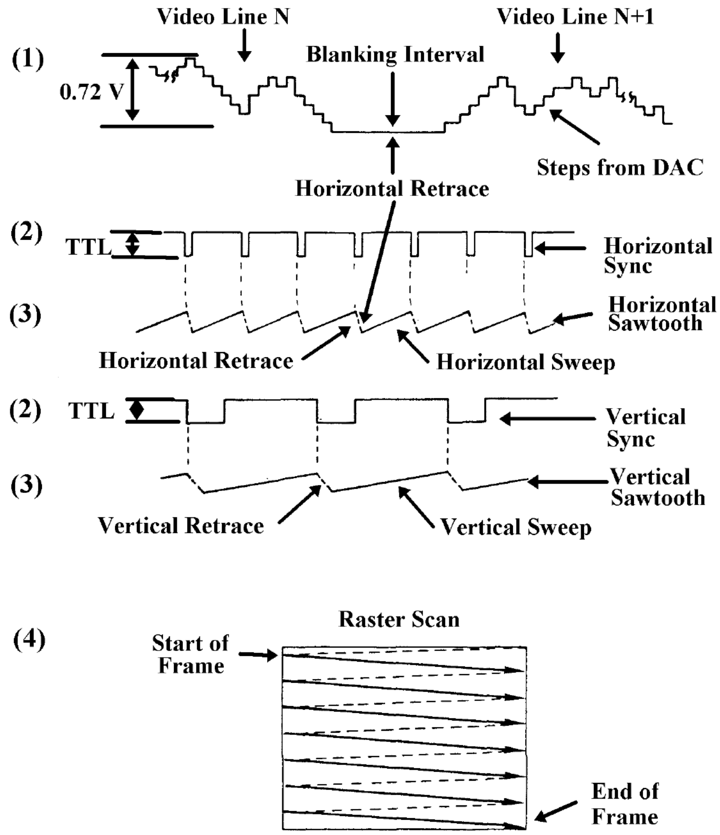


Figure 6. Schematic illustrating (1) the video signal as output of an ideal digital-to-analog converter (DAC) of the display controller, (2) the horizontal and vertical synchronization signals necessary to "write" the raster that carries the video signal, (3) the sawtooth waveform for the deflection circuits, and (4) the raster scan. Note that the video signal consists of discrete steps corresponding to the different digital input values. The inability to reproduce these as described above is the basis for the non-discrete nature of resolution metrics with CRTs.

detector terminology). The more complex resolution characteristics in a CRT compared with an LCD warrant a more detailed discussion of image/pixel formation in medical CRTs.

The video signal is generated by the CRT's interface to the computer, the display controller. It converts digital data into analog display signals and coordinates the display of the data. The scanning of the electron beam and its intensity modulation is achieved with the aid of synchronization pulses. There are usually three signal lines connecting the display controller to the CRT: the video signal, the horizontal sync signal, and the vertical sync signal. Characteristic features of these three signals are shown schematically in Figure 6, together with the actual waveforms (sawtooth) of the circuits providing the beam deflection.

The video signal is applied to the display device's beam modulation circuits within the timing framework created by the sync pulses. The video signal is shown for two adjacent video lines (line N and line N + 1), separated by the horizontal blanking interval. During the blanking interval, the electron beam is turned off in order to move it from the end of line N to the beginning of line N + 1, without writing a visible trace on the CRT screen. Such a blanking interval is also necessary at the end of a video frame in order for the electron beam to return from the end of frame M to the beginning of frame M + 1. The typical time for a horizontal retrace is in the order of 0.33 μs, the time between two video lines is 1.3 μs, and the blanking time for a vertical retrace is about 5.4 μs. For proper frame synchronization, a time interval of about 330 μs is inserted between the beginning of the vertical retrace and the start of the first video line. The video signal consists ideally of discrete steps, which are the analog signals created by the display controller's DACs. The time duration of a step depends on the total number of pixels and the speed with which the image is "written." The sync signals are voltage pulses at TTL level (Transistor-Transistor Logic level, where "on" levels are between 3.5 V and 5 V, and "off" levels are between 0 V and 0.05 V) and affect only the timing of the raster-scan process (Horowitz and Hill 1980). Self-oscillating circuits within the display device will, in fact, deflect the CRT electron beam to form a rasterlike pattern on the phosphor screen, whether or not sync information is being received.

The smallest detail that a CRT can display is determined by a number of factors, as shown in the schematics of Figures 7 and 8. They include the following:

1. The response function $H_{video}(f)$ of the display controller and CRT video circuits, that is, the waveform of the incoming video signal as determined by rise and fall times of the display controller, as well as by the rise and fall times of the CRT's video amplifier, defining how fast the electron beam intensity can follow the voltage of the video signal while the beam moves across a pixel. The rise/fall time is defined as the time it takes for the video voltage to change from 10% (almost black) to 90% (almost white), or vice versa.
2. The nonlinearity of the relation between luminance and video signal voltage.

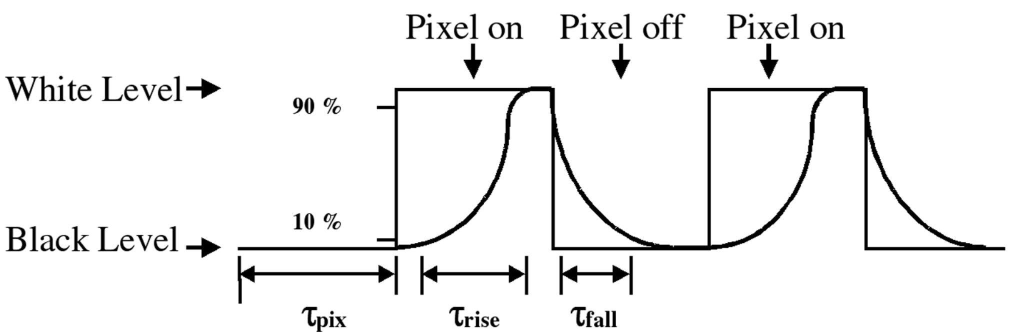


Figure 7. Schematic illustrating the relation between a video amplifier's rise and fall times.

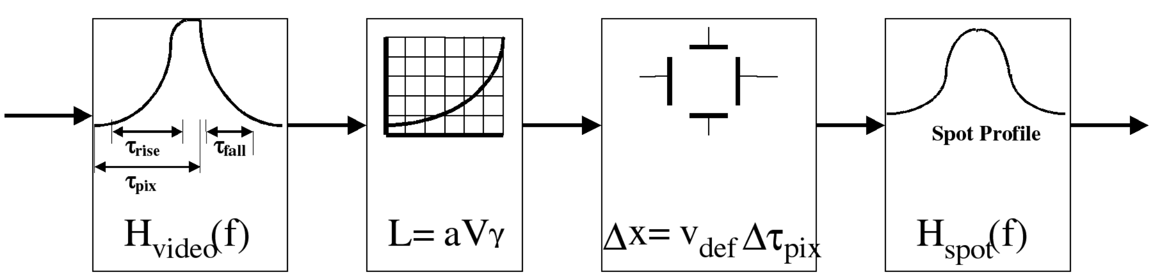


Figure 8. Model of a CRT display device, illustrating components affecting its spatial resolution: (a) response function of video circuits of display controller and CRT display device; (b) the nonlinear relationship between the luminance and the input voltage; (c) the scanning speed of the deflection unit; and (d) the finite size and shape of the focal spot.

3. The motion of the electron beam as affected by the beam deflection circuits; the deflection unit performs the transformation of the temporal input signal into the spatial domain.
4. The response function $H_{spot}(f)$ of the beam spot size formed by the electron optics on the phosphor screen, which is affected by the magnitude of the beam current as well as by the phosphor layer thickness and scatter effects within it.

Figure 9 illustrates the effects of these components on a simulated spot profile in the horizontal direction for a nominal pixel width of 2 ns. We start with an ideal stationary spot profile (Spot Fixed, response function $H_{spot}(f)$). Due to the scanning motion of the electron beam, the spot is broadened, while the integral under spot curve remains equal to that of the stationary spot. This would be the spot size and profile if the electronics were infinitely fast. Finally, the moving spot profile is convolved with the amplifier response function, $H_{video}(f)$, having a rise and fall time of 1.4 ns. The resultant spot profile extends over more than three nominal pixel widths. Due to bandwidth limitations, the peak luminance does not reach the equilibrium value.

Insufficient bandwidth is the main reason for failure of the peak luminance to reach the equilibrium value when only a single pixel is addressed. Equilibrium luminance can be reached for a single pixel only, when the rise time, τ_{rise}, and the fall time, τ_{fall}, are small compared to the pixel time, τ_{pix} (sometimes incorrectly called dwell time), or $\tau_{rise} + \tau_{fall} << \tau_{pix}$. The electronic bandwidth, Δf, is inversely related to the rise and fall times as $\Delta f = 1/(4\ \tau_{rise})$, assuming that rise and fall time are practically equal.

The limiting influence of the video amplifier bandwidth on CRT resolution may be appreciated by an example. Consider the case of the display of an image with a matrix size of 2048 × 2560 pixels at a refresh rate of 71 Hz. Assuming the total time for blanking and video signal

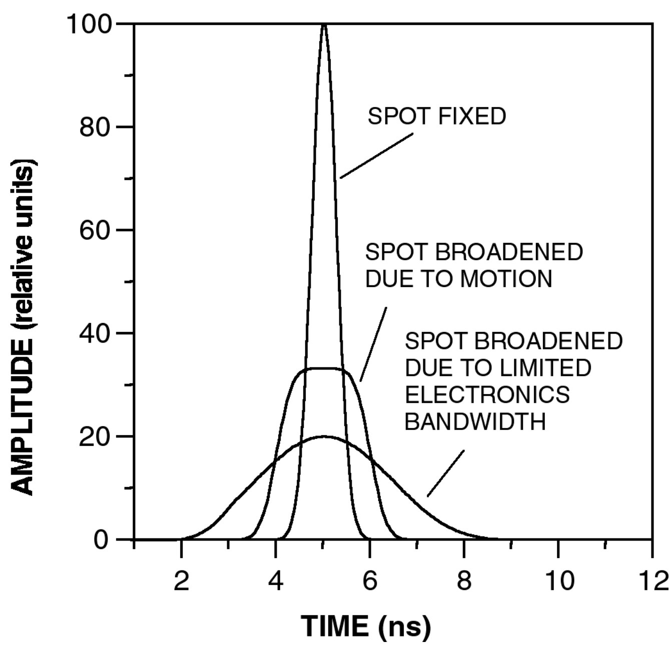


Figure 9. Schematic illustrating width of a single pixel as given by a Gaussian spot, which moves during the "video-on time" for a single pixel (~2 ns) and which is convolved with the time response function of the electronics (rise time and fall time of about 1.4 ns each).

delay is 26% of the time for a frame, the nominal pixel time is 2×10^{-9} s. Ideally, in order to preserve the spatial detail of characters and graphic objects to be displayed, one may wish to have rise and fall times of individual pixel signals of about 1/20 of the pixel time, i.e., $\tau_{rise} = 1 \times 10^{-10}$ s. To realize such rise times, the electronics would need to have a bandwidth of about 2.5 GHz. However, state of the art video amplifiers for CRTs, providing a signal range of 32 to 60 Vpp (i.e., voltage "peak-to-peak") at the G1 electrode, offer electrical bandwidths of only 300 to 400 MHz, with corresponding rise and fall times of $\tau_{rise} = 6.25 \times 10^{-10}$ s. Assuming the rise and fall times are equal, $\tau_{rise} + \tau_{fall} = 1.25 \times 10^{-9}$ s, which is almost equal to the pixel time τ_{pix}, not considering the fact that the definitions of rise time and fall time cover only the time between the 10% and 90% amplitude. Clearly, the requirement described above ($\tau_{rise} + \tau_{fall} << \tau_{pix}$) cannot be met with most state-of-the-art amplifying electronics. As a result, the time for the sharp rendition of a single pixel and, therefore, the size of a single pixel are larger than the nominal pixel size, as presented in Figure 9. Fortunately, the requirements for the display of band-limited digital images are less stringent, with the video bandwidth being limited by the Nyquist limit of the digital image (i.e., 186 MHz for this example).

Two other important factors affecting the pixel size in CRTs are beam current and incident angle. The diameter of the electron beam is related to the area of the cathode from which electrons are extracted. This emissive area is controlled by the voltage difference between the cathode and the G_1 electrode. An increase in emissive area produces increased current but with a consequent increase of the beam spot size. It has also been suggested that the diameter of the electron beam is influenced by the repelling forces between the electrons, on account of their negative charge: the higher the beam current, the larger the forces and the diameter (Paszkowski 1968), but the ultimate spot size of the electron beam at the landing position on the CRT's phosphor is still very much a function of the beam current. Clearly, the resolution achievable with a large beam spot is inferior to that achievable with a small beam spot.

The beam landing angle is also a cause of resolution loss at the edges of CRT displays. Because of deflection distortions, individual pixels lose the round profile that they have at the center when they are further away from the center. The peripheral tear-drop-shaped pixels cause pixel astigmatism and reduce display resolution at the peripheries of the display area. High-resolution displays of 5 megapixels often have dynamic astigmatism compensation to force the pixel back to a nearly round shape and recover some of the resolution losses by this mechanism.

With color CRTs, an additional limitation on spatial resolution is imposed by the shadow mask or the aperture grill, as described above. These beam-restricting devices represent essentially a sampling comb. Recall that color CRTs do not have a continuous phosphor layer, rather they have isolated red, green, and blue phosphor "islands" (for the shadow mask types) or red, green, and blue phosphor stripes (for the aperture grill types). Three such islands are located behind a hole in the shadow mask. Color display devices also have three electron guns, instead of one as for monochrome CRTs, one each for the red, the green, and the blue phosphor islands or phosphor stripes. The human eye integrates each group of the red, green, and blue islands to sense the specific color/luminance of each pixel. So a pixel in a color CRT is represented by at least one set of red, green, and blue subpixels. Since the apertures in the shadow mask act as a sampling comb, some oversampling is used. In practice, the electron beam covers between 5 and 10 sets of red, green, and blue phosphor islands. Consequently, the spatial resolution of color CRTs is much poorer than that of monochrome CRTs.

The resolution of a display system can degrade over time due to phosphor aging and cathode depletion. Phosphor aging varies with the type of phosphor used, either blended or single component. A single-component P45 phosphor ages less rapidly and exhibits less of a color shift over time. Blended phosphors, such as P104, are generally more efficient than P45 but age considerably faster. This loss of efficacy requires additional beam current to maintain the luminance. This in turn requires higher drive levels to the cathode and a larger electron beam current. The net result is a gradual increase in the electron spot size over time and degradation in the display resolution. Likewise, the loss of efficacy of the cathode over time due to the depletion of cathode material requires added drive to achieve as-new luminance. Tests are necessary to monitor and assure consistent display performance over time.

2.3.2 Emerging Display Technologies

Most of the electronic devices used to display medical images are currently CRTs. However, it is expected that new display technologies will gradually replace the heavy and bulky CRT with a thin, lightweight display device with potentially better image quality, lower power consumption, better durability, and reduced cost. AMLCDs have started to find their way into the medical marketplace. In addition, a number of other new technologies have potential in medical imaging. They include organic light-emitting displays, micromirror displays, plasma displays, electronic projection displays, and head-mounted displays. These display devices currently do not meet the resolution, contrast, and display size requirements of medical diagnostic displays, even though they might prove useful for some limited medical imaging applications. However, with the current rapid progress in display technologies, they might be able to meet the specific requirement of diagnostic medical applications in the future.

A multitude of technologies are being developed for different applications (see Figure 10). This subsection focuses on those display technologies that have demonstrated potential to achieve high display quality for medical imaging applications and for which extensive research and development efforts are under way. This subsection also summarizes the basic elements of three technologies: the AMLCD, the field-emitter display (FED), and the organic light-emitting display (OLED). LCDs with high brightness and large pixel array sizes are now available for use in radiology workstations and have become serious candidates to replace CRTs. The FED technology is based on the luminescence of phosphors generated by electron bombardment. Although claiming rapid development into products, this vacuum technology has not achieved the display quality that was predicted in the mid 1990s. Finally, we review the current state of development of active-matrix OLEDs. These devices are being developed for a variety of applications and have the potential for excellent image quality. An LCD may be classified as a "transmissive" display device, as its pixel array alters the transmission of a backlight to the faceplate, while FEDs and OLEDs may be classified as emissive flat-panel displays, as their pixel elements themselves emit light. In this subsection, the fundamentals of these technologies are presented, and current engineering challenges are outlined.

2.3.2.1 Liquid Crystal Displays

LCDs rely on the fundamental electro-optical characteristics of liquid crystals (LCs) to form an image. When the molecular orientation within an LC is altered by the application of an external electric field, the optical characteristics of the material changes. This electro-optical effect is used in LCDs to modulate light transmission. An LCD is composed of a large array of LC cells (each representing a pixel of the image), polarizer filters, and a backlight. The height and volume of the LC cells are controlled by spacers (see Figure 11).

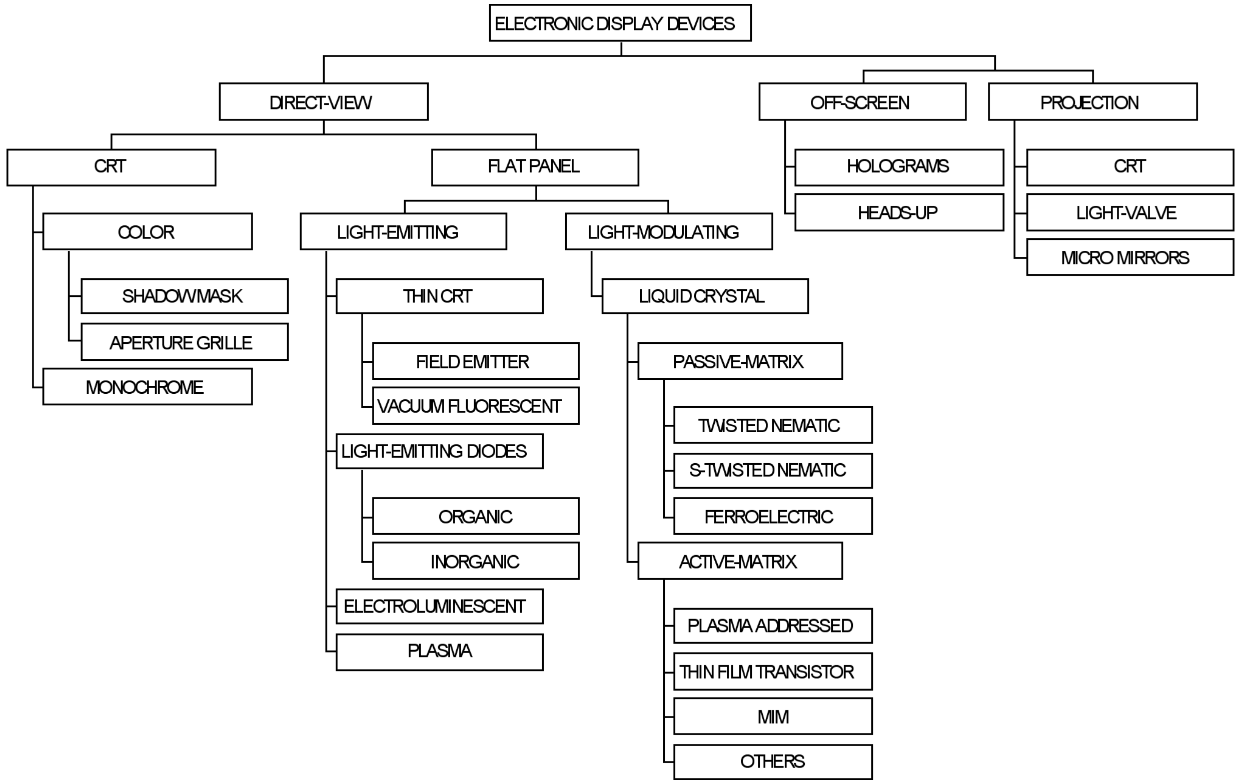


Figure 10. A classification of electronic display devices. Note that displays that are not direct-view CRTs can also be monochrome or color, but the difference does not create a dichotomy in the design of these displays as it does with the direct-view CRTs. This is why color is not listed as an attribute of displays other than for direct-view CRTs.

Light is generated by the backlight and directed to the front through a first polarizing filter, the LC cell, and an exit polarizing filter. The amount of the transmitted light intensity is primarily controlled by the change in polarization induced by the voltage applied to the LC cell in relation to the polarization orientation of the first and second polarizer. The maximum amount of transmitted light (i.e., the maximum luminance of the display) is determined by the intensity of the backlight, the nature of the polarizers, the transmission of the LC cell in its full “on” state, the transmission characteristics of additional color filters (for color displays), and the aperture ratio (the fraction of the pixel area that is transparent). The minimum luminance of the display is primarily determined by the opaqueness of the LC cell in its full “off” state. In an AMLCD, the switch between on and off states is controlled through voltage changes produced by a thin-film transistor (TFT) array.

Displays can be characterized as being normally white or normally black, depending upon the relation of the pair of polarizers relative to the intrinsic “twist” in the LC material. For example, if a pair of crossed polarizers is used, with LC material having no intrinsic twist, all light is linearly polarized after passing through the first of the polarizing filters. When no voltage is applied, all light will be fully blocked by striking the second (crossed) polarizer, and this display is characterized as normally black. Alternatively, the pair of polarizers may be colinear, so that light that passes through the first polarizer is transmitted through the second polarizer in the absence of voltages. This display is characterized as normally white. It is somewhat more

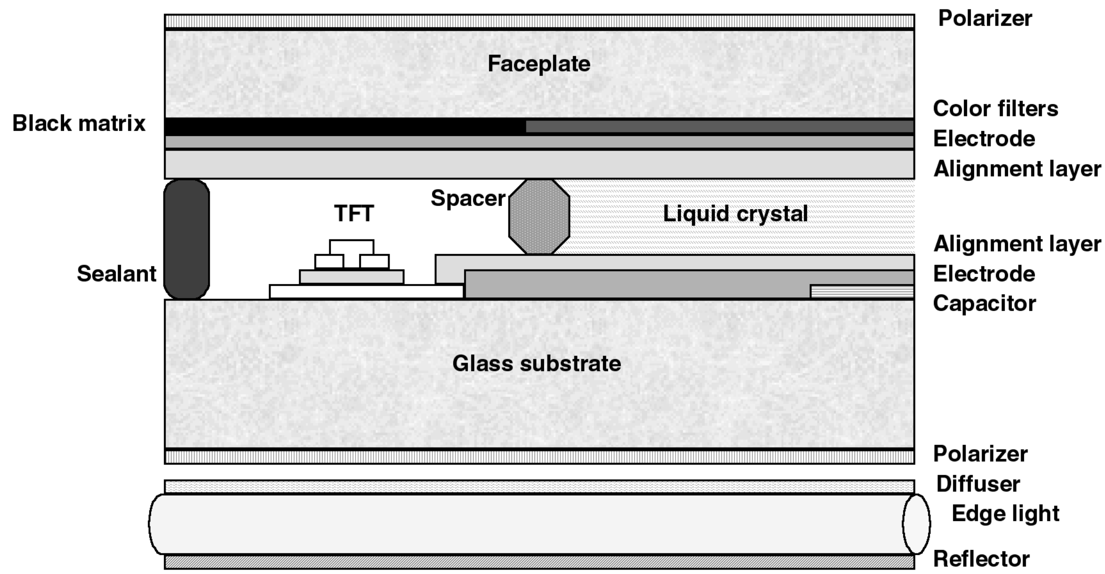


Figure 11. Typical cross section of an AMLCD.

straightforward for normally white displays to provide a higher maximum luminance L_{max}, since the twist is not needed to achieve the maximum luminance. However, for a normally white display it is difficult to achieve a low L_{min} value, since the opaqueness of the display depends upon the efficiency of the LC material in providing the twist.

A unique aspect of LCD devices is that the light emission is non-Lambertian. This is due to two major reasons: first, the optical anisotropy of the LC cell, which depends upon the manufacturing design and the applied voltage, and second, the effect of polarized light being transmitted and viewed in a direction colinear with the polarizing filter (termed a sine-squared effect since it varies as $\sin^2\theta$, where θ is the viewing angle). These two effects result in a potentially severe angular dependence of the luminance. The angular dependency affects the contrast as well as luminance of the presented image as a function of the viewing angle. More advanced LCD designs have aimed to minimize this angular dependence by (1) varying molecular alignments in subregions (domains) within individual pixels (Nam et al. 1997), (2) modifying the orientation of the LC molecules to remain in the plane of the display (in-plane switching) (Wakemoto et al. 1997), or (3) adding a negative birefringence plate to compensate for the optical anisotropy (Hoke et al. 1997). It is common for the first two methods to also include the third.

Using hydrogenated amorphous silicon (a-Si:H) TFT technology, AMLCDs have achieved very high information content and color pixel resolution. Monochrome 2560×2048 (5 megapixels) workstation quality and color 3840×2400 (9.22 megapixels) AMLCDs have recently been introduced commercially.

2.3.2.2 Emissive Flat-Panel Displays

Among the emissive flat-panel technologies, FEDs and display devices based on organic light-emitting materials have a quasi-Lambertian emission that offers constant contrast and luminance at wide viewing angles (like CRTs).

2.3.2.2.1 Field Emissive Displays. FEDs are similar to CRTs in that electrons are emitted from a cathode and accelerated toward the phosphor through a vacuum cell. However, instead of using thermionic emission, electrons are emitted by a cold electron source that typically consists of a large array of microscopic emitter tips made with low work-function material (Gray et al. 1993). A schematic cross section of a typical FED is depicted in Figure 12. Electrons are accelerated through a vacuum cell to impinge on a cathodoluminescent phosphor. As illustrated in the figure, the voltage across the vacuum gap is maintained via thin-layer opaque bottom electrodes and a metallic transparent indium tin oxide (ITO) layer. Spacers are used to maintain the vacuum gap and to ensure a constant height for the electrons to travel through. The large currents needed to generate high-luminance displays require the control of the divergence of the beam due to space charge and Coulomb interactions. Beam spreading results in some defocusing and loss in resolution. In order to control defocusing, instead of using a diode arrangement with a small gap between the emitter and the phosphor screen, a focus electrode can be incorporated to decrease beam spot size and increase resolution (Tang and Swyden 1997).

While most FEDs use metallic microtips, amorphous diamond has shown good current-voltage characteristics. The emission mechanism of the latter, however, is not well understood (Xie et al. 1993). Most FED designs require evacuation to low pressures (10^{-7} torr) to prevent contamination and deterioration of the electron emitters (Holloway et al. 1995). Large display sizes need spacers to prevent bending of the faceplate. In low-voltage designs, small spherical spacers are used. Phosphor efficiency and light emission are greater at high voltages. However, devices with high-voltage designs require focused electron beams and large spacers with high height/width ratios (Tirard-Gatel et al. 1999).

FEDs possess favorable characteristics such as temperature and humidity tolerance, wide viewing angle with Lambertian emission similar to CRTs, and potential for high luminance and contrast. However, severe pixel luminance non-uniformity, due to electron emission non-uniformity, and low reliability of the cathode have been reported for prototype designs.

2.3.2.2.2 Organic Light-Emitting Displays. Electroluminescence (EL) represents an all-solid-state approach for electronic display that provides the most direct conversion of electrical energy into light. EL devices use a phosphor under the influence of an electric field to

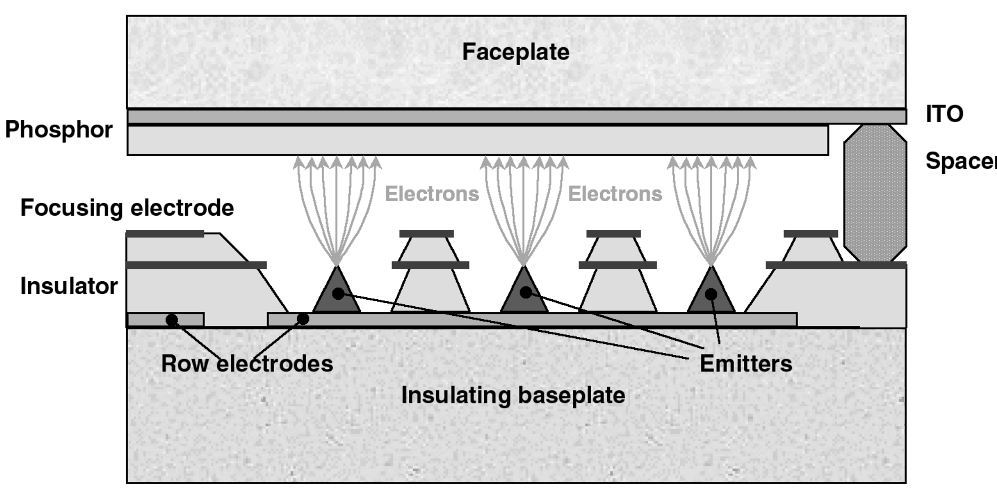


Figure 12. A device cross section of a typical FED.

generate light. EL displays rely on the acceleration of carriers through a material under high voltage, and subsequent production of light due to excitation of luminescent centers. Some EL displays, known as light-emitting diode devices, rely on another mechanism for light production based on the injection and recombination of carriers through thin-films (Tang and Van Slyke 1987). In this class of displays, OLEDs have recently emerged as a superior display technology (He et al. 1999) (Figure 13). OLEDs are based on superior light emission efficiency and other desirable properties of certain small aromatic molecules and polymers (He and Kanicki 2000). In these devices, light is generated by radiative recombination of electron-hole pairs in organic semiconductors. Different organic materials have been used, providing a wide range of emission spectra, although white emission from single nondyed organic layers has not been reported.

To obtain good grayscale performance in large sizes, OLEDs require an active-matrix array that delivers controlled current levels to each pixel, as opposed to controlled voltages in AMLCDs. Pixel designs for OLEDs consequently require more than one TFT per pixel. Still in early developmental stages for large-size devices, OLEDs present reliability challenges such as electrochemical instabilities with formation of radical species; contact degradation; and low thermal, humidity, and oxygen tolerances (Sheats and Roitman 1998). In addition, it is known that a large fraction of the generated photons are absorbed and internally reflected within the display structure (Badano and Kanicki 2001). Devices with improved net phosphor efficiency, made by modifying the geometry, reducing internally reflections, and reducing edge-emission effects, are currently being investigated.

2.4 Engineering Specifications for Display Devices

Display specifications are critical to the ultimate quality of the images displayed by the device. Some of the important engineering specifications of display devices are described below and tabulated in Table 1. When acquiring a display system, the user should carefully evaluate the specifications of the device to assure that the display characteristics meet or exceed the needs of the desired function. The following specifications apply mostly to monochrome displays, unless otherwise noted.

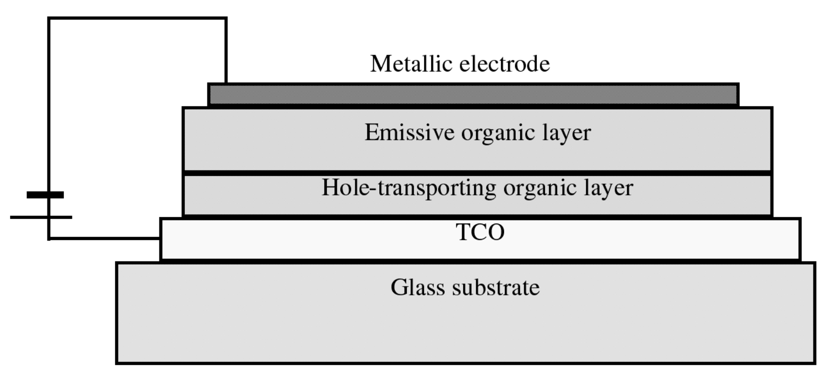


Figure 13. Bi-layer structure showing organic carrier-transporting and emissive layer in an OLED display device on glass substrate with transparent conductive electrode (TCO). The structure shown (not to scale) is typical of polymer emissive materials.

Table 1. Examples of typical medical display specifications.

Specification Line Item	Secondary/Office 1/2 Megapixel	Primary/Secondary 1/2 Megapixel	Primary 3/4 Megapixel	5 Megapixel	Comments
Matrix size (pixel format)	1024×1280	1200×1600	1728×2304	2048×2560	1
Active pixel size, mm	0.28–0.3	0.28–0.3	0.17–0.23	0.15	
Luminance ratios	~50–100	~100–250	250	250	2
Luminance non-uniformity	< 30%	< 30%	< 25%	< 25%	3
Anti-reflection treatments	Optional	Recommended	Recommended	Recommended	4
Miscellaneous	See comments	See comments	See comments	See comments	5
For CRTs:					
Amplifier bandwidth at volts p-p	160–200 MHz, 45 V	160–200 MHz, 45 V	250–290 MHz, 45 V	250–290 MHz, 45 V	6
Phosphor type	P104	P104 or P45	P45	P45	7
Maximum luminance, cd/m²	100	100–300	200–300	200–300	8
RAR at specified pixel format	0.9 to 1.1	0.9 to 1.1	0.9 to 1.1	0.9 to 1.1	9
Pixel size at 5% point	< 3.5:1 ratio to 50%	< 3.0:1 ratio to 50%	< 2.5:1 ratio to 50%	~2:1 ratio to 50%	10
For LCDs:					
Maximum luminance, cd/m²	200	200	700	700	
Viewing angle (40:1 lum. ratio)	Per model	> 80° hor, 50° ver	> 80° hor, 50° ver	> 80° hor, 50° ver	11
Defective pixels	< 30	< 10	< 10	< 10	

Important note: The listed specifications are not intended to be used as guidelines or acceptance criteria. They are only examples to show what is commonly available and in use at the time of this writing. The actual performance requirements and procedures for medical displays are provided later in sections 4, 5, and 6.

1 This represents the addressable pixels the unit will accept, not what it will resolve. (L) = Landscape / (P) = Portrait

2 This represents the end points (factory settings) of black level and peak white, i.e., DAC values of zero and 255.

3 Dependent on glass formula and bulb type. Compensation for uniformity that uses video amplifier compensation decreases the resolution from the center to the edge.

4 Anti-reflective coatings reduce specular reflectance and veiling glare in CRTs. It is strongly recommended for all medical displays. Most effective method is multilayer coating.

5 Miscellaneous specifications might include non-linearity of image (≤10%, 0.05 mm maximum), raster stability (jitter/swim), high-voltage regulation (0.5% max size change), operating range temperature (0 to +40 °C), operating range humidity (10 to 90% noncondensing), storage range temperature (–40 to +65 °C), and storage range humidity (5 to 95% noncondensing).

6 Alternate term is 3db point at volts p-p. Bandwidth should match pixel format requirements in 1k line displays of fixed frequency. Multisync should favor the higher end of the range. Higher bandwidth within range noted yields better resolution.

7 P45 provides long-term stability and low spatial noise compared to other phosphors.

8 Specified at a specific pixel format or multiple formats for multifrequency displays.

9 RAR=Resolution-Addressability-Ratio. Measured pixel at 50% point of luminance at peak or nominal rating expressed as a percentage of addressable space available. Medical displays are recommended to have 0.9 to 1.1 RAR values (Muka et al. 1997).

10 Values are expressed in terms of the diameter of the pixel profile at 5% luminance intensity relative to that at 50% intensity (described by RAR above).

11 Note that within the specified viewing angle, there can still be significant changes in luminance and contrast.

2.4.1 Physical Dimensions

Physical dimensions refer to the height, width, depth, and weight of the display device. These characteristics need to be known for proper space planning and installation.

2.4.2 Power Supply

Power supply requirements of a display device specify the maximum power consumption in watts, as well as the voltage, and power frequency range of the input. Power requirements are specified for global operation in either a continuous range (85 to 264 VAC) or two separate subsets. Wattage is commonly expressed as maximum power at a specific horizontal line (raster) frequency. The amount of heat generated by the display is a direct function of the system's power usage. An excessive rise in the ambient temperature may result in the display shutting down in some situations. Due to improved efficiency and heat management, a switching power supply is preferable to a continuous (linear) power supply. The VESA display power management standards specify logic states, controlled via the sync signals, to put the display in standby or suspend mode. Suspend mode drops the power consumption to as low as 5 W, saves energy, and reduces heat generation but also requires the display to go through a warm-up cycle when restarted.

2.4.3 Input and Output Signals

Display systems (including controllers) have particular specifications for their input and output connections. They include the video connector type (usually BNC or VGA), voltage, and termination impedance (usually 50 Ω or 75 Ω). The industry standard terminations are 75 Ω and 50 Ω, which are applicable to either BNC connectors or 15-pin high-density VGA connectors for 1k line displays. Displays with high pixel densities above 2 megapixels usually use single- or double-shielded cables with BNC connectors. The impedance of system components should be matched. A mismatched impedance termination and/or inferior quality video cable can cause video artifacts such as ringing (ghost images). This is especially true in high-resolution 2k displays. Video artifacts in 1k displays are less pronounced because of the lower resolution and the use of slower video amplifiers. Digital input signal capabilities, such as those provided by digital video interface (DVI) (VESA 2000), have promising advantages over analog modes and are becoming available for newer display devices, including flat-panel displays.

2.4.4 Bandwidth (CRT)

Bandwidth of a display device specifies its video amplifier's performance over a frequency range. Bandwidth is the frequency range over which the peak to peak (p-p) volts output (dynamic range) of the amplifier can be sustained. It is usually specified at the 3 dB down point, the industry standard measure of amplifier roll-off characteristics. In CRTs, video bandwidth is a critical specification that defines the ability to resolve CRT pixels in the horizontal direction. The size of the pixel, the pixel profile, and the extent of pixel overlap in the horizontal direction are controlled by the video amplifier. (Vertical image fidelity is controlled by the electron optics and line spacing.) Larger matrix size displays require higher bandwidths to deliver the desired pixel densities. In general, the bandwidth of the video amplifier has to be larger than half the pixel rate (Mertelmeier and Kocher 1996). For color displays, the same video amplifier is used for each individual video channel (i.e., RGB). The bandwidth needs to support the maximum pixel array of the display.

2.4.5 Environmental Specifications

Environmental specifications include the temperature, humidity, vibration, and shock ranges for operation or storage of the display unit. Typical operating range is 10 to 40 °C temperature and 10% to 90% relative humidity (noncondensing). Vibration and shock ranges vary among different systems.

2.4.6 Matrix Size

Matrix size or pixel array specifies the number of addressable pixels in the horizontal and vertical directions of the display provided by the video graphics controller that can be accepted by the display device. Current medical display devices are able to provide matrix sizes up to 2048 × 2560, referred to as 2k (2000-line) or 5 megapixel displays. Displays with one-fourth that number of pixels, referred to as 1k (1000-line) displays, are less costly and more common. Matrix size, combined with the active display area, specifies the display device's nominal pixel size. It should be noted that contrary to commonly held beliefs, nominal pixel size is not the only factor defining the display resolution. The display resolution is a function of the actual size and luminance profile of the pixels displaying the image. In CRTs, the nominal and actual sizes of the pixels can be notably different because of the spatial spread of the pixels, as described in section 2.3.1.3.

2.4.7 Display Area

Display area specifies the physical size of the active image display area. Traditionally, the display area of a display device is measured as the diagonal length of the active display area. By convention, for CRT displays, the diagonal measure is specified by the glass manufacturer as the outside dimension of the faceplate. The useful display area is less than the specified dimension. For instance, a quoted 17 in. display device may only have 15 in. active display area. In flat-panel displays, there is no difference between the specified and actual display areas. Since modern display devices come in various sizes and aspect ratios, it is now more common to specify the horizontal width and vertical height of the display area along with the diagonal dimension.

2.4.8 Phosphor Type (CRT)

The phosphor type is an important specification for phosphor-based display devices such as CRTs. It determines not only the maximum output luminance of the display, but also its spatial noise, output color tone (hue), and aging characteristics (see also section 2.3.1.1). The common types of display phosphors for monochrome displays are P45, P4, and P104. P45 is a single-crystal phosphor with a blue tint, while P104 and P4 are blended phosphors with blue and greenish yellow components producing a combined color close to white. Note that there are multiple kinds of P45 phosphors that have slightly different luminance and hue characteristics. P104 and P4 phosphors are more efficient than P45 in converting the electron energy to light and thus require less electron bombardment for a given luminance. However, they age more rapidly both in terms of loss of luminance and color shift over time caused by different aging characteristics of the two phosphor components. The multicomponent nature of these phosphors also generates a fixed spatial noise pattern in the displayed images that can be recognized on close examination of the image with a magnifier. In comparison, P45 is more stable at high beam currents, shows less color shift with aging, exhibits slower efficacy loss from aging, and does not exhibit the spatial noise associated with blended phosphors. Presently, P4, P104, and P45 CRTs have all been successfully used in high-resolution diagnostic medical imaging applications; however P45 is the preferred phosphor for primary class CRTs.

2.4.9 Refresh Rate

The refresh rate specifies the frequency at which the display frame is updated. Usually it is given by the frequencies of the vertical and horizontal scans. The vertical scan frequency is often quoted as refresh or frame rate, which is usually between 55 Hz and 150 Hz. A refresh rate that is too low generates a flickering effect detectable by the eyes that may result in lower user performance and fatigue. A minimum refresh rate of 70 Hz is recommended for primary class CRTs. In a CRT, the appearance of flicker is reduced with the use of phosphors having longer decay times (longer persistence). Flat-panel displays such as LCDs exhibit persistence (e.g., in LCDs, switching speed from one polarization state to another) that is longer than that of CRTs. Consequently, flat-panel devices exhibit fewer flickers, thereby allowing refresh rates as low as 20 Hz, compared to CRTs with relatively short phosphor decay.

2.4.10 Pixel Size

Display pixel size refers to the nominal physical dimension of the smallest addressable light-emitting element of the display device. Usually, displays with smaller pixel sizes have potential for better resolution characteristics as expressed in contrast modulation. However, the actual pixel size, which, as pointed out in section 2.2.1, is not necessarily equal to the nominal pixel size, should be taken into consideration.

In CRTs, the actual pixel size is defined by the area of light emission of the phosphor upon excitation by the (single) electron beam within a finite time period. The industry standard is to measure the pixel size at the 50% point of luminance energy of its luminance profile (Figure 4). The ratio of this value and the nominal pixel size is known as the resolution-addressability ratio (RAR). An RAR value of 0.9 to 1.1 is recommended for medical use (Muka et al. 1997). As an example, in a standard 21 in. display with 300 × 400 mm of display area and 2048 × 2560 matrix size, the (portrait) horizontal and vertical addressable pixel spaces are 0.1465 mm and 0.1563 mm, respectively; almost a square pixel. The physical pixel, produced by the electron optics and video amplifier must create an actual FWHM pixel size that is between 0.9 and 1.1 of nominal pixel size.

The size of the CRT pixel in the horizontal and the vertical directions may differ, as they are dependent on two different functions. The vertical height of a pixel is controlled by electron optics, while the horizontal width is controlled by the video amplifier. The optics are generally more stable over the entire screen area, and therefore, the resolution uniformity (i.e., the consistency of resolution response within the entire active display area) is generally better in the vertical direction compared to that in the horizontal direction. The electron optics of a CRT cause distortion and spot growth at larger deflections of the beam from the center of the CRT. The pixel size is, therefore, usually larger in the corners and edges of the screen than in the center. Furthermore, in addition to directionality and location dependency, the pixel size changes with the beam current, and thus it has to be specified at particular luminance levels.

2.4.11 Luminance

In electronic displays, luminance usually refers to the maximum brightness of the display. A regular desktop color display device has a maximum luminance of approximately 100 cd/m^2, while a high-luminance display device can have a maximum luminance up to 300 to 600 cd/m^2. Usually, display systems with higher maximum luminance are preferred for medical images. However, this preference should be balanced with the desired life and resolution capability of the display, as well as its ability to render all luminance values applicable to the display of a medical image, particularly the low luminance values.

The minimum luminance is also an important parameter in medical display devices. Minimum luminance is subject to change during the lifetime of the display. High-quality medical displays have specific electronic circuitry to stabilize minimum luminance. Typical PC grade (home-use) display devices lack reliable stabilizing circuitry and can mask low-luminance image details. The ratio of the maximum and minimum luminance of a display device, the so-called luminance ratio in the presence of ambient lighting and contrast ratio in the absence of ambient lighting, is an indicator of the luminance response capability of a display device. For medical diagnostic applications, a system automatically measuring and stabilizing the minimum and maximum luminance is indispensable for reliable diagnosis over long periods of use. At the same time, these systems substantially prolong required calibration intervals.

2.4.12 Luminance Uniformity

Luminance uniformity refers to the maximum variation in luminance across the display area while displaying a uniform pattern. Most CRT displays have a certain degree of non-uniformity due to differences in the path length and beam-landing angle of the electron beam, the non-uniformity in the application of the phosphor layer, the non-uniformity in the thickness of the thin aluminum backing, and the increase in the thickness of the glass of the faceplate from the center to the edge. The latter is the largest contributor to luminance non-uniformity. Glasses for color CRTs with a typical 55% central transmittance exhibit a 7% decrease in transmission from the center to the edge, while monochrome CRTs at 34% central transmittance exhibit up to a 15% change. Luminance non-uniformity is more significantly noted for CRTs that have faceplates with flat profiles compared to smaller radius or "curved" CRTs, since the faceplate must be even thicker at the edges. Advanced CRT displays have uniformity correction circuits that equalize the luminance over the total screen area. These circuits apply a dynamic (synchronized in real time with the spot movement) modulation of either the video amplifier gain or the G_1 bias (brightness) to compensate the intrinsic luminance non-uniformity of the CRT. Such corrections, however, can impact the resolution response of the devices at the periphery of the display area.

In flat-panel displays, non-uniformity is due to non-uniform luminance output of individual pixels. In AMLCDs, luminance non-uniformity is often caused by non-uniformity of the backlight and the variations in the thickness of the LC layer. As this thickness can vary locally within the active display area, luminance non-uniformity in AMLCDs can have a markedly different pattern, with spatial frequency content higher than CRTs.

2.4.13 Surface Treatments

Most medical CRT manufacturers utilize some anti-glare and anti-reflection (AR) methods to reduce the undesirable effects of veiling glare and ambient light reflection. Anti-glare approaches are usually in the form of absorbing substances in the faceplate of the CRT.[3] Anti-reflection approaches usually involve the application of an anti-reflective coating layer, with a thickness equal to 1/2 of the light wavelength, on the surface of the faceplate. Commonly, multilayer vacuum coatings are first applied to a thin glass substrate (1/8-inch-thick), which is bonded to the CRT faceplate in a subsequent step. The transmissivity of the anti-reflective coating, ranging from 60% to 90%, specifies the portion of light transmitted through the coating. In nonmedical displays, the reflection is sometimes reduced by anti-reflective/glare treatments that make the glass surface rough through the processes of chemical or mechanical etching or spray-on coatings. Such treatments diffuse incident light but also degrade the displayed image and thus are not recommended in displays for medical applications using CRTs.

In flat-panel displays, multilayer thin-film anti-reflective coatings are also used to reduce specular reflections. In addition, transmissive displays such as AMLCDs permit designs that can block light reflection further by introducing absorbers in the structure. An approach that is being used currently is the use of spacers that are light absorptive and made of black glass. LCDs also often use a form of anti-glare faceplate treatment that eliminates distinct specular reflection but produces a haze component.

2.4.14 Bit Depth

The bit depth of a display device specifies the maximum theoretical number of simultaneously displayable gray levels, or color levels, that one can attempt to display. For example, in an 8-bit display, one can attempt to simultaneously display 256 distinct gray levels. The display controller (i.e., the video card) usually determines the bit depth of a display device. Current medical display controllers have bit depths ranging from 8 to 10. However, similar to the difference between nominal and actual pixel sizes, the theoretical number of shades of gray, or color, may be less than the actual number due to limitations in the capability of the display system. Since bit depth is the means by which tonal values from black to peak luminance are defined for a pixel, the ability or inability of the video amplifier of the display device to respond across the full dynamic range determines whether the tonal transitions commanded are actually rendered. Insufficient bandwidth progressively masks the tonal values represented by the least significant bits. The use of LUTs can significantly reduce the actual number of distinct luminance levels commanded by an 8-bit graphic card.

2.4.15 Viewing Angle (LCD)

LCD devices have an angular-dependent luminance and contrast response and chromaticity. Viewing angle measured from the normal to the display faceplate indicates the angular range within which the contrast ratio of the device is maintained within a certain range. It is usually separately specified in the horizontal and vertical directions. It should be pointed out that even within the specified viewing angle, an LCD can exhibit marked changes in luminance, contrast, and chromaticity as the viewing angle is changed.

2.4.16 Aperture Ratio (LCD)

In flat-panel displays, a pixel might utilize only a portion of the nominal pixel size. The ratio between the actual pixel size and the nominal pixel size is called the aperture ratio. With higher aperture ratios, less pixel structure will be visible on the display, and the display may also be brighter.

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[3] Note that anti-glare is also sometimes used to refer to a front diffusing layer that produces a haze component.

2.5 Classification of Display Devices

In recognition of the currently accepted practice and in accordance with the guidelines set forth by the American College of Radiology (ACR 1999) and the U.S. Food and Drug Administration (FDA), display devices for medical imaging are characterized in this report as either primary or secondary. Primary display systems are those used for the interpretation of medical images. They are typically used in radiology and in certain medical specialties such as orthopedics. Secondary systems are those used for viewing medical images for purposes other than for providing a medical interpretation. They are usually used for viewing images by general medical staff and medical specialists other than radiologists and utilized after an interpretive report is provided for the images. In this class of displays, there are also operator's console monitors and quality control (QC) workstations, display devices that are commonly used to "adjust" the images before they are sent to PACS or hard-copy printers. As the performance of these systems (especially their luminance response) directly impacts image presentation at other display devices, their performance needs to maintain a minimum level of acceptability. Ideally, they should comply with the luminance response requirements of primary displays. In other aspects, they may be treated as secondary class displays. In prior literature, primary devices have sometimes been referred to as "diagnostic" and secondary devices as "clinical."

Both display classes must meet specified display performance functionality requirements for the imaging modality for which they will be used. The performance requirements for a given imaging modality are dependent on the modality itself. For example, fully diagnostic information for an MRI examination is obtainable at a matrix size far less than that required for chest imaging. However, this report adopts a conservative general classification independent of the imaging modality. It is possible to have less stringent performance requirements for certain modalities or diagnostic tasks. If so, however, it should be taken into consideration that a display that is originally intended for a certain modality might be used to view images from another modality in the future, so it should meet the more stringent set of requirements.

Differences between primary and secondary displays are evident in the sample engineering specifications listed in Table 1, and in the performance requirements delineated in sections 4, 5, and 6. In acquiring a display system of a certain class, the physicist must understand and establish the desired specification and performance requirements. The requirements must be specified prior to purchase and clearly communicated between the user and the manufacturer. These requirements will also be a basis for performance assessment of the device in the form of acceptance testing and the routine quality control procedures as described in the following sections of this report.

Ideally, the performance of any medical display device that is used in any diagnostic or clinical capacity should be evaluated and monitored accordingly. However, a number of primary class medical displays, including those in fluoroscopic examination suites, digital angiography, or digital subtraction angiography, and secondary displays, including operator console monitors, are "closed" in that the TG18 test patterns (detailed in section 3.2) cannot be easily loaded on them. That severely limits the execution of the performance evaluation steps recommended in this report. It is ultimately the responsibility of the manufacturer to make the TG18 test patterns available on the system. However, if these patterns cannot be loaded and displayed, a minimum level of display evaluation should be undertaken as described in appendix I of this report.

3 GENERAL PREREQUISITES FOR DISPLAY ASSESSMENTS

3.1 Assessment Instruments

Although many display tests can be performed visually, a more objective and quantitative evaluation of display performance requires special test tools. The required instruments vary in their complexity and cost, depending on the context of the evaluation (research, acceptance testing, or quality control) and how thorough the evaluation needs to be. Objective and reliable assessment of many display characteristics can be performed with relatively inexpensive equipment. However, if a complete assessment of display performance is desired, more sophisticated equipment is required. This section provides a description of all the tools referenced in this report. The users are advised to consult sections 4 through 6 to determine the subset of these tools needed for the particular tests being performed.

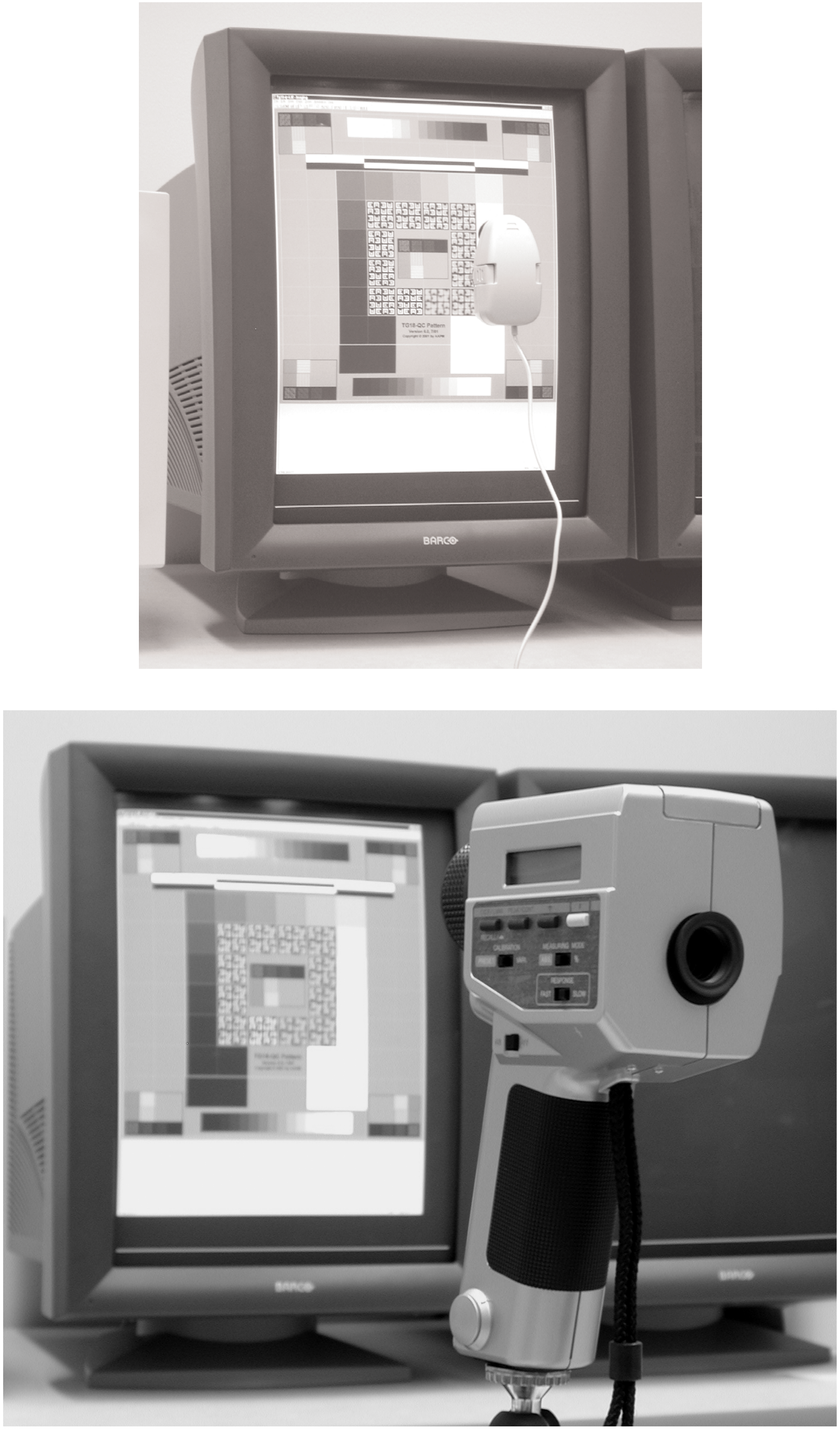
3.1.1 Photometric Equipment

3.1.1.1 Luminance Meter (Photometer)

The luminance response and the luminance uniformity quantitative tests recommended in this report (sections 4.3 and 4.4) require a calibrated luminance meter to measure the luminance of the display device. Two types of such devices are available in the market (Figure 14). For the near-range type of device, the luminance meter is held at a close distance from the faceplate of the display. In the telescopic type of luminance meter, the luminance meter is aimed toward the display from a distance of about a meter. The measured luminance values vary slightly depending on the type of luminance meter used, primarily due to the contributions of stray light to the measurements. Otherwise, either type is acceptable for display assessment as long as the measurements are performed in a consistent manner, which is particularly important for repeated quality control measurements.

To maintain consistency, particular attention should be paid to the ambient light level and the use of light blocking devices. For near-range luminance meters, a stopper ring should be used to block the ambient lighting. For telescopic luminance meters, a baffled cone (frustum) or funnel covered with a black light-absorbing coating may be used. The luminance meter should have a calibration traceable to the National Institute of Standards and Technology (NIST), and be able to measure the luminance in the range of 0.05 to 1000 cd/m^2 with better than 5% accuracy and a precision of at least 10^{-2} and ideally 10^{-3}. The luminance meter should also comply with the CIE standard photopic spectral response within 3%. Telescopic luminance meters should have an acceptance angle equal to or smaller than 1° for infinity focus. If the luminance meter is used for advanced luminance measurements (section 4.3.5), it needs to have a precision of at least 10^{-4} and ideally 10^{-5}.

It should be pointed out that many of the near-range pocket luminance meters used in today's medical calibration packages use photopic filters that do not meet the 3% compliance with the CIE standard photopic spectral response. However, it has been shown that the absolute accuracy of these devices can be improved by making certain assumptions about the chromaticity of the display. Such luminance meters, if calibrated according to a NIST-traceable calibration procedure to the specified display device, meet the spectral response requirement of this report. However, such luminance meters may not meet this requirement for other display devices. In particular, in LCD displays, the variation in backlights introduces a broader range of chromaticities that may result in measured values that are no longer within the specified tolerances.



(a)

(b)

Figure 14. Examples of near-focus (a) and telescopic (b) photometric and colorimetric equipment.

When a near range luminance meter is used to measure the absolute luminance of a display device with non-Lambertian light distribution, such as an LCD, the aperture angle of the luminance meter should be taken into account. As the luminous intensity can change substantially as a function of angle, luminance meters with different aperture angles will measure substantially different values. The differences are further impacted by luminance and temperature. Therefore, it is strongly recommended that for all measurements on LCD displays, near-range luminance meters with an aperture range smaller than 5° be used. Otherwise, certain correction factors should be applied (Blume et al. 2001).

A complete assessment of luminance response for display systems requires luminance measurements at a large number of signal levels. To automate this process, some display device and controller manufacturers offer luminance meters with direct interface to the device or the controller. The luminance values at multiple signal levels are automatically recorded and subsequently used to calibrate the display. The minimum requirements stated above are also applicable to these types of luminance meter devices.

The reflection, veiling glare, and angular emission quantitative tests (sections 4.2, 4.7, and 4.9) require a telescopic luminance meter. Low-flare and wide luminance range characteristics are two important requirements for the veiling glare test. Commercial telescopic luminance meters are acceptable for such assessments as long as they are used along with a light-blocking hood (section 3.1.3), which blocks stray light from the display (Figure 15). The luminance meter should have the same minimum specifications stated above with a 0.33° to 1° acceptance angle. In addition, the luminance meter should be equipped with an lens with focusing capabilities to an area smaller than 6 mm in diameter. In some systems, this requirement can be achieved by the use of an add-on close-up lens. Alternatively, precise assessments of the veiling glare characteristics of the display can be performed by a special purpose collimated luminance meter (Badano and Flynn 2000) (Figure 16).

3.1.1.2 Illuminance Meter

For the quantitative assessment of display reflection and for monitoring ambient conditions, an illuminance meter is required. The device should be able to measure illuminance within the 1 to 1000 lm/m^2 (lux, lx) range with better than 5% accuracy, comply to within 3% of the CIE standard photopic spectral response, have a calibration traceable to NIST standards, and have a 180° cosine response (Lambertian response) to better than 5% out to 50° angulation.

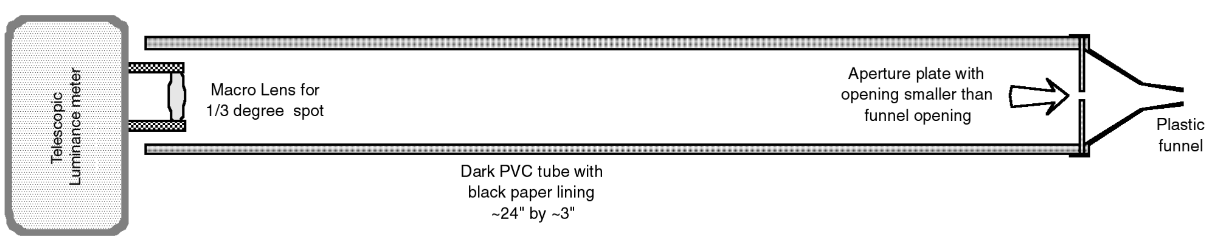


Figure 15. A baffled tube with funnel tip can be used to measure the dark spot in the center of the bright glare pattern. For visual measurements, the same device can be used to view the low-contrast pattern in the dark field. The aperture plate facing the funnel and the funnel exterior and interior should be painted with a nonreflecting black paint.

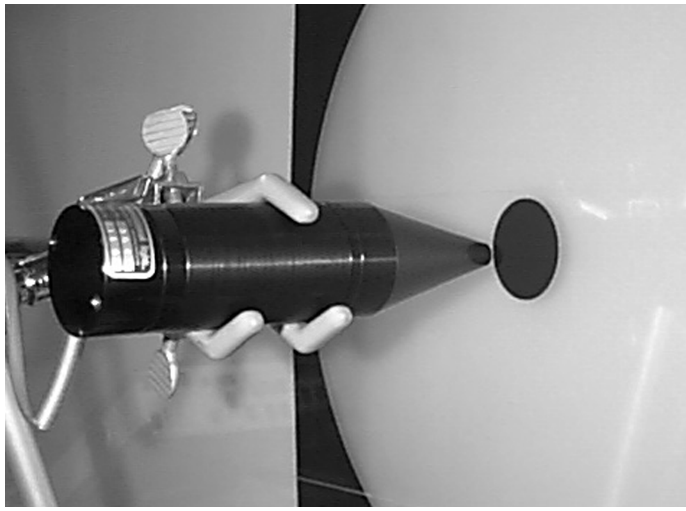


Figure 16. A luminance meter with collimated probe is positioned to record the luminance in a black region surrounded by a bright field.

3.1.1.3 Colorimeter

The quantitative assessment of chromaticity (section 4.8) necessitates the use of a colorimeter (or spectrometer) capable of assessing the CIE-specified color coordinates of the display device (IEC 1976). Colorimeters, similar to luminance meters, come in two different kinds: near-focus and telescopic (Figure 14). Either kind will be acceptable for display assessment as long as the measurements are performed in a consistent fashion with particular attention to maintaining a low ambient light level. The meter should have a calibration traceable to NIST standards and should be able to evaluate the CIE color coordinates with better than 0.004 accuracy in the u',v' space (0.007 in the *x,y* space) within a 1 to 1000 cd/m^2 luminance range.

3.1.2 Imaging Equipment

Quantitative assessment of the resolution and noise characteristics of display systems (sections 4.5 and 4.6) requires equipment to capture magnified images of the display (Figure 17). Charged-coupled device (CCD) digital cameras are well suited for the task. Two types of devices can be utilized in display quality assessments: scientific-grade digital cameras for high-precision assessments and high-quality photographic-grade cameras for more routine evaluations. For each type, a number of performance characteristics are desired, which are described below.

3.1.2.1 Scientific-Grade Digital Camera

For high-precision resolution and noise evaluation of display systems, the camera should be capable of acquiring low noise and wide dynamic range images at luminance levels ranging from 1 to 500 cd/m^2. The camera noise should be small compared to the signal variations (e.g., the fixed-pattern noise of the CRT screen) that need to be measured, while the dynamic range should be large compared to the maximum-to-minimum luminance ratio to provide adequate luminance resolution. The images should be at least 1024 × 1024 in matrix size (512 × 512 if only small fields of view are used) and have 10- to 12-bit pixel values. To achieve low noise and wide dynamic range, cooled CCD sensors with a relatively large pixel size are often employed.

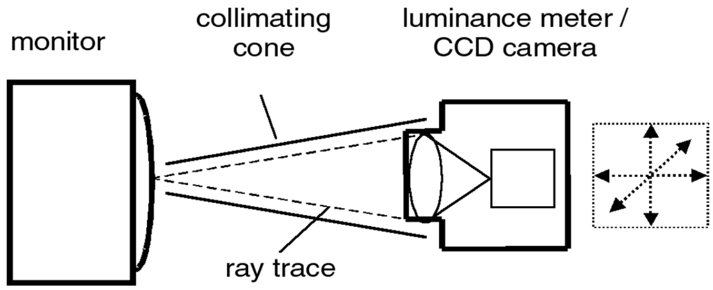


Figure 17. The schematic of a digital camera setup for quantification of resolution and noise in display devices.

The camera should be equipped with a focusable macro lens, preferably a finite-conjugate (fixed-focus) macrophotography lens, and be capable of operating at different frame rates and/or integration times (up to 1 s). The camera should have a digital interface to a computer for capturing and displaying the images. For portability, a notebook computer might be desired, in which case the camera might need to be able to transfer the image data via a high-speed connection. The digital interface should also allow control over the operational parameters of the camera.

It is recommended that the luminance, flat-field response, noise, and modulation transfer function (MTF) response of the camera be determined for the luminance levels and integration times employed in the display measurements. The luminance and flat-field responses are determined by capturing the images of light sources at known luminance values. This task can be accomplished by capturing images of luminance patterns, such as TG18-LN patterns (see section 3.2.2), displayed on a display device for which luminance values have been measured with a calibrated luminance meter previously. A plot of the mean pixel values in the central area of the image versus the luminance is a depiction of the camera's luminance response function. The response should be linear or transferred into a linear form. The noise of the camera is determined by acquiring dark-exposure frames (with the camera lens cover on) with shutter times equivalent to those employed in the display measurement. The noise is represented by the standard deviation in a region of interest of the approximate size of 200×200 camera pixels. The MTF of the camera is found from the edge or the line response in the same way, as described for the MTF measurement in section 4.4.4. An edge pattern or a narrow line, back illuminated by a uniform light source, is imaged with the camera, and the resultant image is analyzed with Fourier transform techniques. The luminance of the light source, the f-number of the lens, and the exposure time should be that same as those employed in the measurement technique. The characteristics of the camera should be taken into account when assessing the performance of a display device.

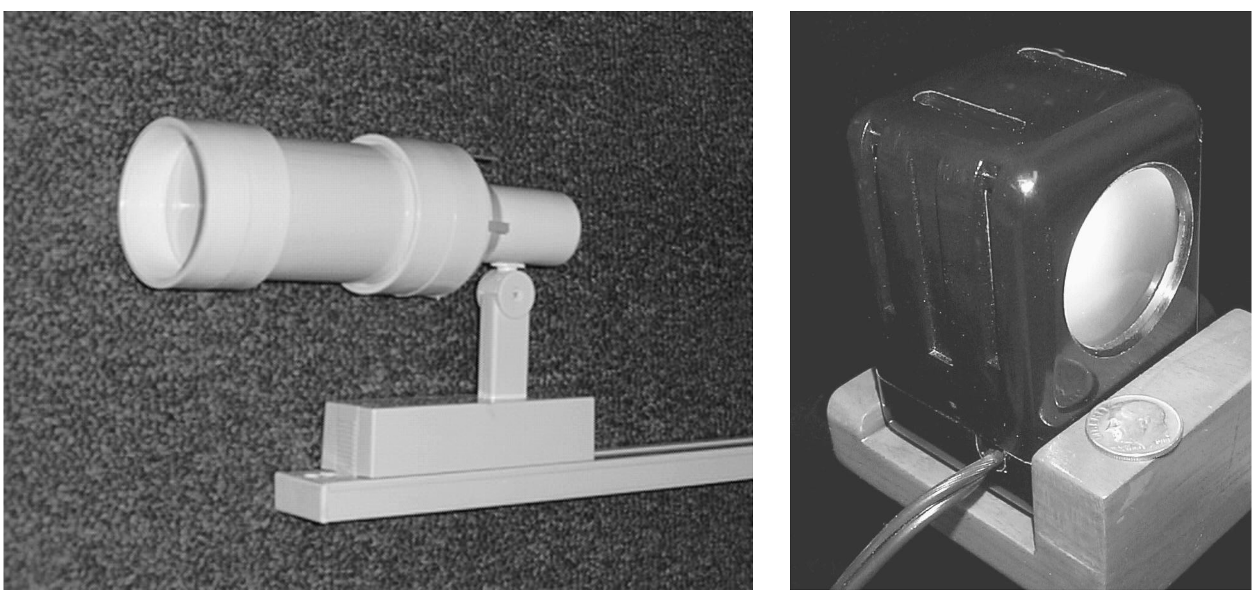
The use of a digital camera as described above requires a firm stand for the camera. In laboratory settings, a positioning device with fine adjustments for moving the camera in *x, y,* or *z* directions and changing its orientation will be preferable. However, such devices are often bulky and difficult to work with for in-field clinical evaluations. In those situations, a sturdy tripod, either floor type or tabletop, or a stand with a desk mount will work sufficiently well. If the stand is connected to the table, care should be exercised to prevent any mechanical instabilities or vibrations during the measurements.

3.1.2.2 Photographic-Grade Digital Camera

Scientific digital cameras of the type described above are expensive. Recent developments in the consumer market have resulted in high-quality photographic digital cameras with modest cost. Recent studies have demonstrated that nonscientific cameras can be used for quantitative assessment of display resolution in clinical settings (Samei and Flynn 2001, Roehrig et al. 1999) with certain precautions. Such cameras, however, should not be used for advanced measurements, for noise power spectra measurements, or for luminance measurements at low luminance levels. Otherwise, the camera must meet a number of minimum performance characteristics if to be used for display assessment. It needs to have a matrix size of at least 600 × 480, be equipped with a high-quality macro lens, have autofocusing capabilities, and be able to export image data in an uncompressed and nonproprietary format to a computer. The luminance, noise, and resolution response of the camera should be ascertained as described above. The camera should also be used in conjunction with a stable positioning device as described above.

3.1.3 Light Source and Blocking Devices

The quantitative assessment of specular reflection (see section 4.2.4) requires a small diameter source of diffuse white light. Suitable light sources include conventional halogen spot lamps with a glass diffuser placed on the exit surface or a small illuminator sold for use with student microscopes (Figure 18). The light source should ideally be brighter than 200 cd/m^2. Ideally, the light source should subtend 15° from the center of the display (Kelley 2002). Larger light sources will excessively illuminate the display surface and add diffusely reflected light to the specular reflection. For advanced evaluations (see section 4.2.5), optical band-pass filters are also required. Thin-film glass filters placed in front of a broadband illuminator can provide various



(a) **(b)**

Figure 18. A light source to measure specular reflection coefficients may be assembled from a halogen spot lamp with a diffuser added to the end (a). Another alternative is to utilize a small illuminator of the type used with microscopes (b).

colors with about 20 to 40 nm bandwidth. A set of filters with six or more colors is adequate to characterize the wavelength dependence of reflective devices.

The quantitative assessment of diffuse reflection (see section 4.2.4) requires an illuminator device. A typical device is illustrated in Figure 19a. The device consists of two compact fluorescent lights with a daylight spectrum of about 10 W each in standard lamp adapters. To eliminate variations in illuminance from the surface materials in the room, a small containment should surround the region in front of the display device including the light sources. A suitable containment can be assembled from flat white poster, or Styrofoam™ boards, or white cloth placed over a cubic frame (Flynn and Badano 1999). The lamps should ideally be baffled from directly illuminating the display surface or otherwise be placed behind the plane of the display illuminating the interior of a semi-hemispherical illumination containment (Figure 19b–c). The back wall of the containment facing the display's faceplate should have two small apertures for luminance measurements, as illustrated in Figure 19. The openings should be about 10° away from the normal to the display faceplate to avoid measuring the specular reflection of the luminance meter. One of the openings is covered with a light-absorptive patch, the luminance at the reflection of which is measured through the other opening. Advanced measurements of the diffuse reflection of the display in laboratory settings (see section 4.2.5) requires a more standardized illumination. The illumination method based on an integrating sphere advocated by NIST may be used (Kelley 2001). Each source is fabricated using an integrating sphere with a standardized design. The reader is referred to the NIST standard for details on the illuminator and illumination geometry.

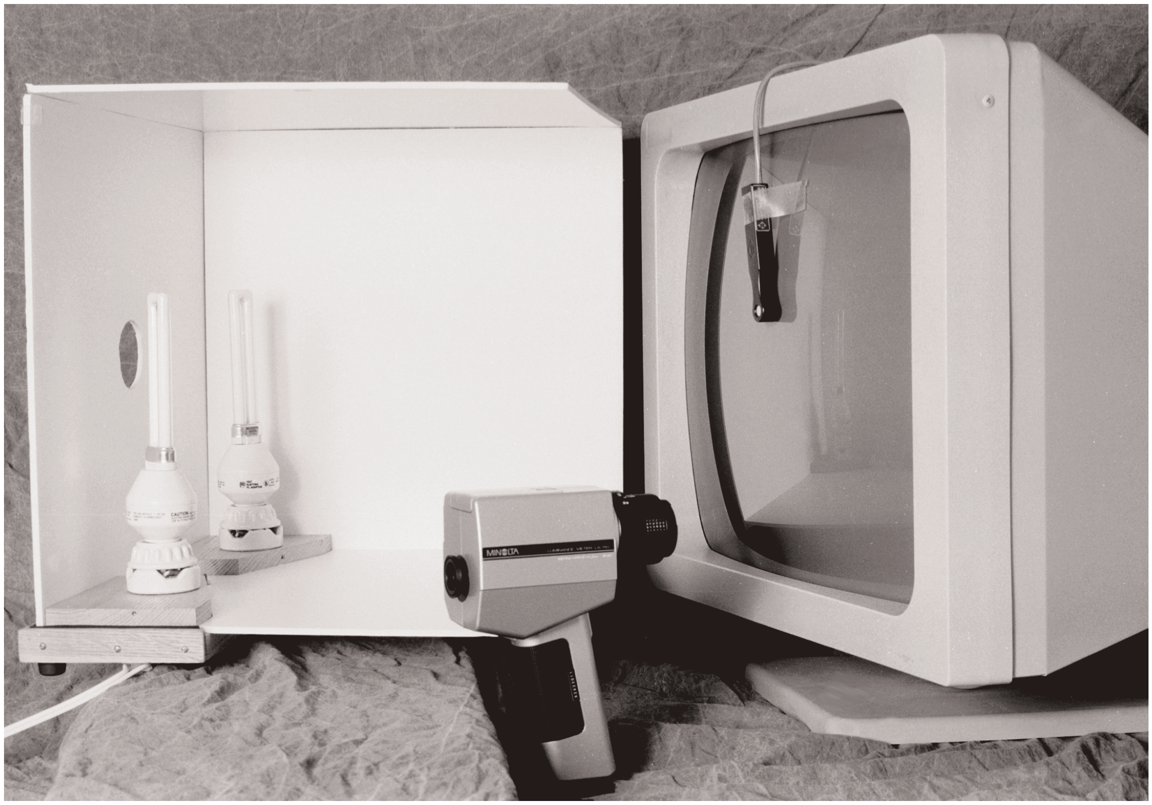
Light-blocking devices in the form of hoods or light-absorbing cloth are used during the evaluations of reflection and veiling-glare characteristics of the display, and when the display cannot be tested in controlled ambient light conditions. The light-absorbing material should be black, nontransparent, and made of nonreflective material. The funnel to be used for the veiling glare assessment should be made of materials with similar light-absorbing characteristics. It should have an opening of 5 mm in diameter at the base and an angular divergence of smaller than 60°. It should also be long enough to block any stray light from the display reaching the luminance meter. The desired length of the funnel, *1*, can be calculated as

$$l = \frac{1.2\,a}{\tan\theta + a\,/\,b} \tag{1}$$

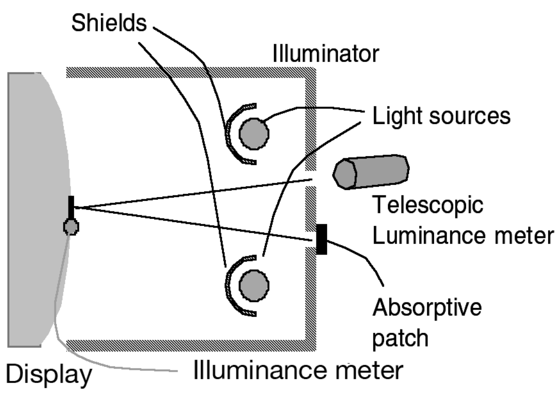
where a is the radius of the glare test pattern, θ is the angle of the funnel, and b is the focusing distance of the luminance meter. This funnel may also be used for the visual assessment of veiling glare (see section 4.7.3), for resolution and noise measurements using a CCD camera, and for luminance measurements with a telescopic luminance meter.

3.1.4 Miscellaneous Accessory Devices

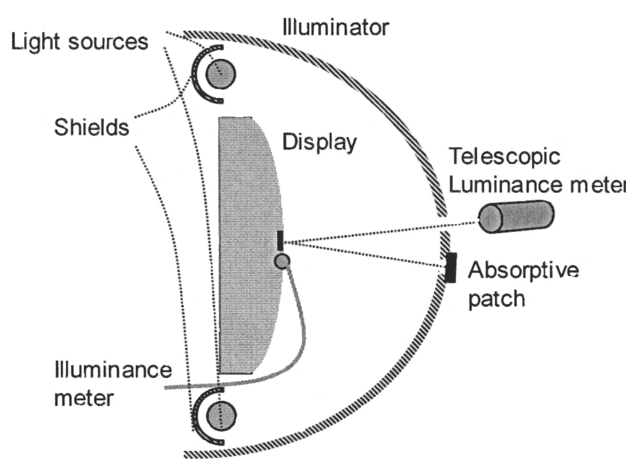
For a semiquantitative assessment of resolution, a measuring microscope or magnifier should be used. Several such devices are available in the market. The device should have a magnification of about 25 to 50×, be equipped with a metric reticle having divisions smaller than 0.05 mm, have focusing capabilities, and allow a working distance of at least 12.5 mm. Microscopes with smaller working distances cannot be used for large size CRTs because of their inability to focus through the thick glass faceplate of the display device.



(a)



(b)



(c)

Figure 19. A typical illuminating device used for quantitative measurements of the diffuse reflection of a display device (a). The lamps should ideally be baffled from directly illuminating the display surface (b) or otherwise be placed behind the plane of the display illuminating the interior of a semi-hemispherical illumination containment (c).

For angular response measurements, a *conoscopic* device or a *gonioscopic* probe may be utilized. A conoscopic device measures a cone of light coming from the display with special transform lenses (Fourier optics) and two-dimensional array detectors. This method provides a fast and complete description of the angular variations of the luminance and chromaticity levels. If such a device is used, its luminance response characteristics should comply with the luminance measure requirement noted above. In the gonioscopic approach, a focused luminance probe with a small acceptance angle is oriented toward the display to reproduce a given viewing direction. A low-flare telescopic luminance meter of the kind described in section 3.1.1.1 may be used for this method.

In testing display devices under low ambient light conditions, it is sometimes necessary to read a serial number or check an adjustment on the back of the device. A normal flashlight is useful in these situations. In addition, for routine quality control tests, it is important to assure that the display's faceplate is clean. Lint-free cloth or cleaning tissue, as well as manufacturer's approved glass-cleaning solution, should be available during the QC tests for this purpose. Other necessary tools include, two 1-m rulers and a device to measure angles for the assessment of the specular reflection, and a flexible tape measure for geometric distortion measurements.

3.2 Test Patterns

A number of test patterns are required to evaluate the performance of display devices. The patterns recommended in this report are listed in Table 2 and explained below. The full specific descriptions of the patterns can be found in appendix III.

While many of the tests described can be performed with different patterns than those recommended, the use of these specific patterns are encouraged in order to allow comparisons of measurements. All of the patterns recommended in this report are designated with a nomenclature of the form TG18-xyz, where *x, y,* and *z* describe the type and derived variants of a pattern. The patterns are provided along with the electronic version of this report. (Alternatively, the patterns may be generated with the aid of the information provided in this report in adherence with the rules and restriction outlined in appendix III). All patterns are provided in three formats: DICOM, 16-bit TIFF, and 8-bit TIFF. The DICOM and 16-bit TIFF patterns contain 12 bits of pixel values, while the 8-bit TIFF patterns only contain an 8-bit range of pixel values. The patterns may be generated by graphic software using the detailed specifications provided in appendix III. However, in testing a display device, it is preferred that the patterns be viewed using the display application that is used clinically. When displaying these patterns, no special processing functions should be applied. Furthermore, for most patterns, it is essential to have a one-on-one relationship between the image pixels and the display pixels. Images in DICOM and 16-bit TIFF formats should be displayed with a window width and level set to cover the range from 0 to 4095 (Window Width, WW = 4096, Window Level, WL = 2048), except for the TG18-PQC, TG18-LN, and TG18-AFC patterns, where a WW of 4080 and WL of 2040 should be used. For 8-bit patterns, the displayed range should be from 0 to 255 (WW = 256, WL = 128).

3.2.1 Multipurpose Test Patterns

Routine visual evaluations of performance are conveniently done using a single comprehensive test pattern. A new pattern designed by the AAPM Task Group 18 committee, referred to in this report as the TG18-QC pattern, is recommended for overall display quality assessment.

Table 2. Test patterns recommended for display quality evaluation. The patterns are divided into six sets. Most patterns are available in 1024 × 1024 size and in either DICOM or TIF format. Some patterns are available in 2048 × 2048 size.

Set	Series	Type	Images	Description
Multi Purpose (1k & 2k)	TG18-QC	Vis./Qnt.	1	Resolution, luminance, distortion, artifacts
	TG18-BR	Visual	1	Briggs pattern, low-contrast detail vs. luminance
	TG18-PQC	Vis./Qnt.	1	Resolution, luminance, contrast transfer for prints
Luminance (1k only)	TG18-CT	Visual	1	Luminance response
	TG18-LN	Quant.	18	DICOM grayscale calibration series
	TG18-UN	Visual	2	Luminance and color uniformity, and angular response
	TG18-UNL	Quant.	2	Same as above with defining lines
	TG18-AD	Visual	1	Contrast threshold at low luminance for evaluating display reflection
	TG18-MP	Visual	1	Luminance response (bit-depth resolution)
Resolution (1k and 2k)	TG18-RH	Quant.	3	5 horizontal lines at 3 luminance levels for LSF evaluation
	TG18-RV	Quant.	3	5 vertical lines at 3 luminance levels for LSF evaluation
	TG18-PX	Quant.	1	Array of single pixels for spot size
	TG18-CX	Visual	1	Array of Cx patterns and a scoring reference for resolution uniformity
	TG18-LPH	Visual	3	Horizontal bars at 1 pixel width, 1/16 modulation, 3 luminance levels
	TG18-LPV	Visual	3	Vertical bars at 1 pixel width, 1/16 modulation, 3 luminance levels
Noise (1k only)	TG18-AFC	Visual	1	4AFC contrast-detail pattern, 4 CD values
	TG18-NS	Quant.	3	Similar to RV/RH, 5 uniform regions for noise evaluation
Glare (1k only)	TG18-GV	Visual	2	Dark-spot pattern with low-contrast object
	TG18-GQ	Quant.	3	Dark-spot pattern for glare ratio measurement
	TG18-GA	Quant.	8	Variable size dark-spot patterns
Anatomical (2k only)	TG18-CH	Visual	1	Reference anatomical PA chest pattern
	TG18-KN	Visual	1	Reference anatomical knee pattern
	TG18-MM	Visual	2	Reference anatomical mammogram pattern

Additionally, TG18-PQC contains elements useful for the evaluation of printed film displays, and the TG18-BR, Briggs pattern, is useful for evaluating the display of low-contrast, fine-detail structures.

3.2.1.1 TG18-QC Pattern

The TG18-QC test pattern is shown in Figure 20. The pattern consists of multiple inserts embedded in a midpixel value background. The inserts include the following:

1. Grid lines (one pixel) with thicker lines (three pixels) along periphery and around central region, for the evaluation of geometric distortions.
2. Sixteen 102 × 102 (1k version) luminance patches with pixel values varying from 8 to 248 (in 8-bit version) [128 to 3968 in 12-bit version][4] for luminance response evaluation. Each patch contains four small 10 × 10 corner patches (1k version) at ±4 [±64] of pixel value difference from the background, +4 [+64] in upper left and lower right, –4 [–64] in lower left and upper right. The small patches are used for visual assessment of luminance response. Additionally, two patches with minimum and maximum pixel value are embedded containing 13 [205], and 242 [3890] pixel value internal patches, similar to 5% and 95% areas in the SMPTE test pattern.
3. Line-pair patterns at the center and four corners at Nyquist and half-Nyquist frequencies for resolution evaluation, having pixel values at 0–255 [0–4095] and 128–130 [2048–2088].
4. "Cx" patterns at the center and four corners with pixel values of 100, 75, 50, and 25% of maximum pixel values against a zero pixel value background, for resolution evaluation in reference to a set of 12 embedded scoring references with various amounts of Gaussian blurring applied, as tabulated in Table III.9 in appendix III.[5]
5. Contrast-detail "QUALITY CONTROL" letters with various contrasts at minimum, midpoint, and maximum pixel values for user-friendly low-contrast detectability at three luminance levels.
6. Two vertical bars with continuous pixel value variation for evaluating bit depth and contouring artifacts.
7. White and black bars for evaluating video signal artifacts, similar to those in the SMPTE pattern.
8. A horizontal area at the top center of the pattern for visual characterization of cross talk in flat-panel displays.
9. A border around the outside of the pattern, similar to SMPTE's.

[4]Unless specified otherwise, the square brackets "[ ]" used in this section refer to the pixel values in the 12-bit version of the test patterns.

[5]The development of the reference set is based on research conducted at Eastman Kodak Company reported in a recent publication (Kohm et al. 2001).

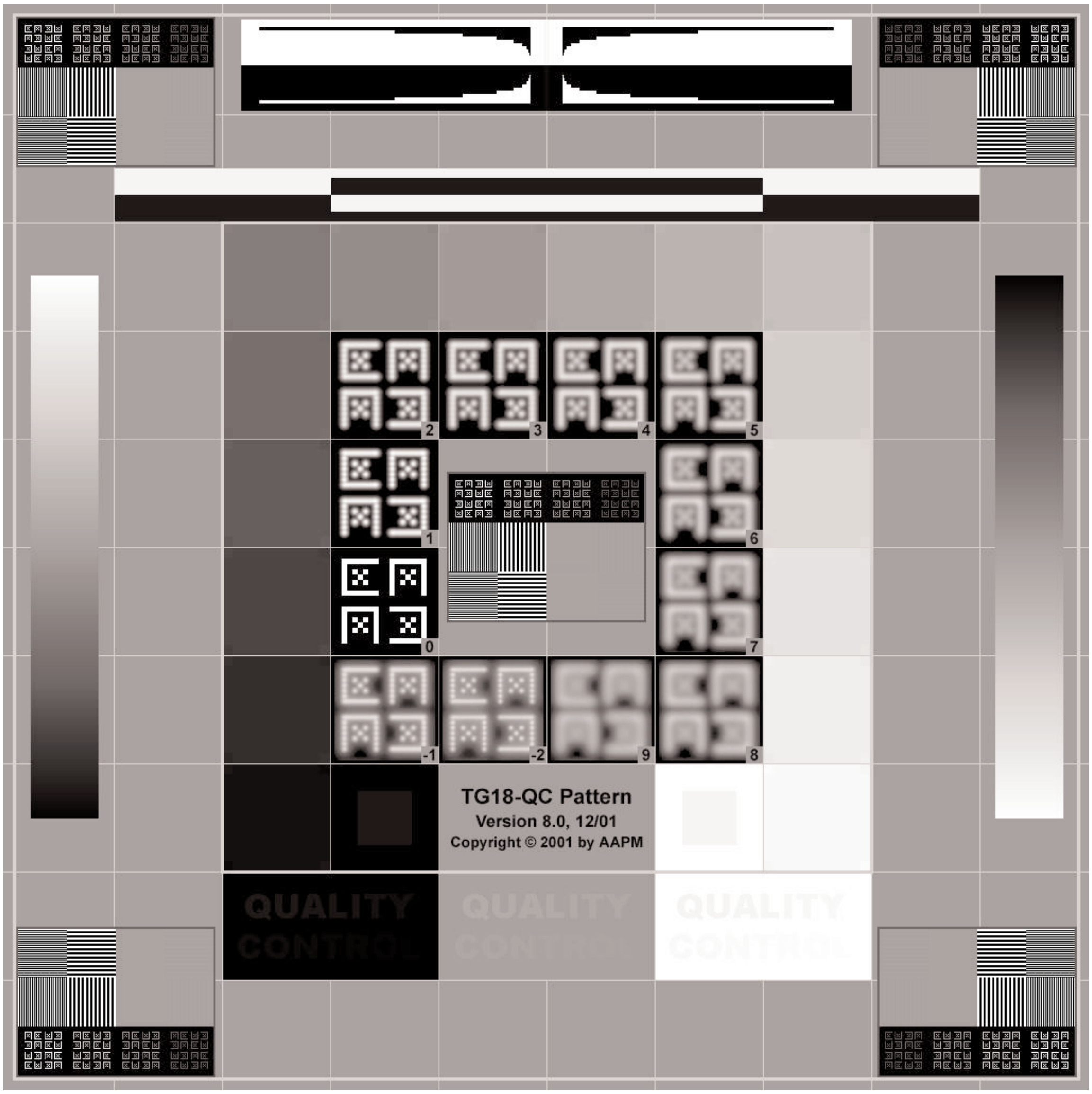


Figure 20. The TG18-QC comprehensive test pattern.

3.2.1.2 TG18-PQC Pattern

The TG18-PQC test pattern (Figure 21) contains bars of varying DDL with regions having various low-contrast horizontal and vertical patterns. The pattern was developed primarily for evaluating the characteristics of a film printer so that printed films can be adjusted to match the luminance response of electronic display devices. Marked regions are provided from which film density measurements can be made. At each density step, low-contrast patterns of varying contrast and frequency are included. Fine-detail test pattern regions are also included to evaluate the resolution of a printer. Continuous ramps are provided at the right and left sides of the pattern to evaluate the film density continuity (see appendix III for a detailed description).

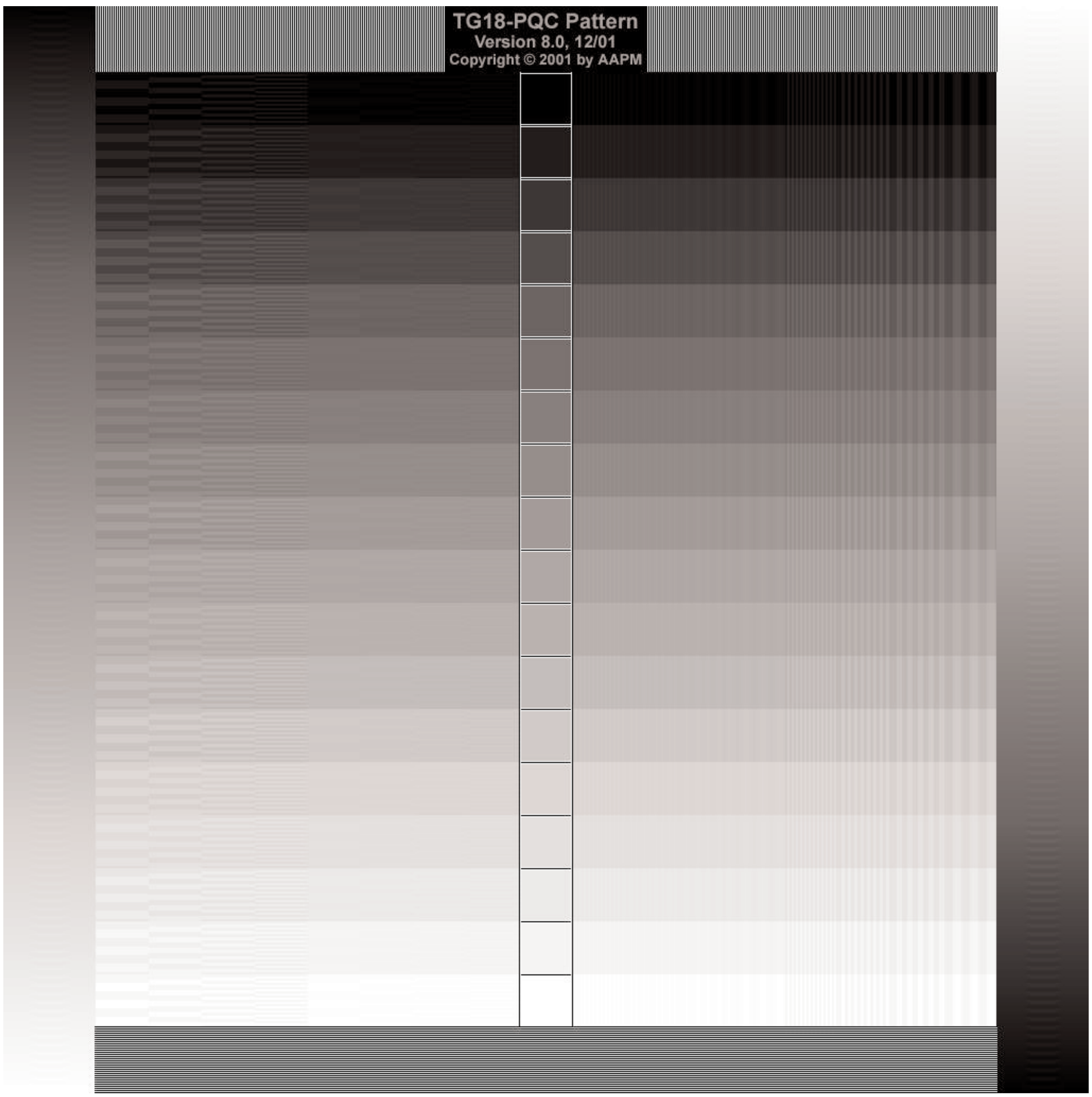
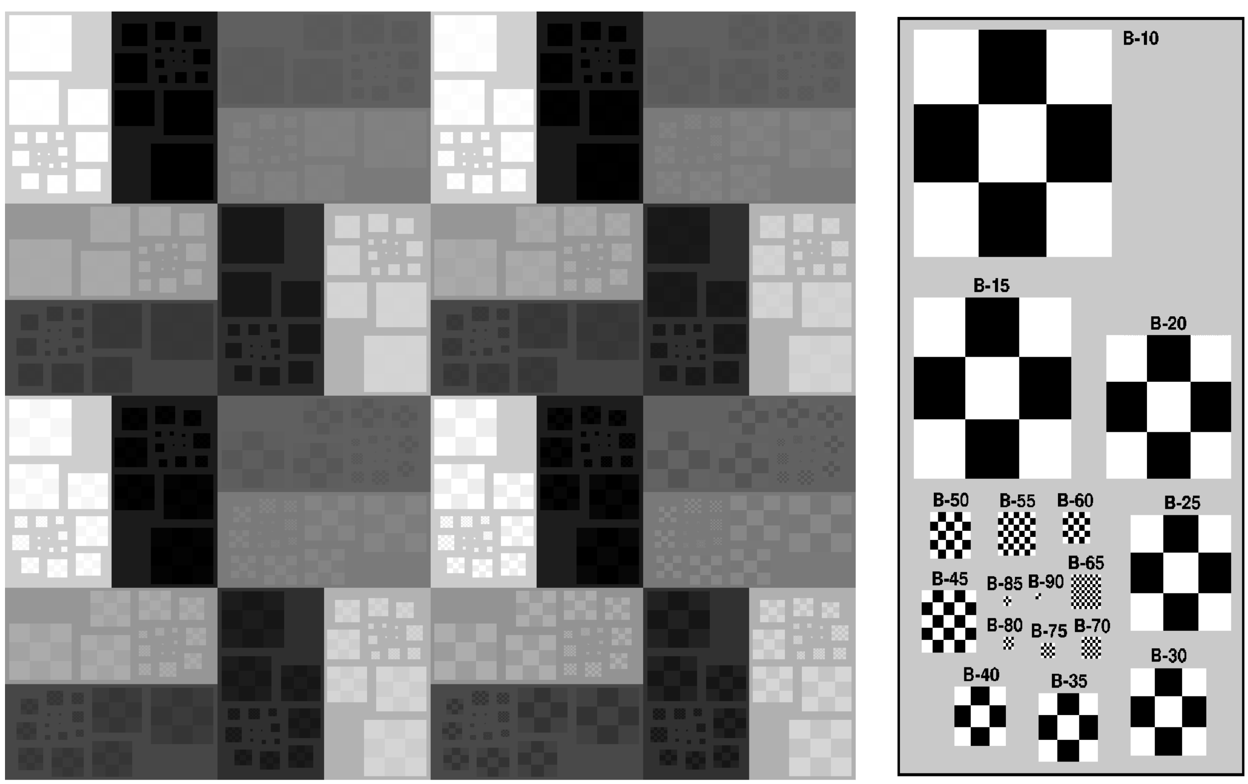


Figure 21. The TG18-PQC developed for the evaluation of printed films.

3.2.1.3 TG18-BR Pattern

Briggs patterns are widely used for visually inspecting whether the contrast and resolution of a display system is properly adjusted (Briggs 1979, 1987). This pattern was originally developed by Stewart Briggs for satellite imaging but has since been adapted for other display systems. Currently, several varieties of the Briggs patterns are in common use. The Briggs test pattern 4 is useful for the visual inspection of medical imaging displays (Figure 22). In this report, this pattern is referred to as the TG18-BR pattern to avoid possible confusions with other Briggs patterns.

The 1k version of the pattern consists of four quadrants, each containing eight panels. The panels are evenly spaced to cover a pixel value range from 0 to maximum, providing a full range of background luminance for the target's checkerboards. Within each quadrant, the panels are also paired so that adjacent panels have background brightness values on either side of the mean brightness of the pattern. Each panel contains 16 checkerboards ranging from a 3×3 checker pattern with 25 pixels per each checker square edge (B-10), down to a 2×2 checker with 1 pixel per checker square edge (B-90). The contrasts of the checkerboards in terms of pixel value difference in the four quadrants are 1 [16], 3 [348], 7 [112], and 15 [240], corresponding to the four least significant bits.



(a) **(b)**

Figure 22. The TG18-BR pattern for the evaluation of the display of low-contrast, fine-detail image structures (a); the designation of the checkerboards in each of the 32 panels (b).

3.2.2 Luminance Test Patterns

3.2.2.1 TG18-CT Pattern

For visual assessments of the contrast transfer characteristics associated with the luminance response of a device, a low-contrast pattern can be used (Figure 23). The pattern includes 16 adjacent regions varying in luminance from 8 [128] to 248 [3968], embedded in a uniform background. Each region differs in pixel value by the same amount. Each patch contains four small 10 × 10 corner patches (1k version) at ±4 [±64] pixel value difference from the background, identical to those in the TG18-QC test pattern. In addition, at the center of each patch is a half-moon target with the two sides of the target at ±2 [±32] pixel value difference from the background.

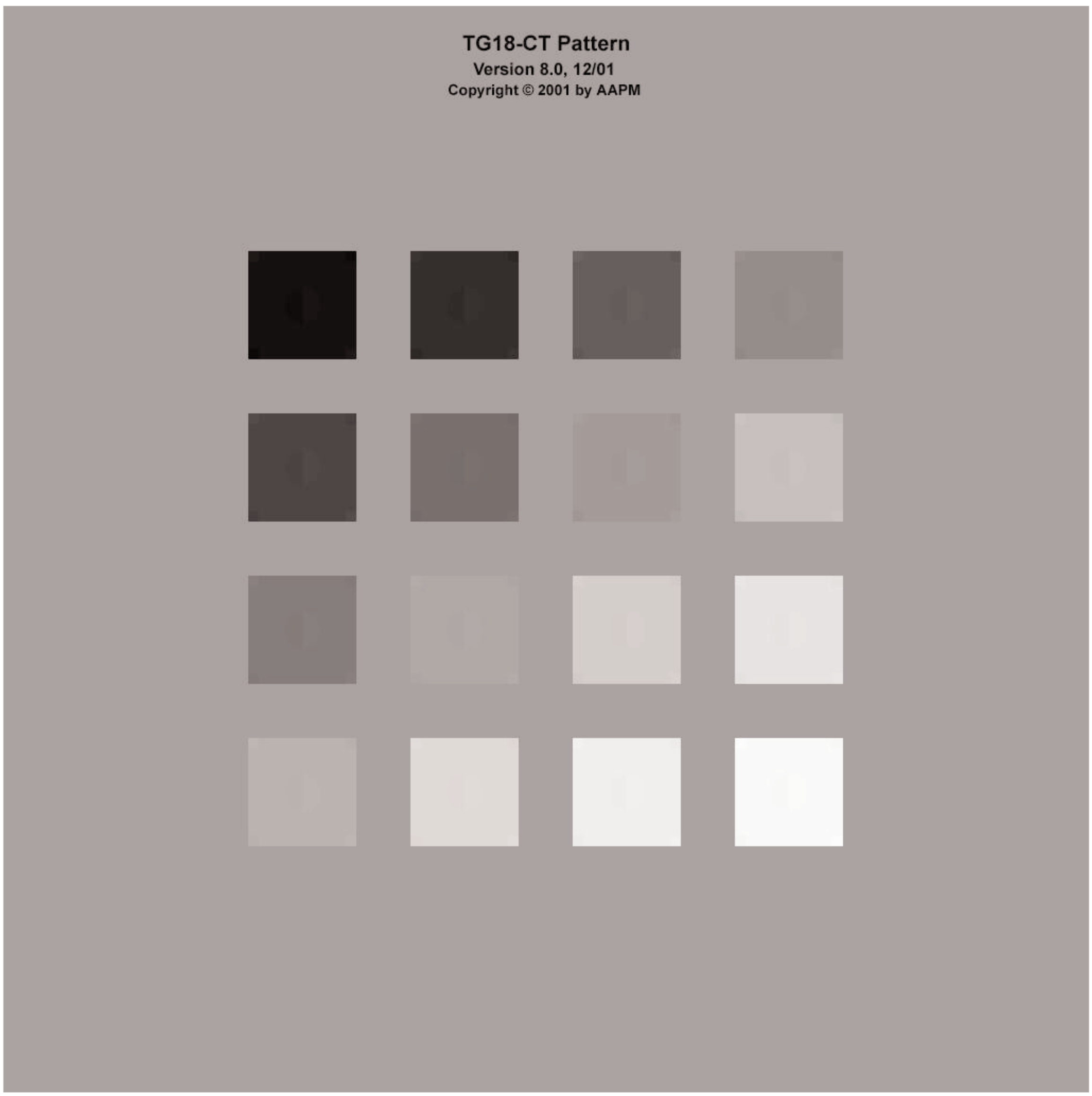
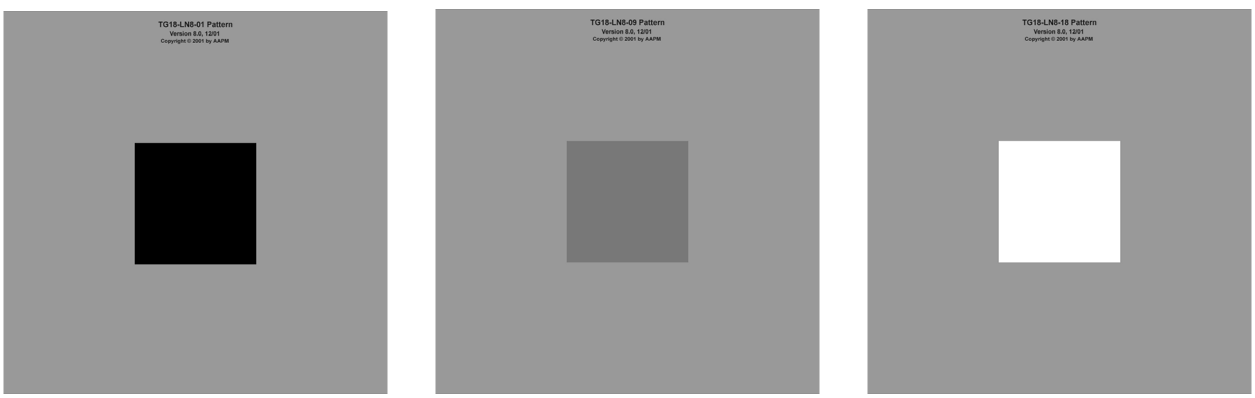


Figure 23. TG18-CT low-contrast test pattern for the evaluation of the luminance response of display systems.

3.2.2.2 TG18-LN Patterns

Two sets of 18 luminance patterns are provided to assess the luminance response of a display system. The patterns are designated as TG18-LNx-y, where x is the bit-depth range of the displayed values in the sets, and y is the image number in the set. The geometry of these patterns conforms to that recommended in DICOM 3.14. Each pattern consists of a central test region with certain pixel value, occupying about 10% of the full image area. The rest of the pattern has a uniform background with a luminance equal to 20% of the maximum luminance. To achieve this luminance level, assuming that the display device is properly calibrated to the DICOM display function (see section 4.3.1), the background pixel value is 153 [2448].

Within a set of patterns the pixel values in the central regions are equally spaced. For example, there are eighteen 8-bit patterns (TG18-LN8-01 through TG18-LN8-18), with central pixel values of 0, 15, 30, . . . , and 255. Likewise, there are eighteen 12-bit patterns (TG18-LN12-01 through TG18-LN12-18), with central pixel values of 0, 240, 480, . . . , 4080. Separate test pattern sets corresponding to these two examples are provided with this report (Figure 24). These test patterns may be magnified to fit the full display area.

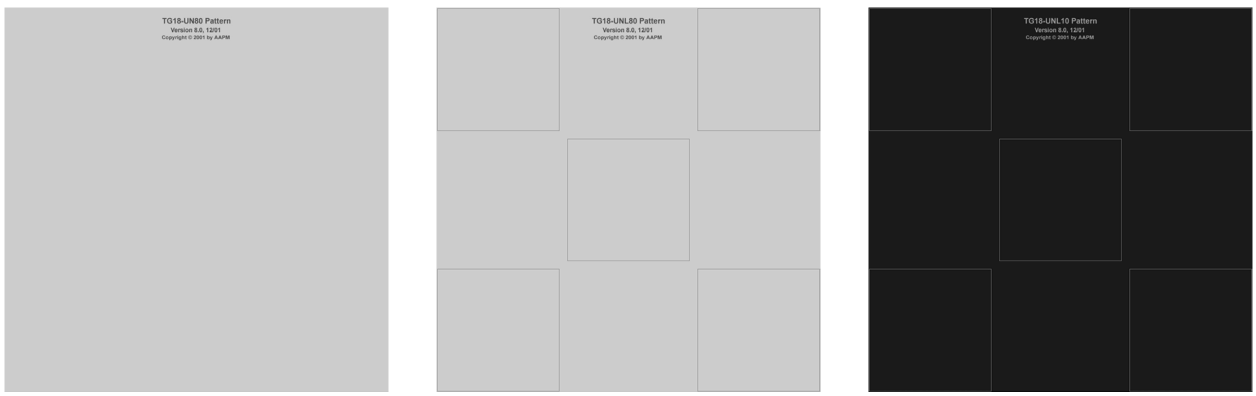


(a) **(b)** **(c)**

Figure 24. Examples of TG18-LN luminance patterns for luminance measurements. The patterns cover equal increments of pixel value to cover the entire range of pixel values. Shown here are TG18-LN8-01 (a), TG18-LN8-09 (b), and TG18-LN8-18 (c).

3.2.2.3 TG18-UN Pattern

For the assessment of luminance uniformity, color uniformity, and angular response, uniform test patterns are used. Two patterns are specified at 10% (26 [410] pixel value) and at 80% (204 [3278] pixel value) of maximum pixel value (TG18-UN10 and TG18-UN80). Two other corresponding patterns are also defined that are identical to the UN patterns except for the presence of low-contrast lines at identifying the central and four 10% corner measurement areas of the pattern (TG18-UNL10 and TG18-UNL80). Figure 25 shows the schematic of three UN patterns.



(a) **(b)** **(c)**

Figure 25. The TG18-UN80 (a), TG18-UNL80 (b), and TG18-UNL10 (c) patterns for luminance uniformity, color uniformity, and angular response evaluations.

3.2.2.4 TG18-AD Pattern

TG18-AD is a low-luminance, low-contrast test pattern developed to visually evaluate the diffuse reflection of a display device (Figure 26). The pattern consists of 49 horizontal line-pair pattern inserts at half-Nyquist frequency, with the black lines at zero pixel value and the bright lines with incrementally increasing contrast levels. The inserts are identified with rows and column numbers. The value of the bright line of each pattern in terms of pixel value is equal to b(C + 7R), where C is the column number, R is the row number, and b is a multiplying factor equal to 1 for the 8-bit version and 4 for the 12-bit version of the pattern. The background pixel value is zero.

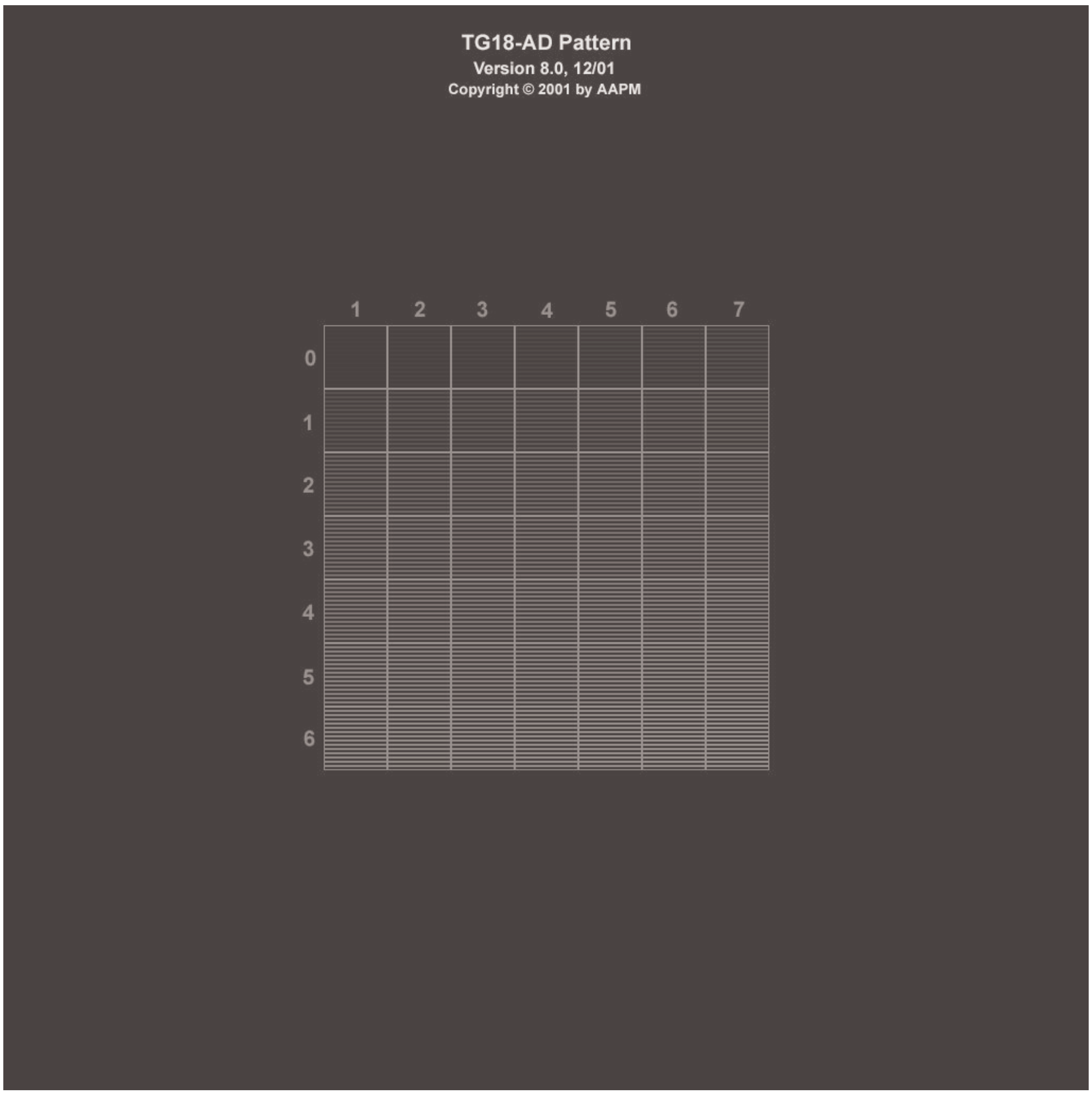


Figure 26. The TG18-AD test pattern for visual evaluation of display's diffuse reflection response to ambient light. The pattern has been brightened and contrast enhanced to illustrate its features.

3.2.2.5 TG18-MP Pattern

TG18-MP is designed for visual assessment of display bit depth (Figure 27). This pattern exists only in the 12-bit version. With a background of 256, the pattern contains 16 ramps, each covering 1/16 of a 12-bit pixel value range from 0 to 4095. Small markers indicate the 8-bit and 10-bit pixel value transitions. For the details of this pattern, see appendix III.

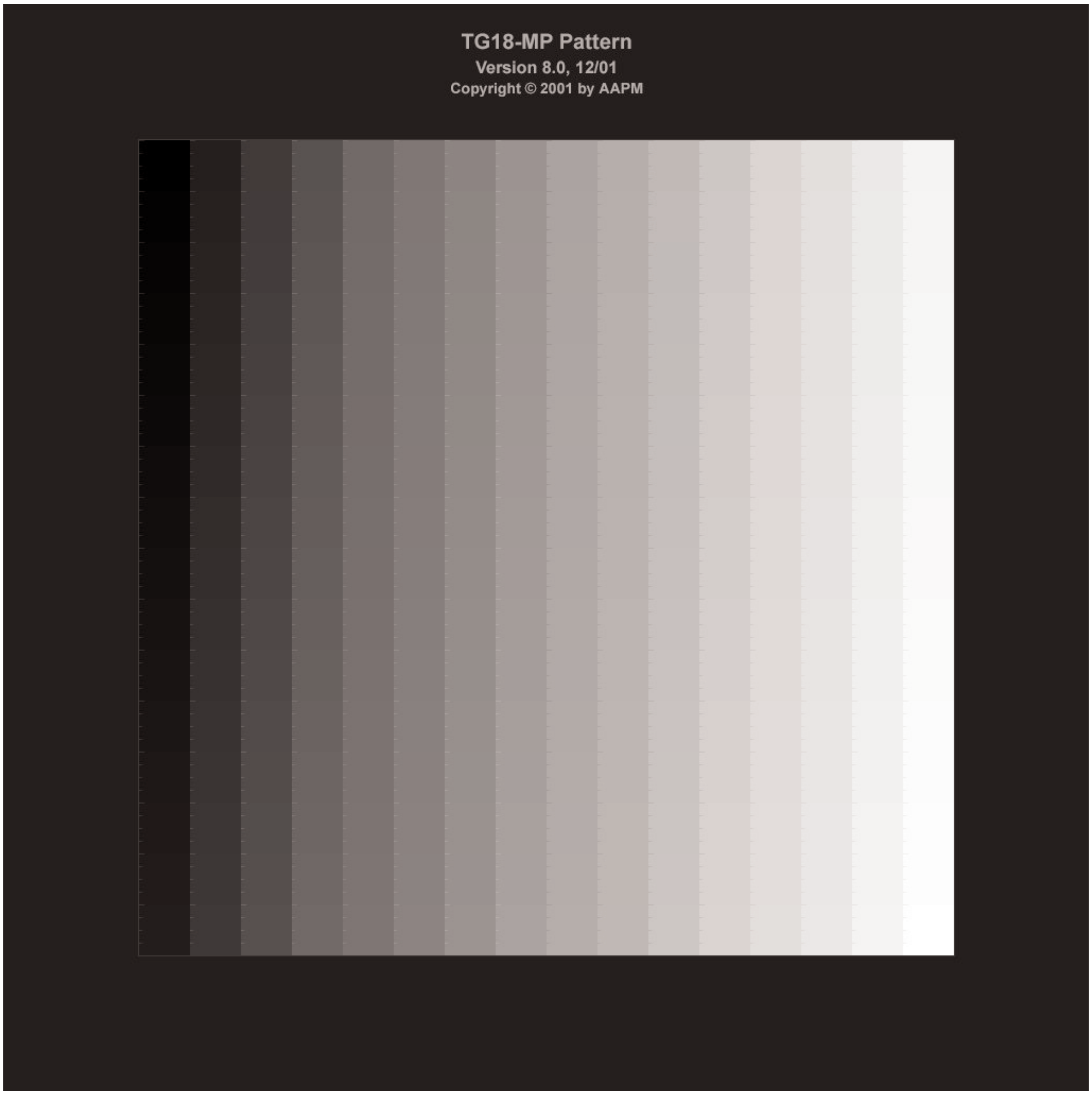
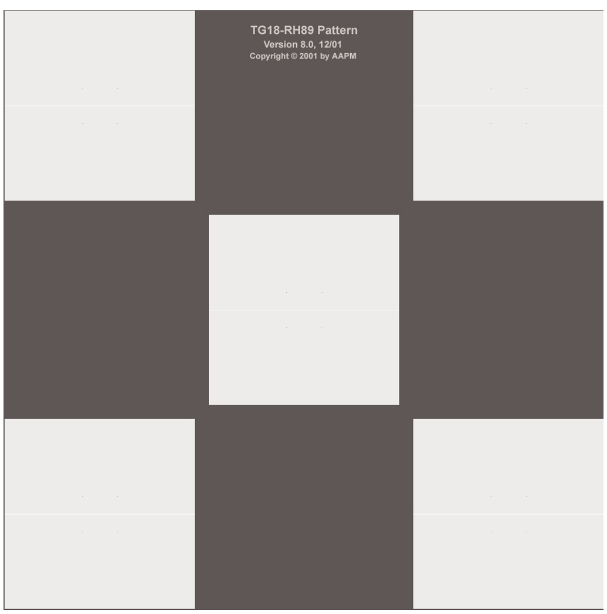


Figure 27. The TG18-MP test pattern for visual evaluation of display bit-depth resolution.

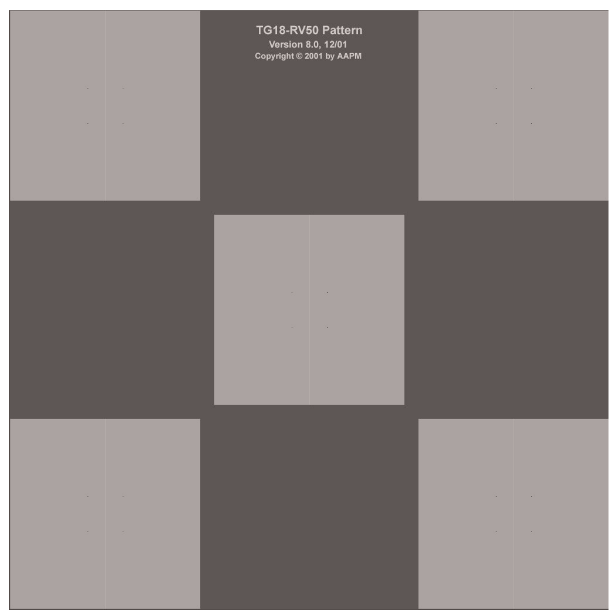
3.2.3 Resolution Test Patterns

3.2.3.1 TG18-RH and TG18-RV Patterns

For the quantitative assessment of display resolution, two sets of test patterns, each containing three patterns, are recommended. The backgrounds for all patterns are at 51 [819] pixel value with five squares overlaid at one central and four corner measurement locations, each occupying 10% of the full image area, in which the pixel value is set at 10% (26 [410] pixel values), 50% (128 [2048] pixel values), and 89% (228 [3656] pixel values) of the maximum value in all five areas. The TG18-RH10, TG18-RH50, and TG18-RH89 test patterns exhibit a central single pixel-wide *horizontal* line with 12% positive pixel value difference at each measurement location. The TG18-RV10, TG18-RV50, and TG18-RV89 patterns exhibit a central single pixel-wide *vertical* line with 12% positive pixel value difference at each measurement location. Thus the patterns enable the assessment of the display line spread function and MTF in the horizontal and vertical directions at a small modulation at three luminance levels and five locations across the faceplate of the display. In addition, single pixel markers are inserted in each measurement location to allow spatial calibration of the digital camera. The markers in each location are the corners of a 60×60 central square area (120×120 for the 2k version) with values equal to 50%, 10%, and 50% of the maximum pixel value, for R10, R50, and R89 patterns, respectively. Two examples of these patterns are shown in Figure 28.



(a)



(b)

Figure 28. The TG18-RH89 (a) and TG18-RV50 (b) patterns for the assessment of display resolution. The TG18-NS test patterns are identical to the RH and RV patterns except for the presence of the lines in the five measurement areas.

3.2.3.2 TG18-PX and TG18-CX Patterns

A quantitative assessment of display resolution may be undertaken by characterizing the luminance profile of single pixels across the faceplate of the display. For this purpose, a pattern can be used with a 0 pixel value background and single non-zero pixels at 100%, 75%, 50%, and 25% of the maximum pixel value (255, 191, 128, and 64 [4095, 3071, 2048, and 1024] pixel values, respectively) (TG18-PX, Figure 29).

A quantitative assessment of display resolution and, particularly, resolution uniformity may also be undertaken by visually assessing the appearance of Cx targets similar to those used in the TG18-QC pattern. The TG18-CX pattern consists of an array of Cx targets at 100%, 75%, 50%, and 25% of the maximum pixel value (255, 191, 128, and 64 [4095, 3071, 2048, and 1024] pixel values, respectively) against a 0 pixel value background, covering the entire display area (Figure 30). In addition, the pattern has embedded a scoring reference similar to that in the TG18-QC pattern for evaluating the targets (see section 3.2.1.1 and Table III.9 in appendix III).

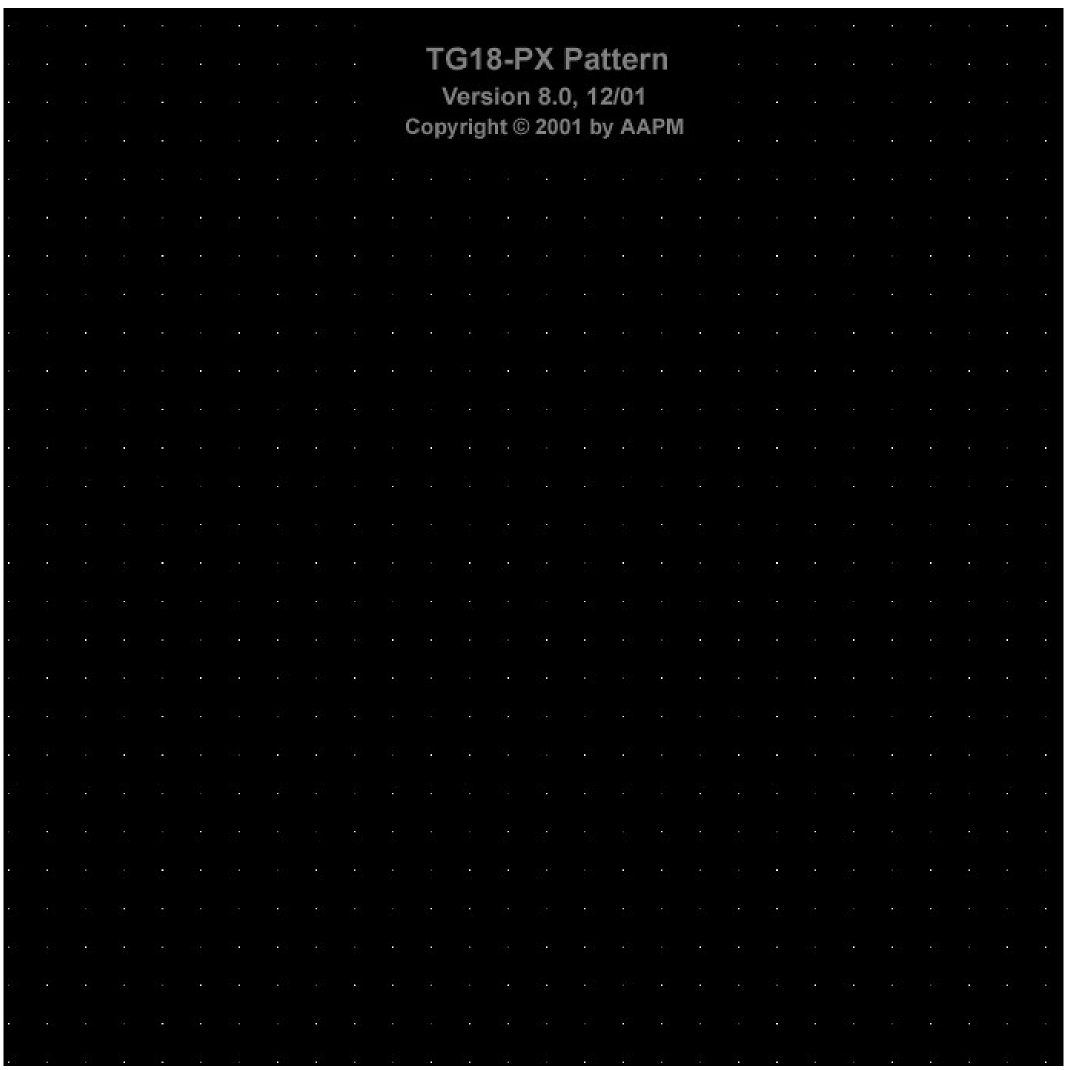


Figure 29. The TG18-PX test pattern for the assessment of display resolution.

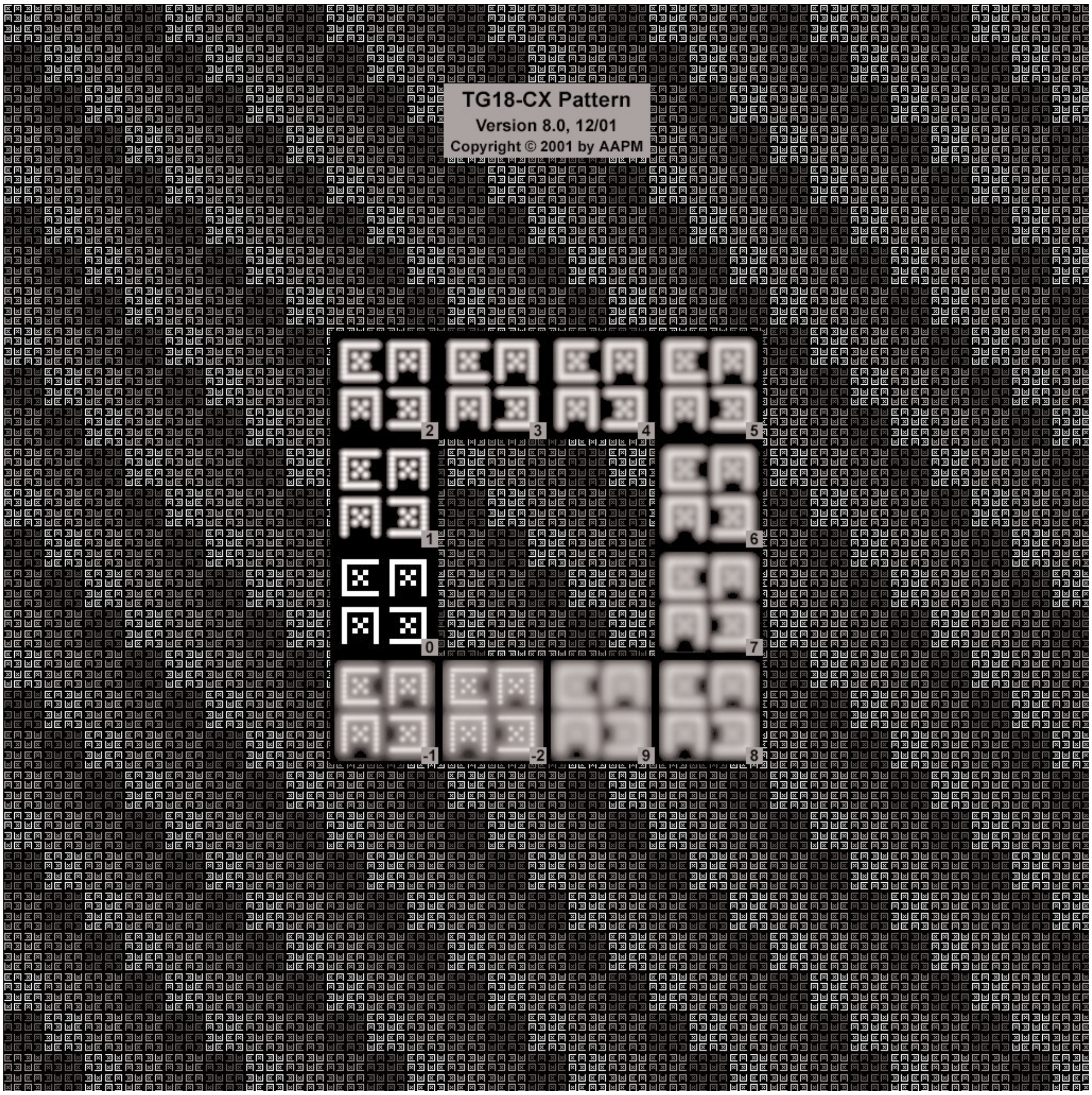


Figure 30. The TG18-CX test pattern for the assessment of display resolution and resolution uniformity.

3.2.3.3 TG18-LP Patterns

A visual assessment of display resolution may also be undertaken by characterizing the luminance profile of line-pair patterns consisting of alternating single-pixel-wide lines across the faceplate of the display. The lines have a 12% positive contrast against three background levels, 10%, 50%, and 89% of the maximum pixel value (26, 128, and 228 [410, 2048, and 3656] pixel values, respectively) across the patterns. The lines are horizontal in the TG18-LPH10, TG18-LPH50, and TG18-LPH89 test patterns and vertical in the TG18-LPV10, TG18-LPV50, and TG18-LPV89 test patterns (Figure 31).

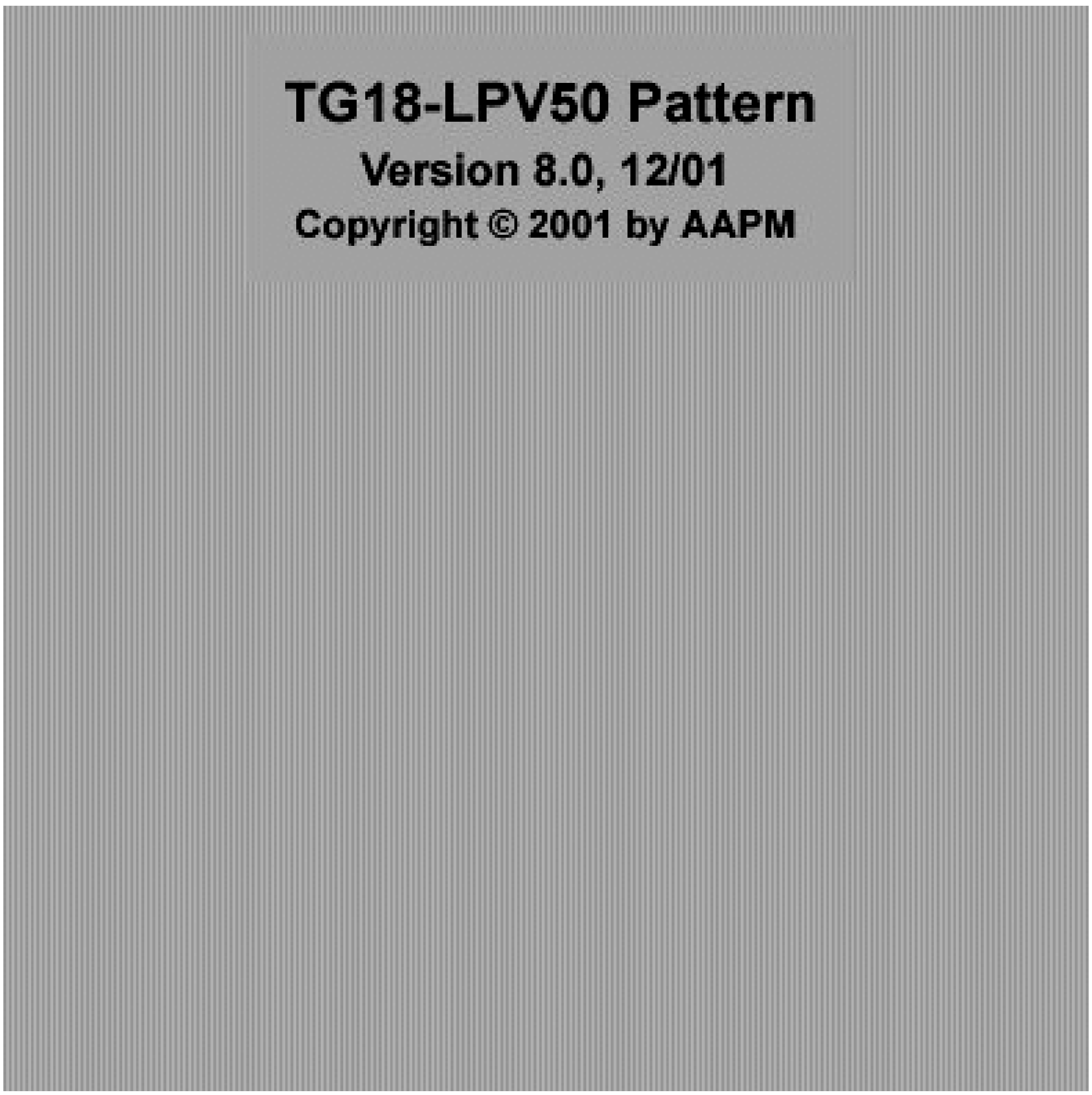


Figure 31. The TG18-LPV50 test pattern (magnified and contrast-enhanced) as an example of TG18-LP patterns.

3.2.4 Noise Test Patterns

3.2.4.1 TG18-AFC Pattern

A test pattern consisting of a series of small boxes containing a small, low-contrast feature in one quadrant of each box provides a useful test of the signal-to-noise characteristics of a system. A test pattern of this type has previously been employed for display evaluation (Hangiandreou et al. 1999). While the sensitivity of this test pattern to changes in electronic display performance variables was found to be limited, it is a useful pattern to evaluate the fixed pattern noise associated with mixed phosphors in CRT systems. The TG18-AFC is divided into four quadrants containing multiple square target areas. Each target area contains a square target near one of the corners. For a 12-bit, 1024 × 1024 pattern, the quadrants have targets with contrast values of +32, 48, 64, and 96 DDLs and corresponding target sizes of 2, 3, 4, and 6 pixels (Figure 32). The contrast and size are scaled accordingly for 2048 × 2048 and 8-bit versions of the pattern. Five larger areas with varying target sizes and contrasts are also included.

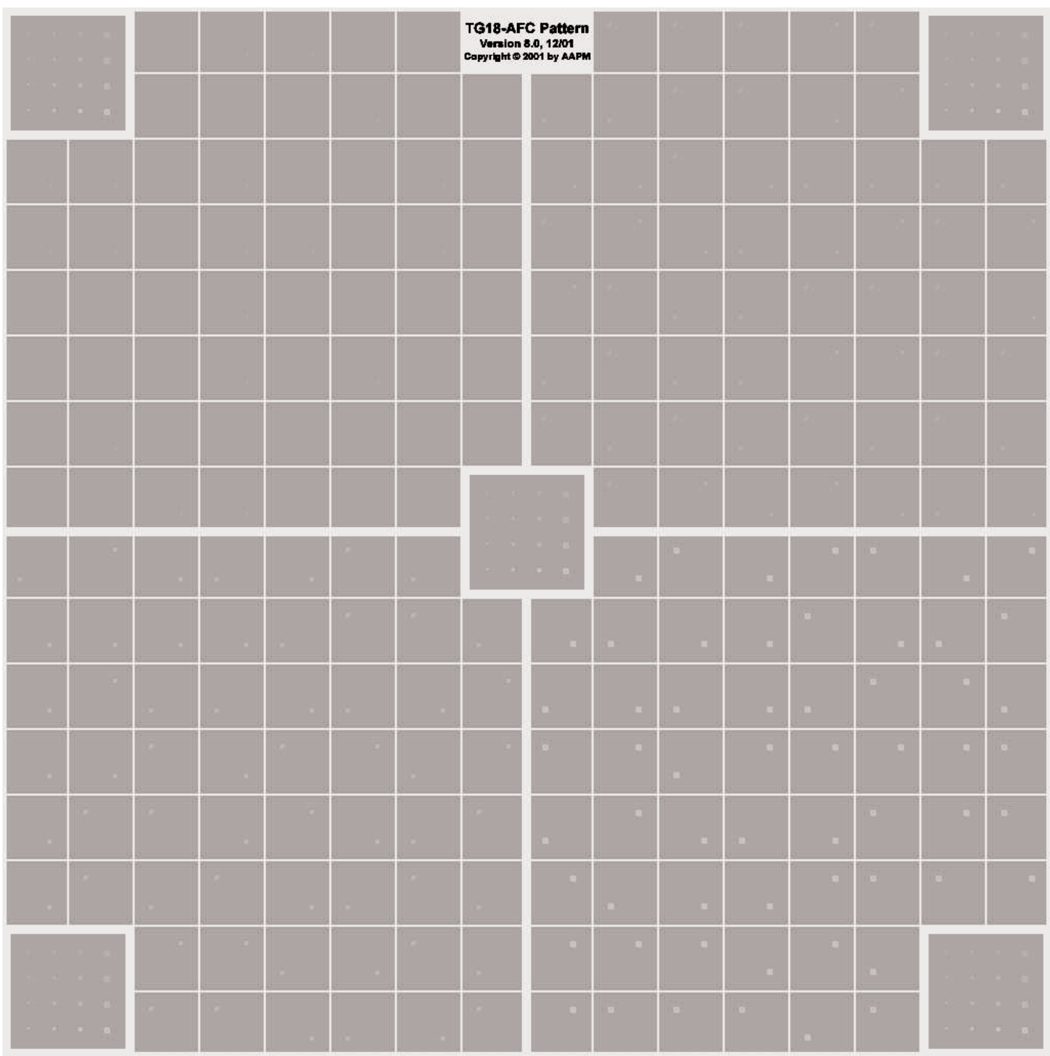


Figure 32. The TG18-AFC test pattern for the visual assessment of display noise. The pattern is contrast-enhanced to illustrate its features.

3.2.4.2 TG18-NS Pattern

For the quantitative assessment of display noise, three patterns are utilized: TG18-NS10, TG18-NS50, and TG18-NS89. The patterns are identical to the RH and RV patterns described above, with the only difference being the absence of the single line at the center of the measurement areas (Figure 28) (see section 3.2.3.1).

3.2.5 Glare Test Patterns

3.2.5.1 TG18-GV and TG18-GVN Patterns

For the visual assessment of display veiling glare, a combination of two test patterns is used. The TG18-GV pattern consists of a black background (zero pixel value) and a central white (maximum pixel value) region of 300 pixel radius. At the center of the white region is a dark, 15-pixel-radius circle with a zero pixel value background and five low-contrast circles, each 4.5 pixel in radius. The low-contrast objects have pixel values equal to 2, 4, 6, 8, and 10 [32, 64, 96, 128, and 160] (Figure 33). The test pattern TG18-GVN is identical to TG18-GV except that the large-diameter white circle is replaced with a black circle, creating a completely black pattern except for the presence of low-contrast targets. To use these test patterns, a mask device must be used to block the bright portion of the image from view so as not to alter the visual adaptation of the observer. In the use of these patterns, the pattern should not fill the display area, rather the display size must be adjusted so that the diameter of the 300-pixel white region is 20 cm.

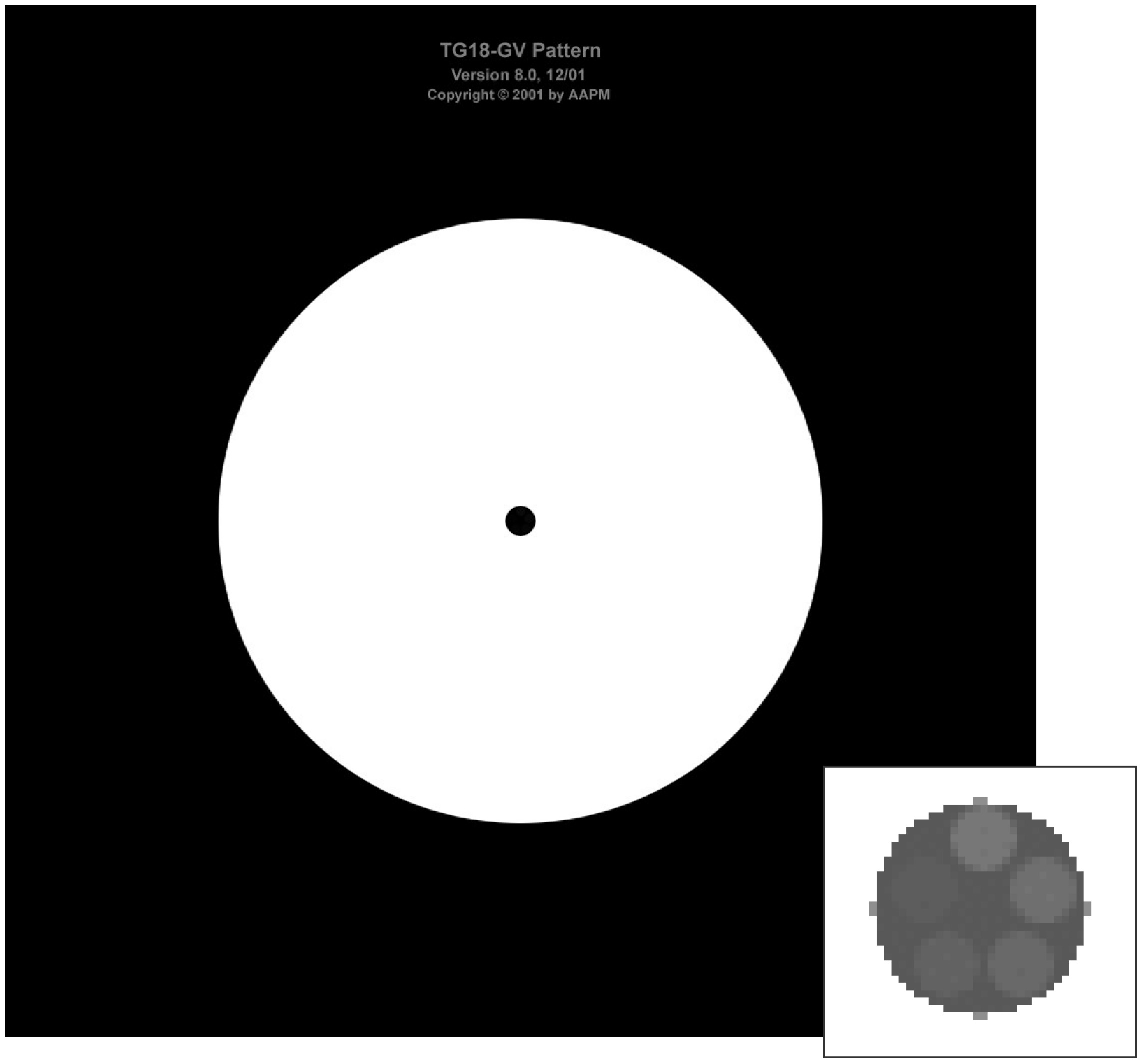


Figure 33. TG18-GV test pattern with a 15-pixel-radius central black region containing five low-contrast objects. To make the target visible in this illustration, the central target area is magnified and contrast enhanced in the lower-right corner of the figure.

3.2.5.2 TG18-GQ and TG18-GA Patterns

These patterns are used for quantitative assessment of veiling glare. The TG18-GQ pattern is identical to TG18-GV except that it lacks the central low-contrast objects. Two variants of this pattern are TG18-GQN and TG18-GQB. In the former, the white circle is eliminated, creating a completely black pattern. In the latter, the central black circle is eliminated. Similarly, the TG18-GAr are a set of eight test patterns that are identical to TG18-GQ except that the radius of the central black circle is varied as r = 3, 5, 8, 10, 15, 20, 25, and 30 pixels, thus TG18-GA03 to TG18-GA30 (Figure 34). Note that TG18-GA15 is identical to TG18-GQ. The patterns should be displayed such that the white region has a diameter of 20 cm.

(a)

(b)

Figure 34. The TG18-GA30 (a) and TG18-GQB (b) test patterns.

3.2.6 Anatomical Test Images

In addition to geometric test patterns described above, a number of reference anatomical images are recommended for overall evaluation of display quality. Four specific images are recommended corresponding to a PA chest radiograph (TG18-CH), a knee radiograph (TG18-KN), and two digital mammograms (TG18-MM1 and TG18-MM2).

3.2.6.1 TG18-CH Image

TG18-CH is a postero-anterior (PA) chest radiograph acquired with a computed radiography system (CR-400, Eastman Kodak Company) at an exposure index of 1740 (the original image is the courtesy of Eastman Kodak Company) (Figure 35). The image has been processed for grayscale rendition and equalization according to an optimum processing scheme for chest radiographs (Flynn et al. 2001). The following are the comments of an experienced chest radiologist on the image: "There is moderate hyperinflation. Projected just above the left diaphragmatic leaf there is a 4 mm opacity that appears to be partially calcified. This could be a part of costal cartilage or more likely a pulmonary nodule. There are small apical caps on each side. There is a fine curved linear fissure in the left mid chest. Pulmonary vessels, heart and aorta are unremarkable. There is minor degenerative change in the spine and minimal scoliosis convex to the right."

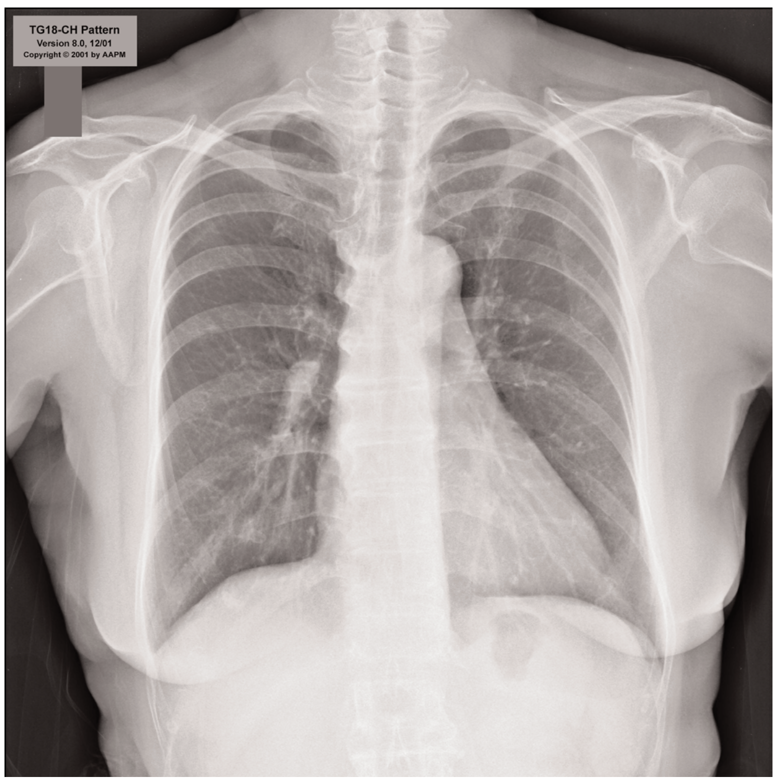


Figure 35. The TG18-CH anatomical image.

3.2.6.2 TG18-KN Image

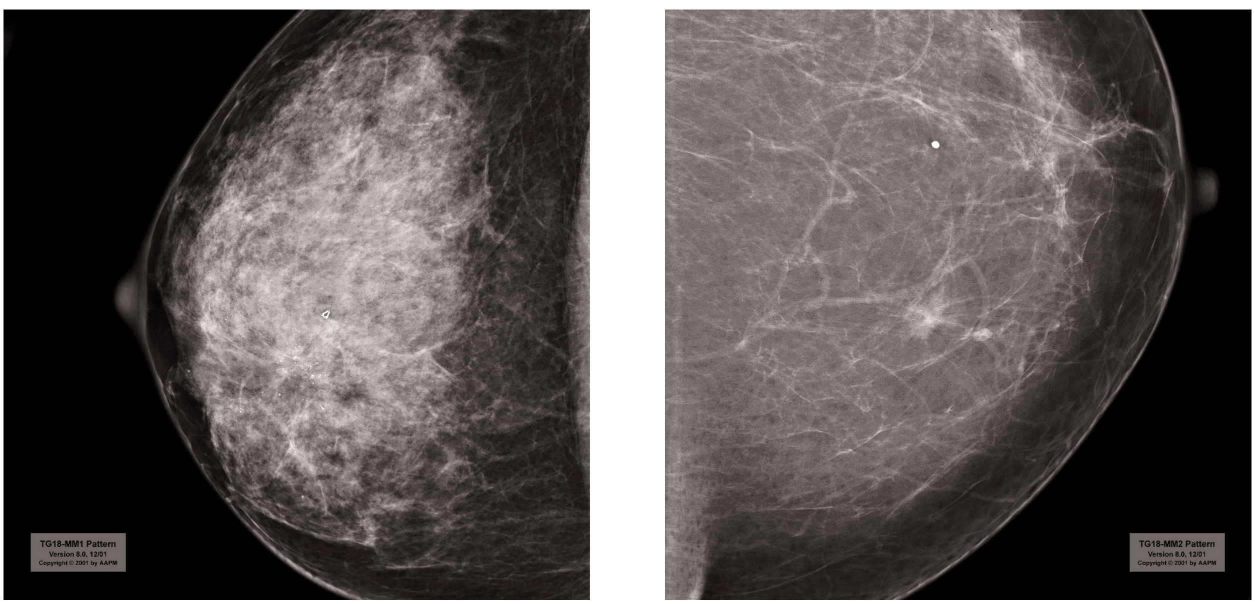
TG18-KN (Figure 36) is a lateral knee radiograph acquired with a selenium-based direct digital radiography system (DR-1000, Direct Ray Corp., the original image is the courtesy of K. Kohm, Eastman Kodak Company). The image has been processed according to the manufacturer's default processing for knee radiographs. The fine trabecular patterns in the femur, proximal tibia, and the cortical shell of the patella require good display resolution for proper visualization.

Figure 36. The TG18-KN anatomical image.

3.2.6.3 TG18-MM1 and TG18-MM2 Images

For the purpose of TG18, two digital mammograms were selected to represent the wide variation in the mammographic presentations. TG18-MM1 and TG18-MM2 (Figure 37) are 2k regions selected from two cranial caudal (CC) view digital mammograms acquired with a full-field digital mammography system (Selenia, Lorad, the original images are the courtesy of the Lorad Division of Hologic, Inc.). The images were processed according to the manufacturer's default processing for such exams. The following are the comments of a qualified mammographer on the images:

> TG18-MM1: "The breast parenchyma is heterogeneously dense. In the caudal and slightly medial breast, there is a cluster of pleomorphic calcifications extending linearly into the subareolar region indicative of invasive ductal carcinoma and DCIS. There are also subtle architectural distortions. A biopsy marking clip is present in the central breast."
>
> TG18-MM2: "The mammogram is a predominantly fatty-replaced breast tissue with an approximately 10 mm highly suspicious, irregularly-shaped mass with spiculated margins in the medial left breast in the middle depth, indicative of invasive ductal carcinoma."



(a) (b)

Figure 37. The TG18-MM1 (a) and TG18-MM2 (b) anatomical images.

3.3 Software

Though not essential, software tools can facilitate the performance assessment of display devices. They include software for semiautomated generation of test patterns, processing software for assessment of resolution and noise, and spreadsheets for recording and manipulating the evaluation results.

3.3.1 Pattern-Generator Software

Using the pattern descriptions given in appendix III, graphics software can be used to generate the desired test patterns. An advantage of this approach is that a large number of variable patterns can be easily generated. However, it is recommended that the patterns be viewed with the clinical software that is used to display actual medical images. The assistance of the PACS vendor (or hospital information systems personnel) will be needed to permanently transfer these images into the PACS database, where they may be viewed by the clinical application. Otherwise, care must be exercised to assure that both the graphics software and the clinical software access the DDL buffer in the same way. In some instances, the medical display application might apply luminance transformations that are different than those used for the graphic display application. An advantage of the test patterns in DICOM format is that they can be viewed by medical display software directly.

A number of public domain programs are available for display performance assessment, some of which are able to dynamically generate and display the TG18 test pattern on a display device. DisplayTools[6] is a program for Windows™ that provides separate graphic routines to present test patterns for evaluating luminance response, resolution, noise, veiling glare, and the contrast transfer characteristics associated with various target objects. SofTrack[7] is a UNIX-based public domain program that can be used to quantify and track the performance of a soft-copy display system over time. There are also a number of public domain software packages for general display of test patterns (e.g., ImageJ,[8] Osiris,[9] and eFilm[10]).

3.3.2 Processing Software

Software tools are needed to process images captured by the digital camera for the MTF and noise power spectrum (NPS) measurements. Programs can be developed based on the processing descriptions given in the assessment sections of this report. Otherwise, some commercial programs for image quality assessment can be adapted for these tasks (e.g., RIT[11]).

3.3.3 Spreadsheets

Spreadsheets can be used for recording the results of the evaluation of a display device. In addition to recording, formatting, and reporting, the spreadsheets can contain macros for computation of luminance response, luminance uniformity, color uniformity, and spatial accuracy.

[6] Henry Ford Health System, Detroit, MI.
[7] National Information Display Laboratory, Sarnoff Corp, Princeton, NJ.
[8] http://rsbweb.nih.gov/ij/.
[9] www.expasy.ch/UIN/.
[10] www.efilm.ca.
[11] RIT, Radiological Imaging Technology, Colorado Springs, CO, www.radimage.com.

3.4 Initial Steps for Display Assessment

3.4.1 Availability of Tools

Before starting the tests, the availability of the applicable tools and test patterns should be verified. Lists of desired tools for acceptance testing and quality control purposes are provided in sections 5 and 6. The TG18 test patterns should be stored on the display workstation during installation or otherwise be accessible from a network archive. This approach ensures that the same pattern will be utilized for all future testing. Network access to test patterns is especially useful in this regard. For any medical display system, it would be the responsibility of the manufacturer to make the TG18 test patterns available on the system. If unable to locate these patterns, the user should consult with the manufacturer's representative, as they are sometimes stored in service directories. If the patterns cannot be loaded and displayed, the user may utilize other quality control test patterns that might be available on the system. Alternatively, digital test patterns supplied via a laptop computer or a video test pattern generator may be utilized, with an understanding that the tests will not be evaluating the full display system, rather only its display device compartment. In the case of a "closed" or legacy system, depending on the kind of patterns available on the system, some of the tests recommended in this report might not be possible or might need major modifications. Therefore, it would be essential that the vendors of such closed display systems permanently install the TG18 test patterns on their systems. Appendix I provides some guidelines for evaluation of a closed display system.

3.4.2 Display Placement

Prior to testing, the proper placement of a display device should be verified and adjustments made as appropriate. In the placement of a display device, the following should be considered:

1. Display devices should always be positioned to minimize specular reflection from direct light sources such as ceiling lights, film illuminators, or surgical lamps. The reflection of such light sources should not be observed on the faceplate of the display in the commonly used viewing orientations.
2. Many display devices, such as CRTs, are affected by magnetic fields; they should not be placed in an area with strong magnetic fields (i.e., in vicinity of MRI scanners), unless properly shielded.
3. Displays should be placed ergonomically to avoid neck and back strain at reading level, with the center of the display slightly below eye level.

3.4.3 Start-up Procedures

Before testing a display device, the device should be warmed up for approximately 30 minutes prior to evaluation so that the electronics can stabilize. In addition, the general system functionality should be verified by a quick review of the TG18-QC test pattern. The pattern should be evaluated for distinct visibility of the 16 luminance steps, the continuity of the continuous luminance bars at the right and left of the pattern, the absence of gross artifacts (such as tearing or smearing of edges, excessive blur, or flickering), and the proper size and positioning of the active display area. The pattern should be of proper size and centered in the active area of the device, and all borders of the pattern should be visible. Any adjustments to vertical and horizontal size must be made prior to performing the luminance measurements.

Dust and smudges on the face of the display will absorb, reflect, or refract emitted light, possibly resulting in erroneous test results. In addition, newly installed displays are sometimes covered with a protective plastic layer, which upon removal can leave residual marks on the faceplate. Before testing a display device, the cleanliness of the faceplate should be verified. If the faceplate is not clean, it should be cleaned following the manufacturer's recommendations. In the absence of such recommendations, specialized display cleaning products and lint-free cloth can be used for this purpose. To avoid introducing cleaning solution into the display case, the cleaning solution should be sprayed on the towel instead of directly onto the face of the display device.

3.4.4 Ambient Lighting Level

The artifacts and loss of image quality associated with reflections from the display surface depend on the level of ambient lighting. As shown in Table 3, illumination of display device surfaces in various locations of a medical facility varies by over two orders of magnitude.

Section 4.2 delineates a method to determine the maximum ambient light level (illumination) appropriate for any given display device based on its reflection characteristics and the minimum luminance. It is important to verify that the ambient lighting in the room is below this maximum. The condition for the tests should be similar to those under normal use of the equipment. By recording ambient light levels at a reference point at the center of the faceplate and noting the location and orientation of the display devices at acceptance testing, it will be possible to optimize repeatability of testing conditions in the future.

Some display devices are equipped with an optional photocell for ambient light detection, which allows the luminance response to be appropriately modified in response to changes in ambient lighting. This feature should be utilized with extreme caution, as dynamic adjusting of the display's luminance response could cause noncompliance with DICOM 3.14. Newer devices allow for dynamic adjustment of the luminance response while maintaining compliance with DICOM. If the user chooses to use this feature, the manufacturer's guidelines should be strictly followed and additional tests performed to validate the operation and accuracy of the option. If an ambient light-measuring sensor is available, it is recommended that it be used to warn the user when variation in ambient lighting from a predefined value makes the diagnosis unreliable.

Table 3. Typical ambient lighting levels.

Area	Illumination (lux)
Operating rooms	300–400
Emergency medicine	150–300
Hospital clinical viewing stations	200–250
Staff offices	50–180
Diagnostic reading stations (CT/MR/NM)	15–60
Diagnostic reading stations (x-rays)	2–10

3.4.5 Minimum and Maximum Luminance Settings

Before the performance of a display system can be assessed, proper display area size should be established, and the maximum luminance, L_{max}, and the minimum luminance, L_{min}, must be checked to verify that the device is properly configured. The desired values should be determined based on the desired luminance and contrast ratios, the reflection characteristics of the system, and the ambient lighting level (see sections 4.2.4.3 and 4.3.4.2.1). Using a luminance meter, the luminance values should be recorded using the TG18-LN8-01 (or TG18-LN12-01) test pattern for L_{min} and TG18-LN8-18 (or TG18-LN12-18) for L_{max}, respectively (see sections 3.2.2.2 and 4.3.4). For these measurements, ambient illumination should be reduced to negligible levels using a dark cloth shroud if necessary.

If the measured values for L_{max} and L_{min} are not appropriate, the display device should be configured to establish proper values (see section 4.3.4.2) using the brightness and contrast controls. Typically the controls are either located on or under the back panel or are accessed using a digital interface. The following procedure should be followed. First, display the TG18-QC pattern. Starting with both contrast and brightness controls turned down to their minimum, increase the brightness to establish the desired minimum luminance. Then increase the contrast control until the maximum luminance is achieved without causing blooming, as judged by the appearance of Cx targets of the pattern or other artifacts. As the brightness and contrast settings typically do not control the minimum and maximum luminance independently, multiple iterative adjustments may be necessary to achieve the desired L_{min} and L_{max} values. Once those values are reached, the brightness and contrast controls as well as any luminance response settings should be fixed, and those calibration controls should be made inaccessible to the general user. If the measured values for L_{max} and/or L_{min} cannot be established within recommended limits, the display device should be serviced before testing its performance.

3.4.6 DICOM Grayscale Calibration

This report recommends compliance of medical display systems with the DICOM Grayscale Standard Display Function (NEMA PS 3.14, see section 4.3 for details). Some medical imaging systems allow calibration of the luminance response of the display unit. Such systems typically allow a luminance probe to be attached to the host computer and can automatically record the measured luminance when test patterns similar to TG18-LN are displayed by the available software. The recorded data is then used to compute a lookup table for the display controller that will provide the desired (calibrated) luminance response.

For such systems, the response should be calibrated at installation and at intervals recommended by the manufacturer and this report (see section 6.2). Before testing a display device as described in the following sections, the date of the last calibration should be checked, and if it is not current, a new calibration should be performed or requested. If a new calibration is required, L_{max} and L_{min} should always be verified first as described above. An example calibration setup is shown in Figure 38.

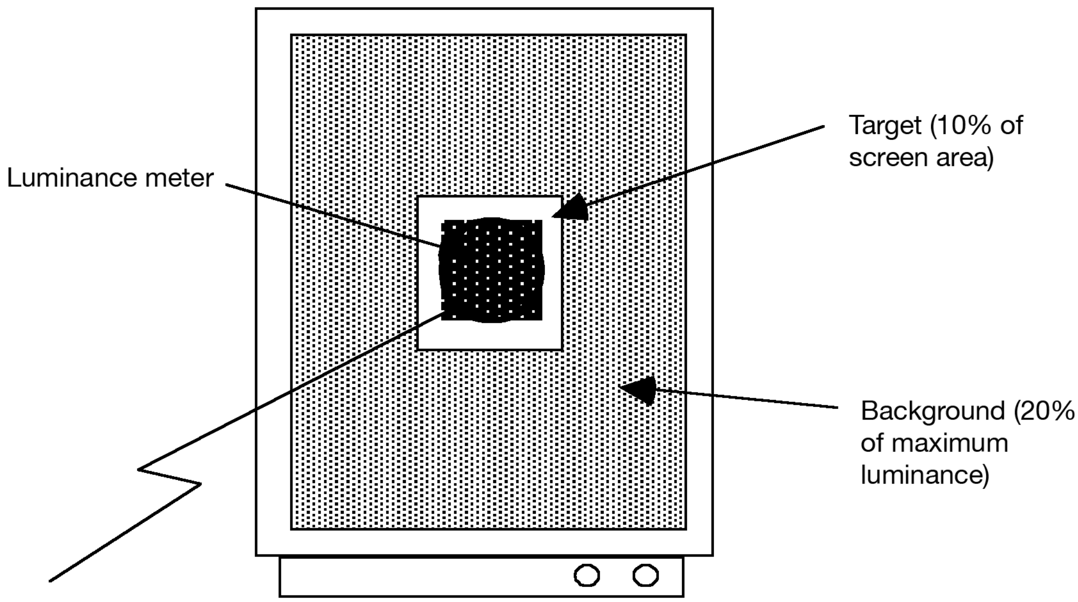


Figure 38. This figure shows an example of a calibration using a common type of calibration system where the luminance meter is attached to the display card, and the software automatically performs the calibration. All that is required is to place the luminance meter against the display screen and run the automated program.

4 ASSESSMENT OF DISPLAY PERFORMANCE

This section describes the assessment methods for the major performance characteristics of an electronic display device. It is generally ideal to perform the tests in the order in which they are discussed, as some of the later tests may be influenced by parameters that are addressed in the earlier tests. The methods are organized, depending on their complexity, as visual, quantitative, and advanced methods. Based on the extent of the display evaluation, the purpose of the evaluation, and the availability of assessment tools, a combination of the recommended methods should be considered. For acceptance testing and quality control evaluation, a combination of visual and quantitative tests can be used, as outlined in sections 5 and 6. The advanced tests described here are generally not for implementation in clinical settings, rather they are meant to provide general guidelines for individuals who wish to more comprehensively evaluate the performance of a display system. The recommendations for the expected response are based on our current state of knowledge. Clinical experience is expected to refine these recommendations in the future.

4.1 Geometric Distortions

4.1.1 Description of Geometric Distortions

Geometric distortions originate from aberrations that cause the displayed image to be geometrically dissimilar to the original image (Dwyer and Stewart 1993). The practical consequences of such distortions affect the relative sizes and shapes of image features, particularly for larger displays or large deflection angles. Three kinds of distortions are commonly seen in CRT displays: departures from linearity in the form of pincushion (concave distortion), barrel (convex distortion), and skew distortions; angulation and improper aspect ratio; and nonlinearity. The first two types of distortions can be observed at the horizontal and vertical edges of the active display area and are compensated by magnetic or electronic adjustments. The nonlinearity distortions are distortions within the active display area, which cause local variation of image geometry and are directly related to the quality of the deflection coils and their driving electronics. Commercial CRT displays intended for office use do not utilize the highest quality coils, while higher-quality medical displays for primary interpretation have more precise windings and built-in correction circuits to control deflection to a higher degree of accuracy.

Some geometric distortions can be traced to improper setup of the display controller and/or a mismatch between the aspect ratio of the display device and the controller. Display controllers have settings for pixel formats that can be either factory installed or user defined under software control. However, display devices often can only accommodate certain aspect ratios. For example, five-megapixel display devices often have a 5:4 aspect ratio while four-megapixel ones have a 4:3 ratio. An improper aspect ratio setting at the controller causes distortions, as squares become rectangles or vice versa. In a digitally controlled display, a return to factory settings will usually correct the basic error. Image scaling is often an option if the user wishes to re-map the video image format to cover all or as large of an area of the screen as possible. Proper aspect ratio is nearly guaranteed when one-to-one pixel mapping is chosen. Image scaling in fixed pixel displays (e.g., LCDs) can result in improper aspect ratio.

Magnetic fields may also cause geometric distortions in CRT devices. These are often encountered in display devices that are used in the vicinity of unshielded magnetic fields (e.g., MRI scanners). In addition to geometric distortions, magnetic fields can degrade the resolution of monochrome CRTs, and color purity in color CRTs. Electrical distribution conduits running in close proximity to the workstation or steel columns used in the building structure can produce large magnetic fields. A simple test to identify magnetic distortions is to rotate the display by 90° (e.g., from facing east to facing south) and see if the distortions change.

4.1.2 Quantification of Geometric Distortions

Geometric distortion can be quantified in terms of the amount of spatial angulation or two-dimensional displacement in a geometric test pattern, and be expressed in terms of pixels, spatial dimensions (i.e., millimeters), or percent differences in various directions or areas. Some of the quantification methods are detailed in the following section.

4.1.3 Visual Evaluation of Geometric Distortions

4.1.3.1 Assessment Method

The geometric distortion of a display system can be visually ascertained using either the TG18-QC or the TG18-LPV/LPH test pattern. The patterns should be maximized to fill the entire usable display area. For displays with rectangular display areas, the patterns should cover at least the narrower dimension of the display area and be placed at the center of the area used for image viewing. The pattern(s) should be examined from a viewing distance of 30 cm. The linearity of the pattern should be checked visually across the display area and at the edges. Some bezels, in conjunction with the curvature of the CRT faceplate, can create an illusion of nonlinearity and should not be used as a visual reference for a straight edge.

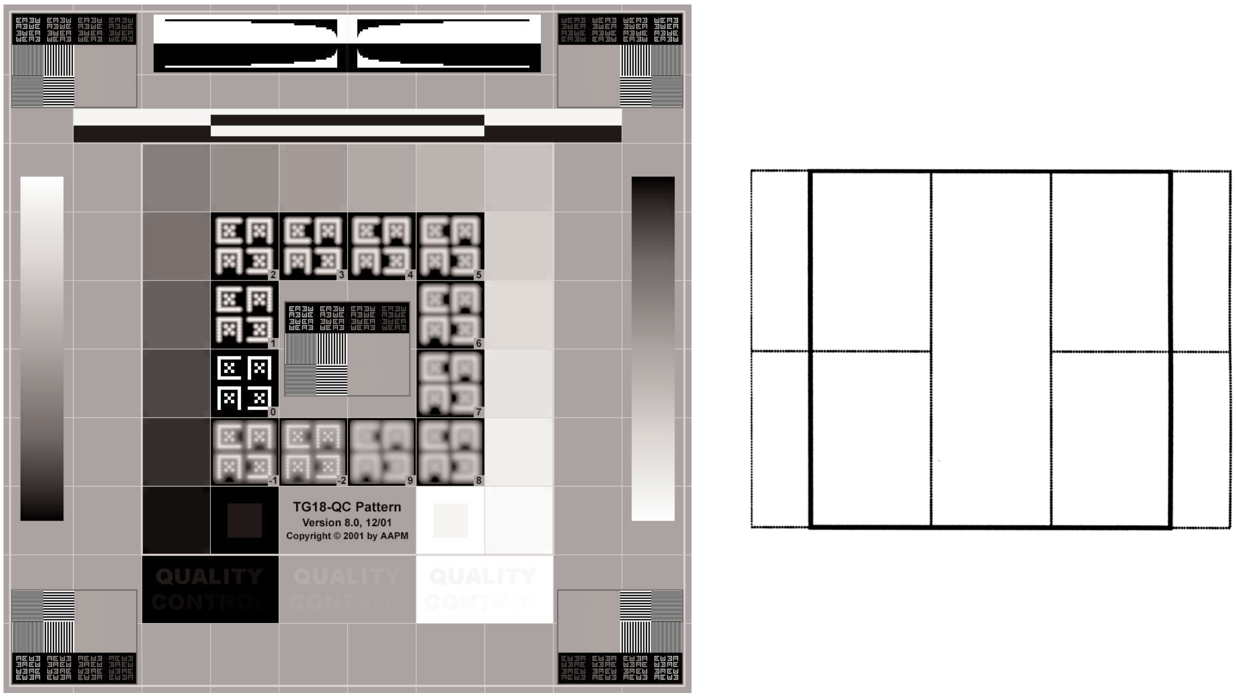
4.1.3.2 Expected Response

The patterns should appear straight without significant geometric distortions and should be properly scaled to the aspect ratio of the video source pixel format so that the grid structure of the TG18-QC test pattern appears square. The lines should appear straight, indicative of proper linearity, without any curvature or waviness. Some small barrel and pincushion distortions are normal for CRT devices but should not be excessive. For the TG18-LPV and TG18-LPH patterns, in addition to straightness, the lines should appear equally spaced.

4.1.4 Quantitative Evaluation of Geometric Distortions

4.1.4.1 Assessment Method

Spatial accuracy for geometric distortions can be quantified using the TG18-QC test pattern. The pattern should be maximized to fill the entire display area. For displays with rectangular display areas, the pattern should cover at least the narrower dimension of the display area and be placed at the center of the area used for image viewing. Using a straight edge as a guide for a best fit and with the aid of a flexible plastic ruler, distances should be measured in square areas in the horizontal and vertical directions in each of the four quadrants of the pattern and within the whole pattern (Figure 39). It is important to assure the locations of the crosshatches be viewed perpendicular to the display's faceplate. In each quadrant, between quadrants, and within the whole pattern, the maximum percent deviations between the measurements in each direction, and between the measurements in the horizontal and vertical directions should be



(a) **(b)**

Figure 39. The spatial measurements for the quantitative evaluation of geometric distortions using the TG18-QC test pattern. The small squares with dashed lines (- - -) define the four quadrants of the pattern, and the large square at the center encompassing the luminance patches is the one to be used for geometric distortion characterization within the whole image.

determined. The percentages should be calculated in relation to the smallest of the values being compared. For facilities that use a large number of displays of the same model, a transparent template is useful and can be marked to delineate the maximum acceptable distortion.

4.1.4.2 Expected Response

For primary class devices, the maximum spatial deviations between orthogonal measurements should not exceed 2% within either direction and between directions, within each quadrant and within the whole pattern. The percent deviation across quadrants should also not exceed 2%. The corresponding criterion for secondary class devices is 5%. In evaluating the performance of a CRT display, it should be considered that the control of horizontal deflection via phase and linearity adjustments is different in the left and right sides of the display. Therefore, it is possible for the distortion to be different on the two sides of the display.

If a display device does not meet the above criteria, adjustments should be made to the distortion control of the device. Often, as the area of the display is increased or decreased, the luminance will also increase or decrease in a nonlinear fashion. Therefore, it is important to make and finalize such adjustment prior to testing and adjustments of the display luminance characteristics. In addition, if a display workstation contains more than one display device, it is important to have the vertical and horizontal sizes of the active areas carefully matched within 2%. This facilitates the subsequent matching of their luminance response characteristics.

4.1.5 Advanced Evaluation of Geometric Distortions

4.1.5.1 Assessment Method

Advanced measurements of a display's response can be obtained with a precision digital camera using the methods for curvature and linearity distortion characterizations described in a recent VESA standard report (VESA 2001). These measurements are simple in principle but require a complex laboratory setting.

Vertical and horizontal lines are displayed along the edges of the addressable screen and along both the vertical and horizontal centerlines (major and minor axes). A digital camera is used to measure the position of the centroid of each line luminance profile at 20 equally spaced points along each displayed line. A precise x-y positioner is needed to accurately center the camera on the display. Linear regression is applied to numerically fit a straight line through the measured coordinates of each displayed line. If large-area pincushion distortions are being quantified, a second-order polynomial curve is also fitted to each line. The curvature of each line is computed as the peak-to-peak deviation of the measured coordinates from the corresponding points along the fitted line. For vertical lines, the curvature error is expressed as a percentage of the total width of the screen. Similarly, for horizontal lines, the curvature error is expressed as a percentage of the total height of the screen.

For nonlinearity distortions, the line-pair patterns of single-pixel horizontal lines and single-pixel vertical lines are used. Lines are equally spaced, and the spacing must be constant and equal to 5% of screen width or height, to the nearest addressable pixel. The digital camera is used to measure screen (x,y) coordinates of points where the vertical lines of the pattern intersect the horizontal centerline of the screen and where the horizontal lines intersect the vertical centerline. The difference between the greatest and the least spacing measured between the lines is calculated as an indicator of nonlinearity. The vertical nonlinearity is quantified as a percentage of total screen height, while that for the horizontal is quantified as a percentage of total screen width.

4.1.5.2 Expected Response

No standards are available at this time for advanced geometric distortion characteristics of medical display devices.

4.2 Display Reflection

4.2.1 Description of Display Reflection

Ideally, the luminance distribution on a display surface would only be associated with light generated by the device, i.e., the image information. In practice, ambient room light reflects off the surface of a device and adds luminance to the displayed image. The performance of a display device is highly dependent on the reflection characteristics of the device. Therefore, it is important to evaluate this response at the outset and, based on that, to determine the maximum level of ambient illumination that can be used in the reading area without compromising the display presentation. Control of ambient light conditions also allows more effective visual adaptation by the observer while interpreting medical images.

Broadly characterized, the reflections can have two general forms: specular and diffuse. Specular reflection is said to occur when the angle of the incident light rays equals that of the emerging rays as dictated by geometric optics. Such a reflection produces a virtual image of the source, as would a mirror. In diffuse reflection, the light is randomly scattered out of the specular direction and no virtual image of the source is produced. There are two types of diffuse reflection. One occurs when the scattering angles of the emergent light are broadly distributed and poorly correlated with the angle of the incident light, such as with a Lambertian reflector where the direction of the incident light has little effect on the observed reflected luminance (e.g., matte wall paint). The other type of diffuse reflection occurs when light is randomly scattered into a narrow distribution of angles in the vicinity of the specular direction. Some have called this a type of reflection haze. Haze requires evaluation of the emerging light distribution as a function of the incident light angle. Haze reflections are particularly notable in AMLCD flat-panel displays, especially those used for laptop computers. For further information and measurement methods for haze, consult the VESA standards (VESA 2001).

4.2.1.1 Specular Reflection Characteristics

Specular reflection produces a mirror image of the light source, although surface roughness of the display that produces haze may blur the reflected image. Specular reflection of brightly lit objects or light sources adds structured, position-dependent patterns to the image, which can interfere with the interpretation of features. Illuminated objects in a room will appear as a reflection having a luminance proportional to the illumination of the object for purely specular reflections. Anti-glare (AG) treatments that produce random microstructure on the surfaces (e.g., a slight etching of the faceplate glass for CRTs) produce haze that can manifest itself as a fuzzy ball of light surrounding the specular images of sources. For some applications the haze-blurring of the specular image assists in reducing the confusion produced from a specular reflection (the mirrorlike image is no longer distinct). Anti-reflective (AR) glass coatings, darkening of the faceplate glass, and the reduction of ambient light levels can also reduce the visibility of these reflections (Figure 40).

4.2.1.2 Diffuse Reflection Characteristics

Diffuse Lambertian reflection (to distinguish from diffuse haze reflection) produces a uniform luminance on the display device with no visually detectable structured patterns. The added luminance reduces contrast in the displayed image by altering the relative luminance change associated with specific features in the image. The contrast reduction is predominantly in the dark areas of an image since those areas are more prone to relative changes in luminance. Display devices that generate light within an emissive structure, such as CRTs, are designed to promote transport of light out of the structure. As a consequence, they typically have higher Lambertian-like diffuse reflectance than transmissive displays, including film and LCDs. CRT display devices extensively diffuse incident light in the phosphor layer and may have excessive diffuse reflection unless these are damped by light absorption in the glass faceplate or the phosphor material (Figure 40), which, in turn, reduces the luminance of the device. The white phosphor in a monochrome CRT device produces higher diffuse reflectance than color phosphors or black matrix material used in color CRT devices (Figure 41).

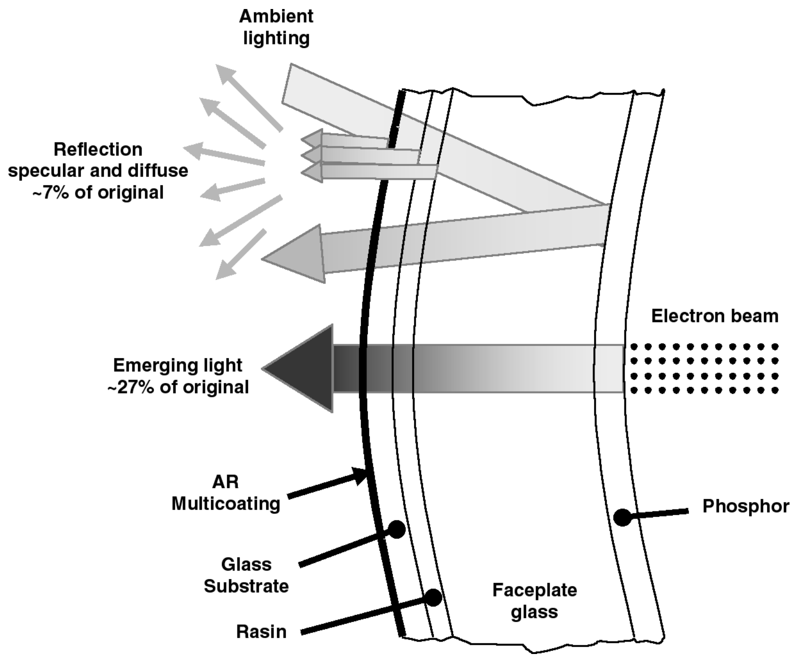


Figure 40. Longitudinal cut through a high-contrast CRT with absorptive glass illustrating light absorption in the faceplate of a CRT.

Figure 41. Diffuse and specular reflections are illustrated for a color (left) and a monochrome (right) display device with the power off. Reduced diffuse reflections are seen in the color display device due to the black matrix emissive structure. Reduced specular reflections are seen in the monochrome display device due to an improved anti-reflective coating.

4.2.2 Quantification of Display Reflection

4.2.2.1 Specular Reflection Characteristics

Specular reflections can be described by a dimensionless specular reflection coefficient, R_s, which is the ratio of the apparent luminance of a reflected light source to the actual luminance of the source.[12] Evaluation of R_s is done using an external light source shining on a display device. A telescopic luminance meter is then directed at the display device. The display should be in the power-save mode or turned off. Since medical images are observed with the viewer most often directly in front of the device, R_S is appropriately measured with the light source at about 15° from the surface normal. The light source should be relatively small in diameter to minimize the illumination of the display device and consequent diffuse reflection yet large enough to produce an image area larger than the response region of the telescopic luminance meter. Ideally, the light source should subtend 15° from the center of the display and be placed at 15° from the normal (Kelley 2002).

4.2.2.2 Diffuse Reflection Characteristics

Diffuse reflections are described by the diffuse reflection coefficient R_d, which relates the induced luminance to the ambient illumination of the display surface.[13] The units of R_d are thus those of luminance per illuminance (cd/m^2 per lux) or sr^{-1}. A telescopic luminance meter and an illuminance meter are used in conjunction with a display illuminator. For comparable measurements, the illumination conditions need to be standardized. Both the wavelength spectrum of the illumination source and the incident angular distribution need to be comparable to the clinical situation. Fluorescent lamps provide a spectrum similar to room lighting, and small fluorescent lamps may be placed in a box covering the display surface (Flynn and Badano 1999) (see Figure 19). Note that this type of measurement may not be robust in the general case of a flat-panel display with a strongly diffusing front surface.

To the extent that some diffuse luminance from ambient lighting is always present in reading areas, it is important that the luminance calibration of the display device boost the contrast in dark regions to account for the effects of diffuse reflection. When properly calibrated, the contrast of an object seen in a dark region should be the same as for an equivalent object seen in a bright region when typical ambient illumination is present.

4.2.3 Visual Evaluation of Display Reflection

4.2.3.1 Assessment Method

4.2.3.1.1 Specular Reflection Characteristics. An effective and simple visual test is to observe a display device, with the display in the power-save mode or turned off, from a position typical of that for interpreting images. The ambient lighting in the room should be maintained at levels normally used. The display's faceplate should be examined at a distance of about 30 to 60 cm within an angular view of ±15° for the presence of specularly reflected light sources or illuminated objects. Patterns of high contrast on the viewer's clothing are common sources of reflected features.

[12]Note that in CIE terminology, the specular reflection coefficient is referred to as the reflectance with a symbol of ρ (or ρ_s).

[13]Note that in CIE terminology, the diffuse reflection coefficient is referred to as the luminance coefficient with a symbol of q.

4.2.3.1.2 Diffuse Reflection Characteristics. The effect of diffusely reflected light on image contrast may be observed by alternately viewing the low-contrast patterns in the TG18-AD test pattern in near total darkness and in normal ambient lighting, determining the threshold of visibility in each case. A dark cloth placed over both the display device and the viewer may be helpful for establishing near total darkness. The pattern should be examined from a viewing distance of 30 cm.

4.2.3.2 Expected Response

4.2.3.2.1 Specular Reflection Characteristics. In examining the display's faceplate under normal ambient light conditions, no specularly reflected patterns of high-contrast objects should be seen. If light sources such as that from a film illuminator or window are seen, the position of the display device in the room is not appropriate. If high-contrast patterns such as an identification badge on a white shirt or a picture frame on a light wall are seen, the ambient illumination in the room should be reduced.

4.2.3.2.2 Diffuse Reflection Characteristics. The threshold of visibility for low-contrast patterns in the TG18-AD test pattern should not be different when viewed in total darkness and when viewed in ambient lighting conditions. If the ambient lighting renders the "dark-threshold" not observable, the ambient illuminance on the display surface is causing excess contrast reduction, and the room ambient lighting needs to be reduced.

4.2.4 Quantitative Evaluation of Display Reflection

4.2.4.1 Assessment Method

4.2.4.1.1 Specular Reflection Characteristics. The specular reflection coefficient for a display device can be measured with a small diameter source of diffuse white light as described in section 3.1.3. The display should be in the power-save mode or turned off. The light source, subtending 15° from the center of the display, should be positioned d_1 cm from the center of the display and be pointed toward the center at an angle of 15° from the surface normal. The reflected luminance of the light source should then be measured with a telescopic luminance meter from a distance of d_2 cm from the center of the display and similarly angled at 15° to the normal. Finally, the directly viewed luminance of the light source should be measured with the same luminance meter from a distance of $d_1 + d_2$ cm. The specular reflection coefficient R_s is the ratio of the reflected spot luminance to the directly viewed spot luminance. All measurements should be made in a dark room.

It should be noted that due to curvature of the display surface, the R_s values measured for a display device may be different from that expected for the surface coating material, which is normally quoted for a flat surface measurement. This can magnify the apparent size of the reflected test illuminator and reduce the observed luminance. Since the effects of the curvature are relevant to the final image quality, it is recommended that no correction of measurement results be made to account for surface curvature.

4.2.4.1.2 Diffuse Reflection Characteristics. The diffuse reflection coefficient may be measured using standardized illumination of the display with the illuminator device described in section 3.1.3 (Figure 19). The display should be in the power-save mode or turned off. The lamps should only indirectly illuminate the faceplate, ideally by placing them on the sides behind the faceplate plane in a semihemispherical illumination geometry (Figure 19b–c). The illuminance should then be measured in the center of the display device using a probe placed on the center of the display surface. The sensitive area of the meter should be held vertically to measure the illuminance incident on the display faceplate. The induced luminance at the center of the display surface should then be measured with a telescopic luminance meter. The luminance measurement should be made through the small aperture at the back of the containment device so as to not perturb the reflective characteristics of the containment structure. The viewing aperture must be located from 8° to 12° off to the side from the normal so as to not interfere with the measurement result. The diffuse reflection coefficient, R_d, is computed as the ratio of the luminance to the illuminance in units of sr^{-1}.

4.2.4.2 Expected Response

4.2.4.2.1 Specular Reflection Characteristics. The artifacts associated with specular reflections and the potential loss of contrast associated with diffuse reflections both depend on the ambient lighting. Whereas ideally one would like to have $R_s = R_d = 0$, the measured values can be related to the maximum ambient room lighting that is appropriate for viewing a display device with a specified minimum inherent luminance. Suppose an illuminated white object with 90% diffuse (Lambertian) reflectance is found to be in a specular direction when the display surface is observed, e.g., a white wall that is behind the observer. The luminance of that object is $L_0 = 0.9\ E/\pi$, where E is the illumination in lux and L_0 is the observed luminance in cd/m^2. The specularly reflected luminance of this object should thus be less than the just noticeable change of luminance in dark regions of the display,

$$R_s\, L_0 \leq C_t\, L_{min}\,; \qquad (2)$$

and therefore,

$$\mathrm{E} \leq (\pi\, C_t\, L_{min}) \,/\, (0.9\, R_s)\ , \qquad (3)$$

where the contrast threshold, $C_t = \Delta L/L$ (see section 4.3.1), corresponds to its value at the minimum luminance, L_{min}. Contrast threshold ranges from 0.032 and 0.021 for L_{min} values between 0.5 and 1.5 cd/m^2 (as illustrated in Figure 43 later in this report). For convenience, this relationship is tabulated (Table 4) so that the maximum room lighting can be identified if R_s and L_{min} are known.

Uncoated glass faceplates have R_s values of about 0.04. Devices with uncoated glass faceplates should only be used in very dark rooms (2 to 5 lux). High-quality multilayer anti-reflective (AR) coatings can achieve R_s values of about 0.005. A relatively bright display device (2 to 500 cd/m^2) with such coatings can be used in a room of modest lighting (25 lux). By comparison, transilluminated film (10 to 2500 cd/m^2) has a substantially higher R_s value of about 0.013 in high-density regions. However, the high L_{min} value permits viewing without specular reflections

Table 4. Maximum allowable ambient illuminance, based on specular reflection.

$L_{max} - L_{min}$ (cd/m²)	C_t	Maximum Room Illuminance (lux)				
		$R_s = 0.002$	$R_s = 0.004$	$R_s = 0.008$	$R_s = 0.020$	$R_s = 0.040$
5000 – 20	0.010	349	175	87	35	17
2500 – 10	0.011	192	96	48	19	10
1000 – 4	0.015	105	52	26	10	5
500 – 2	0.018	63	31	16	6	3
250 – 1	0.024	42	21	10	4	2

For a display device with a specific minimum luminance, L_{min}, and a specific specular reflection coefficient, R_s, the ambient illumination that maintains specular reflections from high-contrast objects below the visual contrast threshold (C_t) is tabulated.

with twice the ambient lighting (54 lux). For a typical CRT with AR coating ($R_s = 0.004$) operated at minimum luminance values of 0.5, 1, 1.5, and 2.0 cd/m², the ambient lighting based on specular reflection consideration should be less than approximately 14, 21, 28, and 31 lux, respectively. Note that in the adjustment and measurement of the appropriate level of ambient lighting, illuminance in the room should be measured with the illuminance meter placed at the center of the display and facing outward, so the proper amount of light incident on the faceplate can be assessed.

4.2.4.2.2 Diffuse Reflection Characteristics. The luminance from diffuse reflections adds to that produced by the display device. The ambient illumination produces a luminance of $L_{amb} = R_d E$, where E is ambient illuminance on the display surface, and R_d is the diffuse reflection coefficient in units of cd/m² per lux or sr^{-1}. In the dark areas of a low-contrast image, the change in luminance, ΔL_t, will produce a relative contrast of $\Delta L_t/(L_{min} + L_{amb})$. For some devices, the luminance response can be calibrated to account for the presence of a known amount of luminance from ambient lighting, L_{amb}, and produce equivalent contrast transfer in both dark and bright regions. However, if L_{amb} is sufficiently large in relation to L_{min}, even if the device has a high contrast ratio, the overall luminance ratio of the device is compromised. For primary class display devices, it is recommended that L_{amb} be maintained at less than 0.25 of L_{min}, $L_{amb} < 0.25\ L_{min}$, or that the illuminance E be restricted to

$$E \leq (0.25\ L_{min})/R_d\ . \tag{4}$$

This ensures that the contrast in dark regions observed with ambient illumination will be at least 80% of the contrast observed in near total darkness. Table 5 identifies the ambient lighting for which L_{amb} is 0.25 of L_{min} as a function of R_d and L_{min}. For a typical CRT with AR coating ($R_d = 0.02\ sr^{-1}$) operated at minimum luminance values of 0.5, 1, 1.5, and 2.0 cd/m², the ambient lighting based on diffuse reflection consideration should be less than approximately 7, 12, 19, and 25 lux, respectively. Note that in situations in which the level of ambient lighting can be strictly controlled and taken into account in the luminance calibration of the display device, a

Table 5. Maximum room lighting based on diffuse reflection.

$L_{max} - L_{min}$ (cd/m^2)	Maximum Room Illuminance (lux)				
	R_d = 0.005	R_d = 0.010	R_d = 0.020	R_d = 0.040	R_d = 0.060
5000 – 20	1000	500	250	125	83
2500 – 10	500	250	125	62	42
1000 – 4	200	100	50	25	17
500 – 2	100	50	25	12	8
250 – 1	50	25	12	6	4

For a display device with a specific minimum luminance, L_{min}, and a specific diffuse reflection coefficient, R_d, in units of cd/m^2 per lux or sr^{-1}, the ambient illumination which maintains 80% contrast in dark regions is tabulated. The maximum room illuminance is calculated as 0.25 L_{min} / R_d.

larger L_{amb} can be tolerated ($L_{amb} < L_{min}/1.5$) as noted in section 4.3.4.2. Note that in the adjustment and measurement of the appropriate level of ambient lighting, illuminance in the room should be measured with the illuminance meter placed at the center of the display facing outward, so the proper amount of light incident on the faceplate can be assessed.

4.2.5 Advanced Evaluation of Display Reflection

4.2.5.1 Assessment Method

4.2.5.1.1 Specular Reflection Characteristics. The specular reflection coefficient of a display device with AR coatings will often vary significantly with wavelength, and specular reflection of white light will have a characteristic color determined by this filtering effect. To best describe the specular reflection characteristics of a display device, R_s should be measured as a function of wavelength over the full visible range. Measurement of R_s at 6 wavelengths in the visible range is adequate to report the wavelength dependence. The same light source and telescopic luminance meter as described above can be used for these measurements. The specific wavelength band for a measurement can be established by using thin-film, optical band-pass filters. Since these filters are designed for filtering light that is perpendicularly incident on the filter surface, they should be placed near the luminance meter and not in front of the light source. If the photopic filter on the telescopic luminance meter can be removed, some increase in sensitivity can be achieved with no impact on the value of measured R_s. Alternatively, advanced measurements can be performed using a spectrometer.

4.2.5.1.2 Diffuse Reflection Characteristics. While the quantitative test method described in section 4.2.4.1.2 is adequate for most field measurements, intercomparison of different devices requires more standardized illumination. The angular distribution of the incident light can affect the diffuse reflection coefficient, particularly for flat-panel devices. For advanced measurements, which can probably only be performed in laboratory settings, the illumination method advocated by NIST is recommended (Kelley 2001). For devices having complex angular distributions for diffusely reflected light, measurement of the bidirectional reflectance distribution function provides a more complete description of diffuse reflection. Methods to measure this function are described by VESA (VESA 2001, section A217).

4.2.5.2 Expected Response

The criteria for the quantitative evaluations described above with respect to the relations between reflection coefficients and luminance apply also to the advanced measurement methods. In the case of specular reflections, the advanced methods provide an understanding of possible wavelength dependence, which is seen as a color shift in the reflected patterns. Good multilayer AR coatings achieve R_s values of less than 0.005 for wavelengths from 450 to 680 nm, and substantially lower values from 500 to 600 nm. In the case of diffuse reflections, the advanced methods provide a more accurate measure of R_d, which permits valid intercomparison of results obtained at different centers.

4.3 Luminance Response

4.3.1 Description of Luminance Response

The luminance response of a display device refers to the relationship between displayed luminance and the input values of a standardized display system (section 1.2.2). The displayed luminance consists of light produced by the display device that varies between L_{min} and L_{max}, along with a fixed contribution from diffusely reflected ambient light (section 4.2), L_{amb}. (Specular contribution is neglected here as it varies significantly as a function of geometry.) In this report, L_{min}, L_{max}, and the intermediate luminance values, $L(p)$, refer only to light produced by the display device as measured with negligible ambient illumination. Actual luminance values associated with specific ambient lighting are denoted using a primed variable name:

$$
\begin{aligned}
L'_{min} &= L_{min} + L_{amb} \\
L'_{max} &= L_{max} + L_{amb} \\
L'(p) &= L(p) + L_{amb}
\end{aligned}
\tag{5}
$$

The function $L'(p)$ is the display function that relates luminance to input values over the range from L'_{min} to L'_{max}. The term “luminance ratio” specifically refers to the ratio of the maximum luminance to the minimum luminance in the presence of an ambient luminance component, L'_{max}/ L'_{min}. The term contrast ratio is used to characterize a display device and refers to L'_{max}/ L'_{min} as measured with low ambient lighting.

In order to have similar image appearance with respect to contrast, all display devices should have the same luminance ratio and the same display function. Appendix II further discusses how image presentation may be adjusted to achieve equivalent appearance when the luminance ratio is not the same. Because the human visual system adapts to overall brightness, two display devices can have similar appearance with different L_{max} values as long as L'_{max}/ L'_{min} and $L'(p)$ are the same. $L'(p)$ is typically set to a display function.

DICOM working group 11 considered a variety of alternatives for a standard display function. The final recommendation for the DICOM Grayscale Standard Display Function (GSDF) was based on the Barten model for the contrast threshold of the human visual system (Barten 1992, 1993, 1999) when measured using specific experimental conditions. For a small test target with sinusoidal luminance modulation, $(\Delta L/2)\sin(\omega)$, placed on a uniform background, the

Barten model predicts the threshold contrast, $\Delta L/2L$, that is just visible. The threshold contrast is defined as the Michelson contrast, $(L_{high} - L_{low})/(L_{high} - L_{low})$ or $\Delta L/2L$ for sinusoidal modulation between $+\Delta L/2$ and $-\Delta L/2$. The GSDF is specifically based on a target size of 2° relative to the observer's eyes with a modulation of $\omega = 4$ cycles/degree. The GSDF is defined as a table of luminance values such that the luminance change between any two sequential values corresponds to the peak-to-peak relative luminance difference, $\Delta L/L$, predicted by the Barten model. The index values to the series of luminance values are known as JND indices since a unit change of the table index corresponds to a just noticeable difference in luminance. The DICOM standard also provides a continuous fit for the GSDF as

$$\mathrm{Log}_{10} L_j = \frac{a + c(\mathrm{Log}_e j) + e(\mathrm{Log}_e j)^2 + g(\mathrm{Log}_e j)^3 + m(\mathrm{Log}_e j)^4}{1 + b(\mathrm{Log}_e j) + d(\mathrm{Log}_e j)^2 + f(\mathrm{Log}_e j)^3 + h(\mathrm{Log}_e j)^4 + k(\mathrm{Log}_e j)^5} \quad , \qquad (6)$$

which can be used to compute luminance values at any index level. In this equation, j is the index (1 to 1023) of the luminance levels L_j of the JNDs, and

a = -1.3011877,
b = -2.584019×10^{-2},
c = 8.0242636×10^{-2},
d = $-1.0320229 \times 10^{-1}$,
e = 1.3646699×10^{-1},
f = 2.8745620×10^{-2},
g = $-2.5468404 \times 10^{-2}$,
h = $-3.1978977 \times 10^{-3}$,
k = 1.2992634×10^{-4}, and
m = 1.3635334×10^{-3}.

In Europe, the CIELAB function suggested by the International Illumination Commission has been used in some centers. The CIELAB proposes a modified cube root between the luminance L' and a perceived brightness variable, L*, as

$$L^* = 116\,(L'/L'_{max})^{1/3} - 16 \qquad \text{for } L'/L'_{max} > 0.008856, \qquad (7)$$
$$L^* = 903.3\,L'/L'_{max} \qquad \text{otherwise.}$$

In this scale, L* varies between 0 and 100. A perceptually linear display curve $L'(p)$ will be obtained if the above function is inverted and L* is identified with the DDL p-values ($0 \le p \le p_{max}$), where p is the presentation value. As an example, for $p_{max} = 255$,

$$L'(p) = [(100\,p/p_{max} + 16)/116]^3\,L'_{max} \qquad \text{for } p/p_{max} > 0.08, \qquad (8)$$
$$L'(p) = 1/903.3\,(100\,p/p_{max})\,L'_{max} \qquad \text{otherwise.}$$

By specifying a range between 0 and 100 for L^*, the CIE standard forces a zero L'_{min} value for $p = 0$. Considering the fact that L'_{min} is always larger than zero due to a nonzero L_{min} value and the presence of ambient lighting, the ambiguous requirement of the CIE may need to be modified to accommodate a non-zero minimum L'_{min} value as suggested in a recent publication (Roehrig et al. 2003).

As shown in Figure 42, the CIELAB function has more contrast in low-luminance regions than the DICOM GSDF. For consistency among all centers, TG18 specifically recommends that the DICOM GSDF be used to define $L'(p)$ for all display devices.

In the DICOM conceptual model of a standard display device (see section 1.2.2, Figures 1 and 2), image values produced by an acquisition device are transformed to a range of presentation values, *p*. The p-values are then scaled to match the input range of the display controller (e.g., 256, 1024, etc.) and mapped to DDLs based on a previously established LUT. While DDL values are typically scalar numbers, some devices may use red, green, and blue color values that are converted in the monitor to gray. DICOM calibration of a device is done by measuring luminance versus DDL and computing an LUT that makes $L'(p)$ follow the DICOM GSDF between L'_{min} and L'_{max}. Within this range of luminance, p-values are linearly proportional to the JND indices, with a constant number of JND indices for each p-value change. Devices that store the calibration LUT in the display controller or its device driver are advantageous in that the desired luminance response can be obtained by any application.

It is important to recognize certain limitations of the DICOM standard response. When viewing the varied brightness of a medical image, the human visual system adapts to the average quantity of light falling on the retina. This is referred to as *fixed adaptation.* However, the DICOM 3.14 luminance response is based on contrast threshold data that is derived from experiments where the background luminance is changed to equal the luminance of the target pattern, and the observer fully adapts to the new background. The contrast threshold associated with the GSDF thus reflects *variable adaptation.* When the eye is adapted to the mixed bright and dark regions of a medical image, the contrast threshold as a function of luminance differs significantly from that associated with variable adaptation (Samei 2004). The difference is illustrated

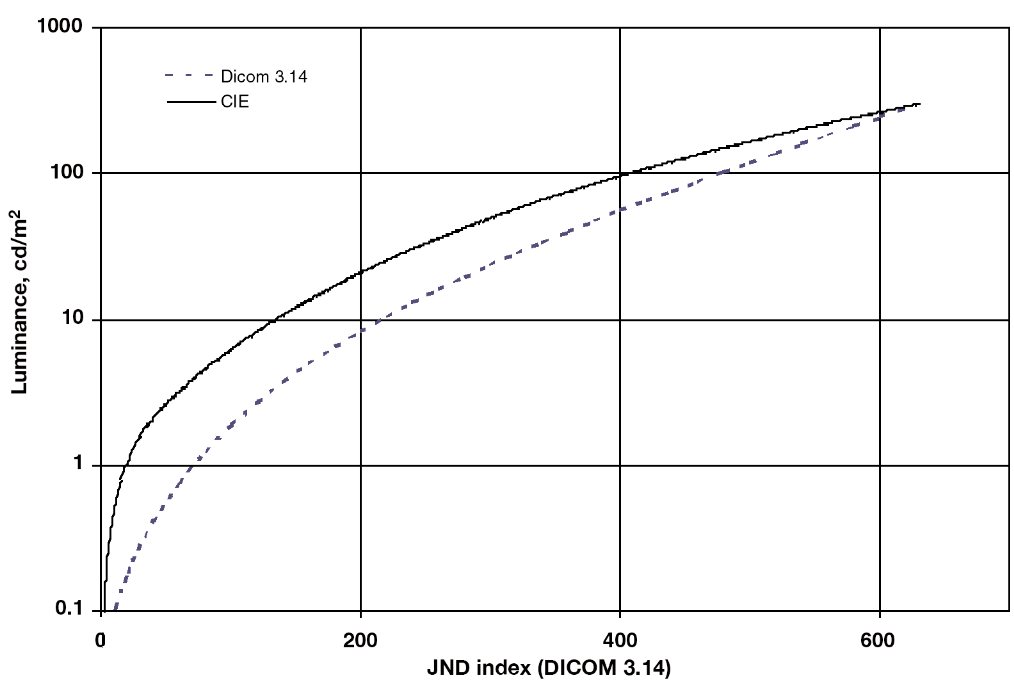


Figure 42. The DICOM 3.14 GSDF tabulates the desired luminance in relation to an index that corresponds to a just noticeable difference (JND) in brightness. For comparison, the CIELAB display function is shown for the case where L_{max} equals 300 cd/m^2.

in Figure 43, where visual contrast response under fixed adaptation conditions is seen to be worse in the bright and dark regions of an image (Flynn et al. 1999). Additionally, the GSDF reflects visual performance for a specific spatial frequency under threshold detection conditions. The performance of the human visual system for features of interest in a medical image will be different if the features have different size, spatial frequencies, and (noisy) background, or have suprathreshold contrast. For these reasons, the GSDF does not represent the luminance response that would be optimal for observing the features of a particular image. Rather, the GSDF allows an application to render an image with a specific grayscale transformation (modality LUT) with the expectation that the resulting p-values will produce similar appearance on all display systems that are both GSDF-calibrated and have the same luminance ratio.

It is worth noting that the characteristic curve of a display device (i.e., the DDL to luminance transformation) is technology and monitor dependent. Flat-panel display systems can have a complex luminance response with discontinuous changes. CRT display devices have a continuous response with luminance proportional to the input drive signal raised to a fractional power,

$$(L - L_{min})/(L_{max} - L_{min}) = [(v - v_{min})/(v_{max} - v_{min})]^{\gamma}\,, \tag{9}$$

where L is luminance, v is the video signal voltage, and γ is the dimensionless "display gamma" (Muka et al. 1995). The subscripts "max" and "min" refer to the maximum and minimum luminance or video voltage states, respectively. This intrinsic power response is primarily due

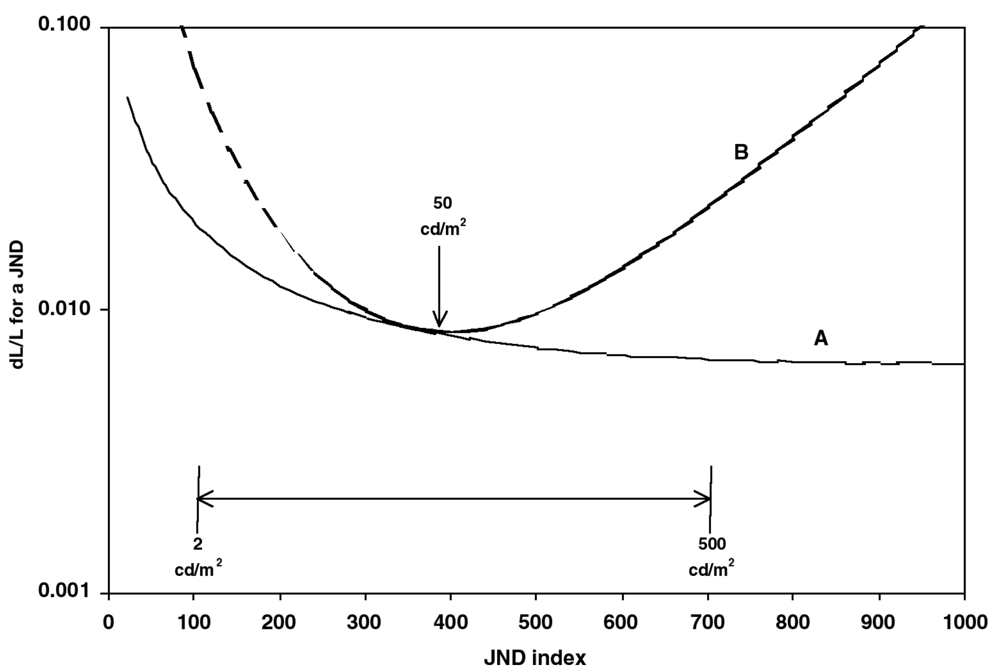


Figure 43. Contrast threshold for varied (A) and fixed (B, Flynn et al. 1999) visual adaptation. The contrast threshold, $\Delta L/L$, for a just noticeable difference (JND) depends on whether the observer has fixed (B) or varied (A) adaptation to the light and dark regions of an overall scene. $\Delta L/L$ is the peak-to-peak modulation of a small sinusoidal test pattern.

to the drive response of the electron gun in the CRT (Moss 1968). The gamma value, γ, associated with CRT devices is typically about 2.2 but can range from 1.5 to 3.0. For a particular device, care must be taken to ensure that appropriate calibration methods are used. Flat-panel systems may require that calibration data be measured for all DDL states. CRT systems with extreme gamma values may be difficult to calibrate, particularly if the number of DDL states is low (e.g., 256).

4.3.2 Quantification of Luminance Response

Visual assessment of the luminance response is done using a test pattern that has a sequence of regions with systematically varied luminance. The perceived contrast associated with the luminance change for each adjacent region will vary due to the contrast transfer characteristics of both the display device and the adapted human visual system. Test patterns that include low-contrast features within each region in the sequence can be used to provide a more sensitive indication of contrast transfer. Luminance response is evaluated by confirming the expected perceived contrast in regions of varying luminance.

Quantitative assessment of the luminance response is done using defined test patterns and luminance meters to measure the luminance response of the display device at a limited number of values. The protocol for making measurements, described in the following sections, is similar to that described in the DICOM standard (NEMA 2000, annex C). The results are then evaluated to determine the average contrast transfer characteristics based on the luminance difference between two measurements.

Complete characterization of the luminance response can be accomplished by measuring the display luminance for all possible values associated with the display controller. $\Delta L/L$ is then evaluated in relation to the desired values of DICOM 3.14. For a system supporting 1024 or 4096 DDLs, complete characterization requires that a large amount of data be acquired with very small luminance differences between each sequential data point. This is generally done automatically using a specialized software application and a luminance meter having a computer interface. If only a subset of the available levels (32–64 values) is acquired, local anomalies in the luminance response may not be revealed.

The veiling-glare characteristics of a display significantly affect the assessment of minimum luminance. This complicates the evaluation of luminance response at low luminance and of the contrast ratios. In Figure 44, the display device was first adjusted to L_{min} = 1 cd/m^2 using a full black image. The minimum luminance was then measured as a function of the percent area of the black region within which the luminance was measured, and as a function of the pixel value in the remainder of the display area. All measurements were made in a darkened room using a luminance probe (Figure 16). Figure 43 illustrates the dependence of Lmin on veiling glare for both a CRT device and an LCD device. For the methods recommended in this report, luminance is measured using DICOM standard test patterns that have specified target size and background luminance (i.e., TG18-LN test patterns, 10% central area, surround at ~0.2 L_{max}). This provides reproducible measurements of minimum luminance and contrast ratio that have similar conditions for veiling glare.

4.3.3 Visual Evaluation of Luminance Response

Visual evaluation methods can be used if a luminance meter is not available. However, it is highly recommended that the luminance response be verified using the quantitative evaluation method described in section 4.3.4.

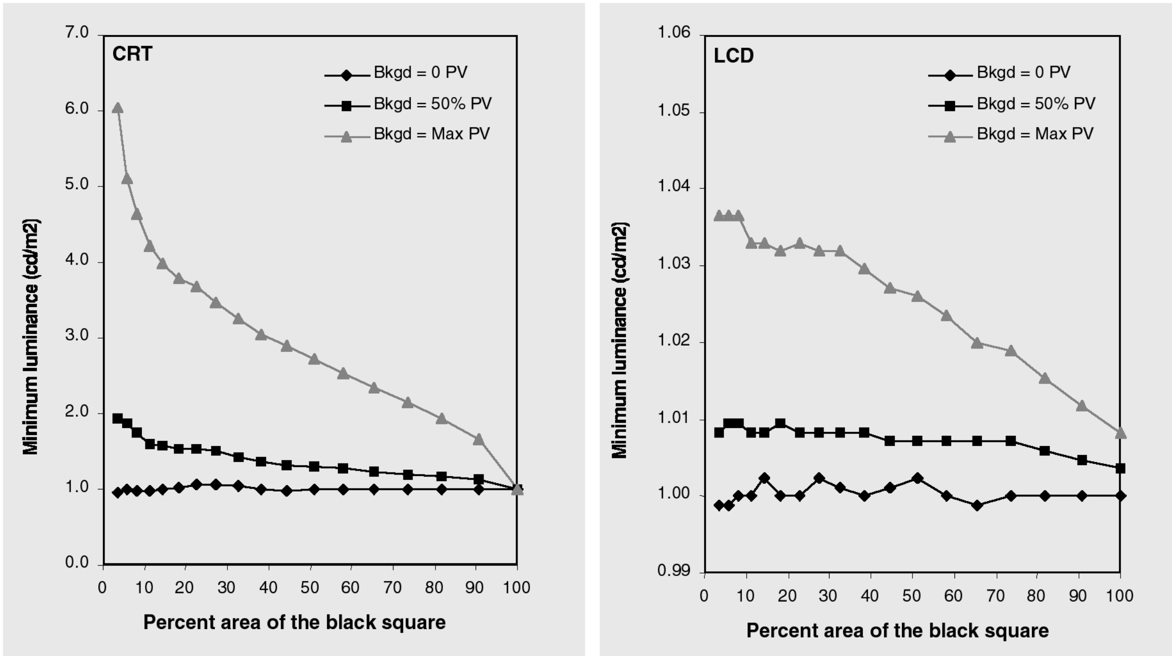


Figure 44. The dependence of minimum luminance on the size of the area within which the luminance is measured and the surround pixel value (PV) in a monochrome CRT (left) and an AMLCD (right).

4.3.3.1 Assessment Method

The luminance response of a display device is visually inspected using the TG18-CT test pattern (see section 3.2.2.1). The TG18-CT pattern should be evaluated for visibility of the central half-moon targets and the four low-contrast objects at the corners of each of the 16 different luminance regions. In addition, the bit-depth resolution of the display should be evaluated using the TG18-MP test pattern. The evaluation includes ascertaining the horizontal contouring bands, their relative locations, and grayscale reversals. Both patterns should be examined from a viewing distance of 30 cm.

4.3.3.2 Expected Response

The appearance of the TG18-CT test pattern should clearly demonstrate the low-contrast target in each of the 16 regions. Since this pattern is viewed in one state of visual adaptation, it is expected that the contrast transfer will be better at the overall brightness for which the visual system is adapted as opposed to the darkest or the brightest regions. Nevertheless, the low-contrast targets should be seen in all regions. With experience, the visual characteristics of this test pattern can be recognized for a system with quantitatively correct luminance response. A common failure is not to be able to see the targets in one or two of the dark regions. In the evaluation of the TG18-MP pattern, the relative location of contouring bands and any luminance levels should not be farther than the distance between the 8-bit markers (long markers). No contrast reversal should be visible.

4.3.4 Quantitative Evaluation of Luminance Response

4.3.4.1 Assessment Method

Using a calibrated luminance-meter and the TG18-LN test patterns, the luminance in the test region should be recorded for the 18 DDLs as described in section 3.2.2.2. The measurement of $L(p)$ using patterns other than the TG18-LN patterns may result in different values due to the influence of veiling glare. The effect of ambient illumination should be reduced to negligible levels, by using a dark cloth if necessary. To enable the evaluation of luminance differences, measurements should be made with a precision of at least 10^{-2} and ideally 10^{-3}. If a telescopic luminance meter is used, in order to minimize the influence of meter's flare on the low-luminance measurements, the measurements may need to be made through a cone or baffle to shield the instrument from the surrounding light, as described in sections 3.1.1.1 and 3.1.3. For display devices with non-Lambertian light distribution, such as an LCD, if the measurements are made with a near range luminance meter, the meter should either have an aperture angle smaller than 5° or display-specific correction factors should be applied (Blume et al. 2001) (see section 3.1.1.1).

After all luminance values have been recorded, the ambient luminance on the display faceplate (L_{amb}) should either be estimated from the measured R_d values as L_{amb} = ER_d or measured directly. In the case of direct measurement, the display device should be put in the power-save or blank screen-save mode (otherwise turned off). A telescopic luminance meter normal to the display surface is used with a light-absorbing mask placed behind the meter to minimize specular reflection from the display. Otherwise, the room lighting should be set to the conditions established for the normal use of the equipment (see section 4.3.4.2 below). The values for L'_{max} and L'_{min} should be computed by the addition of L_{amb} to the measured L_{max} and L_{min} values.

4.3.4.2 Expected Response

Acceptable responses are delineated for different aspects of the luminance response. The failure of the display device to meet these criteria should prompt repair, replacement, or recalibration of the device.

4.3.4.2.1 L'_{max}, L'_{min} and L_{amb}. The recommended value for L'_{max} is typically specified by the vendor as the highest value that can be used without compromising other performance characteristics, such as lifetime or resolution. For primary displays, that value should be greater than 171 cd/m^2 (ACR 1999). In cases where this criterion is not achievable (e.g. color CRTs used for US or nuclear medicine primary diagnosis), the primary class requirements for luminance ratio and ambient luminance (i.e., LR' = L'_{max}/ L'_{min} ≥ 250 and L_{min} ≥1.5 L_{amb} or L'_{min} ≥ 2.5 L_{amb}, as described below) should be maintained. The secondary class devices should have a maximum luminance of at least 100 cd/m^2. L'_{max} should be within 10% of the desired value for both classes of display. Furthermore, for workstations with multiple monitors, L'_{max} should not differ by more than 10% among monitors.

L'_{min} should be such that the desired luminance ratio, LR' = L'_{max}/L'_{min}, is obtained. If the manufacturer's recommendations are not available, it is recommended that the luminance ratio of a display device be set equal to or greater than 250 for all primary class devices. As a comparison, this corresponds to a film density range between 0.1 and 2.5, which is a typical range of film densities that are interpretable without the aid of a high-brightness illuminator. This ratio maintains all contrast information in an image within a luminance ratio where the eye has reasonably good response (Flynn et al. 1999). For secondary class devices, LR' should be no less than 100. In general L'_{min} should be within 10% of the nominally desired values for both classes of display.

As discussed in section 4.2, ambient lighting can impact the low luminance response of a display device and reduce the device's effective luminance ratio. A limit on the measured L_{amb} is, therefore, necessary to prevent fluctuations in room lighting from altering the contrast in dark regions of a displayed image. For both classes of display devices, L_{amb} should ideally be less than 0.25 L_{min} (or 0.2 L'_{min}). In situations where the level of ambient lighting can be strictly controlled and taken into account in the luminance calibration of the display device, a larger L_{amb} can be tolerated, but L_{amb} should always be less than $L_{min}/1.5$ (or $L'_{min}/2.5$). If necessary, arrangements should be made to reduce the room lighting in order to achieve a sufficiently small L_{amb}.

4.3.4.2.2 Luminance Response. In order to relate measured luminance values to the DICOM 3.14 standard luminance response, the gray levels (p-values) used in the 18 measurements of luminance should be transformed to JND indices. Using the DICOM's table of JND indices versus luminance, the JND indices for the measured L'_{min} and L'_{max}, J_{min} and J_{max}, should first be identified. The JND indices for the intermediate values should then be evenly spaced within the JND range and linearly related to the actual p-values used, *P,* as

$$J_i = J_{min} + \frac{P_i\left(J_{max} - J_{min}\right)}{\Delta P}, \tag{10}$$

where J indicates the JND indices. Note that in this methodology, J_i values are not those directly related to the measured luminance values per the Barten model. Figure 45 illustrates the measured luminance response for a display system that was calibrated using 256 p-values. The p-values have been converted to JND indices and the results are plotted in relation to the GSDF. As described above, the luminance response is measured in near total darkness and does not include the effects of ambient luminance. Therefore, L_{amb} should be added to all measured luminance values before comparing to the GSDF.

The expected response of quantitative measurements should be evaluated in terms of the contrast response rather than the luminance response; i.e., the slope of the measured response should agree with the slope of the standard response. Thus, the luminance difference between each measured value should agree with the expected difference associated with the GSDF. The measured data should be expressed as the observed contrast, δ_i, at each luminance step, L'_n, as a function of mean JND index value associated with that step.

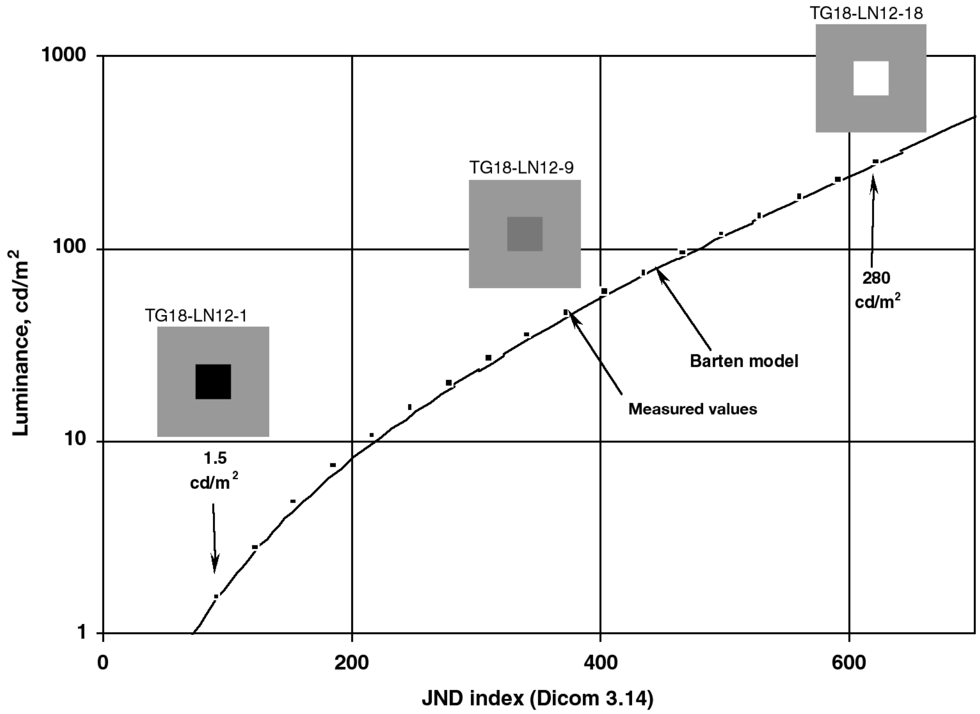


Figure 45. An example of the measured luminance for 18 display levels is plotted in relation to the GSDF. The p-values used to measure luminance have been linearly scaled to JND indices, with the values at L'_{max} and L'_{min} set to be equal to the JND corresponding indices.

$$\delta_i = \frac{2\left(L'_i - L'_{i-1}\right)}{\left(L'_i + L'_{i-1}\right)\left(J_i - J_{i-1}\right)} @ 0.5\left(J_i + J_{i-1}\right). \tag{11}$$

The expected response according to GSDF, δ^d_i, should be similarly computed as the following:

$$\delta^d_i = \frac{2\left(L^d_i - L^d_{i-1}\right)}{\left(L^d_i + L^d_{i-1}\right)\left(J_i - J_{i-1}\right)} @ 0.5\left(J_i + J_{i-1}\right) \; . \tag{12}$$

Figure 46 shows the contrast response associated with the data shown in Figure 45. As a quantitative criterion for primary class devices, the measured contrast response at any given point, $k_\delta = \text{Max}(|\delta_i - \delta^d_i|)$, should fall within 10% of the standard. This criterion applies specifically to contrast evaluated from the 18 measurements of luminance made at uniformly spaced p-value intervals. In Figure 46, the measured contrast response is slightly high at JND = 138. This is related to high luminance values seen in Figure 45 in the lower portion of the luminance response. Secondary class devices may not have a mechanism for calibrating the luminance response and thus may exhibit more deviation from the standard response. It is recommended that secondary class devices be used that can be adjusted to have a contrast response (i.e., slope) that agrees with the standard to within 20%.

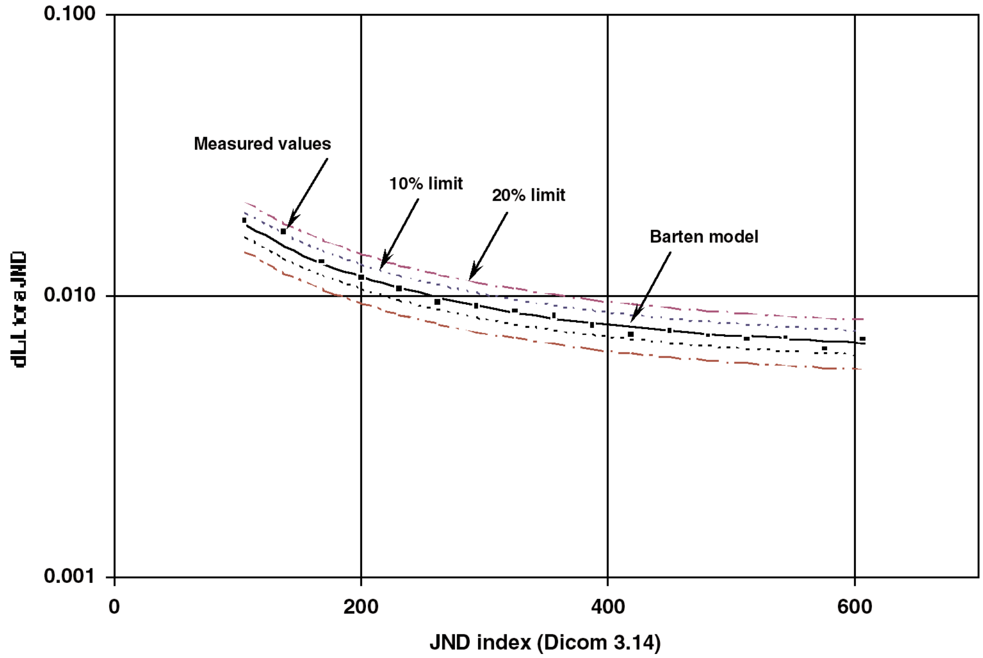


Figure 46. An example of the contrast response computed from 18 gray levels is related to the expected contrast response associated with the GSDF with 10% tolerance limits indicated.

4.3.5 Advanced Evaluation of Luminance Response

4.3.5.1 Assessment Method

A complete evaluation of the luminance response requires that the luminance be recorded for all possible luminance values that a system can use. Measurements should be made using displayed patterns similar to the TG18-LN patterns in conditions that minimize the effect of ambient illumination. The central region of the pattern should be systematically set to all possible p-values of the display controller and the displayed luminance values measured. Since the number of values can be large, these measurements will typically be performed using graphics software that can change the test region's p-value and automatically record luminance from a meter with a computer interface. Because of the need to evaluate the change in luminance for each p-value change, a luminance meter with a precision of at least 10^{-4}, and ideally 10^{-5}, should be used. To further improve measurement precision, some signal averaging may be used for each recorded value.

4.3.5.2 Expected Response

The expected response for advanced evaluations should be considered in terms of the contrast response using methods similar to those described for quantitative evaluations. The measured contrast associated with the luminance difference between each sequential gray level available from the display controller, dL'_p/L'_p, should be compared to the expected contrast per JND associated with the DICOM GSDF. The average JND indices per p-value, J_p, should first be computed by dividing the JND index difference between L'_{max} and L'_{min} by the total number of displayed luminance steps as

$$J_p = \frac{J_{max} - J_{min}}{P_{max} - P_{min}} \quad . \tag{13}$$

The observed contrast per p-value increment should then be normalized by dividing dL'_p/L'_p by J_p. The result is the observed contrast per JND, dL'_j/L'_j. This can then be compared directly to the contrast per JND defined by the DICOM standard, dL^d_i/L^d_i. Figure 47 illustrates the measured and expected contrast per JND for a calibrated device with 256 input gray levels (i.e., p-values).

Because the contrast per p-value is generally very small, significant noise can be associated with the accuracy of digital-to-analog conversion, the digital precision of the controller DAC, and other sources of electronic noise. This can be evaluated by considering the ratio of the measured contrast per JND to the GSDF contrast per JND, $(dL'_j/L'_j)/(dL^d_i/L^d_i)$. The product of this ratio and J_p is referred to as the JNDs per luminance interval. The JNDs per luminance interval should be computed for each p-value and a linear regression performed as described in DICOM 3.14 annex C. The data should be fitted well by a line of constant JNDs per luminance interval equal to J_p. The contrast noise can then be described by the maximum deviation and the root mean squared error of the observed JNDs per luminance interval values. It should be noted that

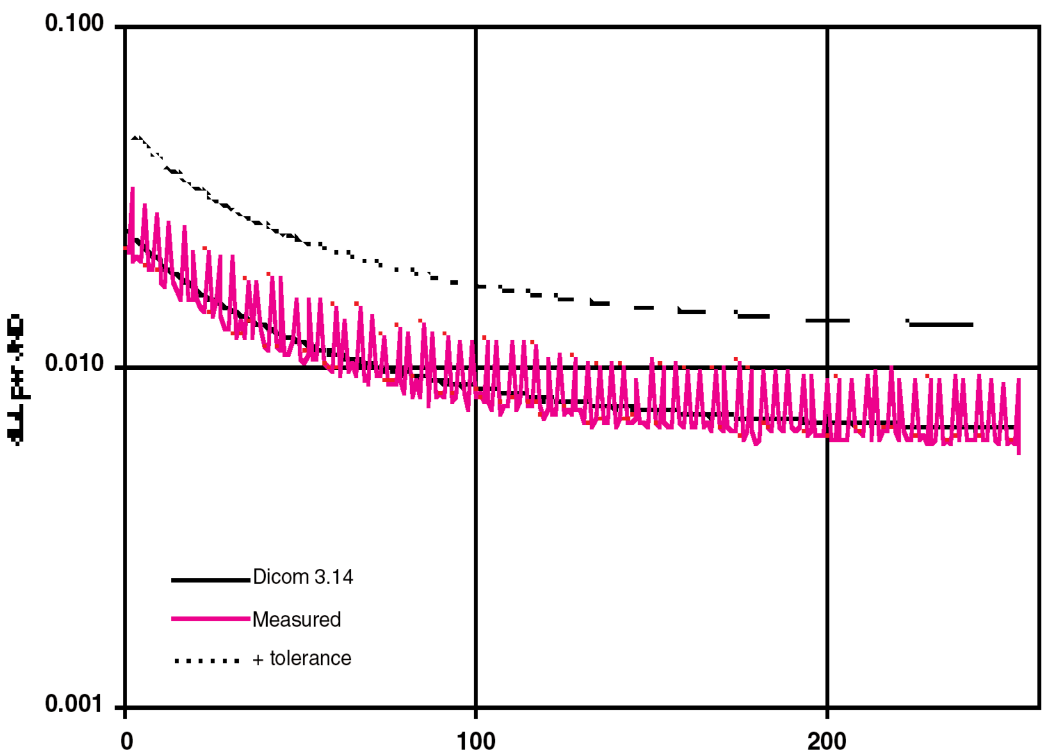


Figure 47. An example of the measured contrast, dL/L, associated with the luminance difference between each of 256 gray levels. The measured contrast has been reduced by the mean number of JND indices per gray level (p-value) and compared to the contrast per JND associated with the DICOM gray scale display function. The results characterize a monochrome LCD display having a luminance calibration derived from a set of 766 possible luminance values.

systems with few luminance values (e.g., 256) tend to have a higher contrast per p-value than systems with more luminance values (e.g., 1024 or 4096) and therefore tend to have lower noise for $(dL'_j/L'_j)/(dL^d_i/L^d_i)$. The visual performance is not better but the noise in the relative contrast is less because it is evaluated for a larger luminance change. Evaluating the contrast noise in terms of the error associated with the JNDs per luminance value removes this bias and more accurately reflects display quality.

All the criteria recommended for quantitative method above are also applicable for the advanced test. For primary class display devices, J_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 differ from J_p by more than 2.0. The root mean square deviation relative to J_p should not be larger than 1.0. No advanced criteria are specified for secondary class display devices.

4.4 Luminance Spatial and Angular Dependencies

The luminance response evaluations described in section 4.3 only relate to the luminance characteristics of a display device at one location on the display faceplate viewed perpendicularly. However, display devices often exhibit spatial luminance non-uniformities and variation in contrast as a function of viewing angle, both of which should be characterized as a part of display evaluation protocol.

4.4.1 Description of Luminance Dependencies

4.4.1.1 Non-uniformity

Luminance non-uniformity refers to the maximum variation in luminance across the display area when a uniform pattern is displayed. Luminance non-uniformity is a common characteristic of CRT displays, with the luminance typically decreasing from the center to the edges and corners of the display. Various factors cause this behavior including electron beam path length and landing angle as well as the faceplate glass transmission characteristics.

In LCDs, contributions to luminance non-uniformity include backlight non-uniformity, mura (visible non-uniformity due to imperfections in the display pixel matrix surface), latent image (i.e., image retention from previous frames), spatial constancy of color coordinates, and the thickness of the liquid crystal elements. However, luminance non-uniformities in LCDs may be less pronounced than in CRTs.

The human visual system is generally not sensitive to very low spatial frequencies. Therefore, gradual non-uniformity extending over the full display surface is not a problem, unless the variation is very pronounced. Smaller scale non-uniformities that have dimensions on the order of 1 cm are of more significance and should not be visible when viewing a uniform test pattern. Non-uniformities of smaller dimension are classified as noise and are considered in section 4.6.

4.4.1.2 Angular Dependence

The light emission from a display is ideally Lambertian, for which the luminance is independent of viewing angle. AMLCD devices are attractive as bright transilluminated devices but can suffer from severe variations in luminance as a function of viewing angle, including contrast reversal. The viewing angle problem with conventional LCD devices results from the perturbation of the orientation of the LC molecules by the electric field in the surface normal direction. At intermediate gray levels, the direction of the LC molecules (director) is tilted obliquely in the display plane and the intensity of light transmitted becomes a function of the incident angle relative to the director orientation. For higher electric fields, the director becomes predominantly normal to the surface, and the light deflection is reduced. Figure 48 illustrates the contrast ratio associated with a conventional AMLCD measured at off-axis horizontal and vertical orientations. In addition to reduction of contrast ratio with viewing angle, note that in some cases, the black luminance level for certain viewing angles can also be at a higher luminance level than the maximum luminance level due to luminance-inversion artifacts.

Three notable approaches have recently been introduced to reduce the viewing angle artifact:

1. *Retardation films:* Negative birefringence films may be placed at the entrance or at the exit (or both) of the LC structure. These films tend to compensate for the asymmetries in molecular orientation within the LC layer responsible for the angular dependencies (Hoke et al. 1997).
2. *Multidomain LCDs:* For each pixel, 2, 4, or more subpixels, each with a different orientation, may be used in the alignment layers. A multidomain design with 2 or 4 cells provides averaging of the artifact and is being widely used in the current generation of wide viewing angle AMLCD devices (Nam et al. 1997).

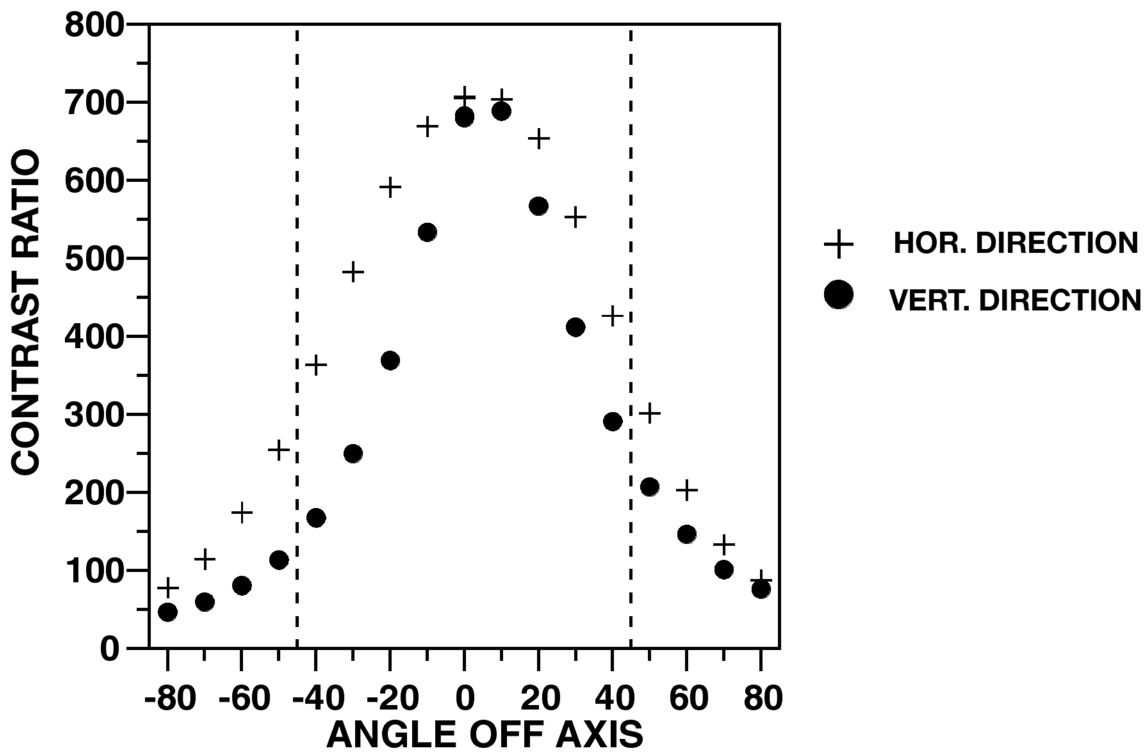


Figure 48. Maximum-to-minimum-luminance contrast ratio of the AMLCD in horizontal and vertical directions. The dashed vertical lines indicate a 90° viewing range (±45° off-axis) within which the contrast ratio average of the horizontal and vertical directions is always greater than 200 (Blume et al. 2001) (used with permission).

3. In-plane switching (IPS): Electrode pairs can be used on one side of the LC structure such that the electric field rotates the director in the plane of the display. IPS is particularly attractive in that it resolves the artifact problem at its source by maintaining the director orientations in the display plane. Electric fields are commonly provided by interdigitized electrodes formed on the entrance side of the structure (Wakemoto et al. 1997).

A multitude of combinations or variations of these approaches is now being considered and implemented into products. While the IPS method is relatively old, it is now recognized to provide excellent viewing angle performance. However, a reduced transmission of about 70% is encountered with this approach which is problematic for portable display applications.

4.4.2 Quantification of Luminance Dependencies

4.4.2.1 Non-uniformity

Luminance uniformity is determined by measuring luminance at various locations over the face of the display device while displaying a uniform pattern. Non-uniformity is quantified as the maximum relative luminance deviation between any pair of luminance measurements. An index of spatial non-uniformity may also be calculated as the standard deviation of luminance measurements within 1×1 cm regions across the faceplate divided by the mean. This regional size approximates the foveal area at a typical viewing distance. Non-uniformities in CRTs and LCDs may vary significantly with luminance level, so a sampling of several luminance levels is usually necessary to characterize luminance uniformity.

4.4.2.2 Angular Dependence

The angular response of a display is usually quantified in terms of variation in the luminance response of the display as a function of polar and azimuthal viewing angles. The values may be used to determine the variation in luminance ratio as a function of viewing angle, as well as the deviation of the luminance response from the desired on-axis response as a function of viewing orientation. The viewing angle limitation for medical use of the device should be clearly labeled on the device for optimum viewing. If multiple devices of the same design are used, it is sufficient to assess the viewing angle limits on one device. For such systems, the acceptable viewing angle cone should be used to arrange the monitors for minimum contrast reduction due to the angular dependencies of luminance.

4.4.3 Visual Evaluation of Luminance Dependencies

4.4.3.1 Assessment Method

4.4.3.1.1 Non-uniformity. The visual method for assessing display luminance uniformity involves the TG18-UN10 and TG18-UN80 test patterns. The patterns are displayed and the uniformity across the displayed pattern is visually assessed. The patterns should be examined from a viewing distance of 30 cm.

4.4.3.1.2 Angular Dependence. Angular response may be evaluated visually using the TG18-CT test pattern. The pattern should first be viewed on-axis to determine the visibility of all half-moon targets. The viewing angle at which any of the on-axis contrast thresholds are rendered invisible should then be determined by changing the viewing orientation in polar and azimuthal changes. Alternatively, a uniform test pattern with uniformly embedded test targets may be used. The viewer distance at which all targets along the axial or diagonal axes are visible may be used as an indication of the angular response performance of the display.

4.4.3.2 Expected Response

4.4.3.2.1 Non-uniformity. The patterns should be free of gross non-uniformities from the center to the edges. CRTs typically exhibit symmetrical non-uniformities, while LCD displays exhibit nonsymmetrical non-uniformities. No luminance variations with dimensions on the order of 1 cm or larger should be observed.

4.4.3.2.2 Angular Dependence. The viewing angle cone within which the TG18-CT test targets remain visible is the cone within which the device may be used clinically. The established viewing angle limits should be clearly labeled on the front of the display device. For multiple-monitor workstations, the LCDs should be adjusted such that the displays optimally face the user.

4.4.4 Quantitative Evaluation of Luminance Dependencies

4.4.4.1 Assessment Method

4.4.4.1.1 Non-uniformity. Using the TG18-UNL10 and TG18-UNL80 test patterns, luminance is measured at five locations over the faceplate of the display device (center and four corners) using a calibrated luminance meter. If a telescopic luminance meter is used, it may need to be supplemented with a cone or baffle, as described in sections 3.1.1.1 and 3.1.3. For display devices with non-Lambertian light distribution, such as an LCD, if the measurements are made with a near-range luminance meter, the meter should have a narrow aperture angle, otherwise certain correction factors should be applied (Blume et al. 2001) (see section 3.1.1.1). The maximum luminance deviation for each display pattern is calculated as the percent difference between the maximum and minimum luminance values relative to their average value, $200^*(L_{max} - L_{min})/(L_{max} + L_{min})$.

4.4.4.1.2 Angular Dependence. The luminance of an LCD display may be quantitatively evaluated as a function of viewing angle. This can be done with two basic approaches: the conoscopic and the gonioscopic methods. In the conoscopic method, a cone of light coming from the display is analyzed with special transform lenses (Fourier optics) and two-dimensional array detectors. This method provides a fast and complete description of the angular variations of the luminance and chromaticity levels, but the measuring equipment is usually expensive and more useful in development laboratories. In the gonioscopic approach, a focused luminance probe with a small acceptance angle is oriented toward the display to reproduce a given viewing direction. The method is flexible and versatile and can be easily implemented in a clinical environment.

A basic test should include the evaluation of luminance ratio as a function of viewing angle using the TG18-LN test patterns. For this measurement, it is useful to have a subjective understanding of the viewing angle dependence, as illustrated in Figure 48, to determine the specific horizontal and vertical angles at which quantitative measurements should be made. If the needed instrumentation for angular measurements is readily available, it is best to determine the angular luminance variations of a display at 18 luminance levels using a conoscopic device or equivalent and TG18-LN test patterns.

4.4.4.2 Expected Response

4.4.4.2.1 Non-uniformity. The maximum luminance deviation for an individual display device should be less than 30%. This large tolerance limit is recommended based on the current state of display technology. For CRTs, imposing a restricted criterion necessitates an increased beam current at off-center locations, which further increases the spot size and consequently degrades the resolution toward the edges of the display. For LCDs, non-uniformities arise from non-uniformity of the backlight, as well as that associated with the LC array. However, it should be recognized that in a display device with up to 30% luminance non-uniformity, the luminance response over some areas of the image might not comply with GSDF. Measured responses outside the acceptable range should prompt corrective actions, repair, replacement, or readjustment of the display device.

4.4.4.2.2 Angular Dependence. Ideally, the angular response of a display should not reduce the luminance ratio by more than 30%. Thus, an acceptable viewing angle cone can be defined within which LR' is greater than 175 (250×0.7) for primary displays and 70 (100×0.7) for secondary displays (Samei and Wright 2004). If the luminance in midluminance values is measured, the angular luminance results should be evaluated the same way they are processed for on-axis measurements, described in section 4.3, to evaluate conformance to the GSDF. Figure 49 shows examples of luminance plots and corresponding contrast response for typical CRT and AMLCD displays as a function of viewing angle. The contrast response for any viewing angle should not be greater than three times the expected limits on axis ($k_\delta \leq 3 \times 10\% = 30\%$ for primary displays, $k_\delta \leq 3 \times 20\% = 60\%$ for secondary displays) (section 4.3.4.2). For a display device, both LR' and k_δ requirements should be met. The established viewing angle limits (ascertained either visually or quantitatively) within which the contrast response is acceptable should be clearly labeled on the front of the display device. For multiple-monitor workstations, the LCDs should be adjusted such that the displays optimally face the user.

4.4.5 Advanced Evaluation of Luminance Dependencies

4.4.5.1 Assessment Method

4.4.5.1.1 Non-uniformity. In the advanced method, the index of spatial non-uniformity is determined from a digital image of the faceplate captured using a digital camera. The image is divided into 1×1 cm regions. The mean of the luminance value within each block is computed and the maximum luminance deviation computed as described above using the maximum and minimum values. Next, a low order two-dimensional fit is applied to the 1×1 cm luminance values to estimate the broad trend within the data. The deviation of the luminance values from this trend is then computed. The intermediate-scale non-uniformities are described as the maximum deviation from the broad trend. The measured data should be corrected for the non-uniformity associated with the camera itself and angular luminance characteristics of the display, notably for LCD devices.

4.4.5.1.2 Angular Dependence. If the needed instrumentation for angular measurements is readily available, it is best to analyze the angular luminance variations of displays to determine the available contrast at all luminance levels. To achieve this, one approach is to measure the luminance emission from the displays using a rotating arm with the rotation axis lying in the plane of the display surface. The luminance probe used must have a small acceptance angle and

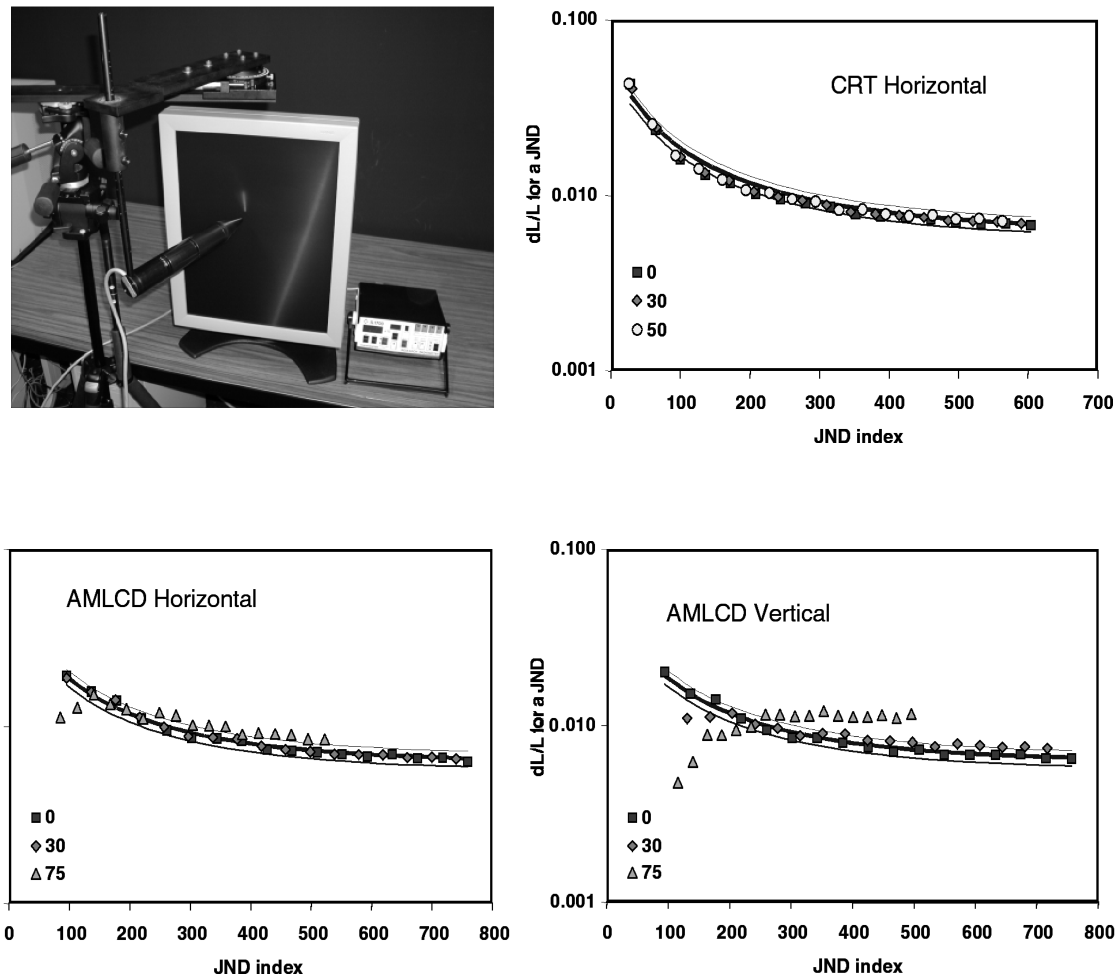


Figure 49. Measurement setup for assessing angular dependency (a). An example of luminance plots and corresponding contrast (expressed as dL/L per JND) response along the horizontal direction for a medical imaging 5-megapixels CRT monitor at three different angles (0°, 30°, and 50°) (b), and for a monochrome high-resolution AMLCD monitor along the horizontal (c) and vertical (d) directions. Thin lines indicating the 10% tolerance based on the DICOM GSDF limits (thick lines) specified for normal viewing have been added for comparison. For the CRT, the results for negative angles along the horizontal, and for all vertical angles are essentially similar due to the rotational symmetry of the CRT phosphor emission. That is not the case for the AMLCD.

must be shielded from light coming from other angular directions, since as the probe rotates it comes closer to the display and can be sensitive to light coming from outside the desired spot. Alternatively, the measurements may be made using a conoscopic device.

4.4.5.2 Expected Response

4.4.5.2.1 Non-uniformity. The contrast threshold of the human visual system is about 0.03 for frequencies of 0.5 cycles per cm at a close viewing distance of 30 cm (~0.3 cycles/degree) at typical display luminance levels. The requirements for the maximum deviation of the intermediate-scale non-uniformities are derived by requiring that the index be less than half of this contrast. Thus, the maximum relative deviation should be less than 0.015.

4.4.5.2.2 Angular Dependence. No advanced requirements have been established for angular dependencies of medical displays.

4.5 Display Resolution

4.5.1 Description of Display Resolution

Spatial resolution is the quantitative measure of the ability of a display system to produce separable images of different points of an object with high fidelity. Systems designed with adequate spatial resolution characteristics are necessary to assure that spatial details of interest are preserved when a medical image is displayed. Portraying image data on a display with insufficient resolution will compromise the accuracy of the radiological interpretation.

The resolution limitation imposed by the limited bandwidth of the video amplifiers in CRTs is primarily evident in the horizontal direction; in the vertical direction, the resolution is primarily governed by electron optics. The described mechanisms significantly contribute to the anisotropic resolution properties of CRT display devices: the magnitude of the modulation transfer function (MTF) in the horizontal direction is typically lower than in the vertical direction. Consequently, a vertical line is often rendered with lower luminance compared to the respective horizontal line. The more the signal magnitude after the video amplifier is reduced, the higher becomes the energy reduction and, thus, display luminance. Even in properly designed high-resolution display systems, the directional dependence of resolution is noticeable. Because of the typically large difference in modulation transfer function between vertical and horizontal directions, some CRTs utilize resolution restorations using anisotropic filtering. In testing a CRT display, it is useful to know the resolution restoration methodology of the device before hand.

4.5.2 Quantification of Display Resolution

Limiting resolution and maximum perceivable contrast at the limiting resolution are two ways that the spatial resolution response of a display system can be characterized. Resolution is more formally quantified by the MTF of the display. The MTF is defined as

$$MTF(f_x,f_y) = |P(f_x,f_y)|/P(0,0) \ , \tag{14}$$

where $|P(f_x,f_y)|$ is the modulus of the Fourier Transform of the imaging system's point spread function, $P(x,y)$ (Gaskill 1978, Barrett and Swindell 1981). Note that $MTF(f_x,f_y)$ is normalized to unity at the spatial frequencies of $f_x = f_y = 0$ lp/mm. Most commonly the user quotes the MTF response at the Nyquist frequency. For a CRT with a pixel size of d_x in x-direction and d_y in y-direction, the respective Nyquist frequencies are $f_{Ny,x} = 1/(2^*d_x)$ and $f_{Ny,y} = 1/(2^*d_y)$.

The MTF is applicable only to linear or quasi-linear imaging systems. Most display devices, including CRT displays, have a nonlinear luminance response and a nonlinear relationship between resolution and luminance. To correctly apply the use of the MTF in testing, the display system response must be made linear, or the measurements must be made using small-signal modulations such that a linear assumption is reasonable for the range being used. The former is difficult, since the luminance response of a display system is often dependent on the spatial frequency content of the image being displayed. Thus, the MTF measurement should rely on the latter approach.

The MTF of a display system can be obtained using different methods based on the ability of the system to display square wave patterns, a line, an edge, a single pixel, or white noise input (broadband response) (Weibrecht et al. 1997). The methods vary in their level of difficulty to implement and generate slightly different results. The method of broadband response is perhaps the most labor intensive one in which the noise power spectra (NPS) of a displayed white noise pattern are measured and averaged many times. The line response is perhaps the easiest and most intuitive method. Research on the advantages of any one method over others is still in progress. The line method provides a simple and fairly accepted method for the assessment of the MTF of display systems and, thus, is recommended in this report. However, other methods can be considered in advanced evaluations.

4.5.3 Visual Evaluation of Display Resolution

4.5.3.1 Assessment Method

Display resolution can be evaluated by visually assessing the appearance of the Cx patterns in the TG18-QC or the TG18-CX test patterns. In displaying these patterns, it is important to verify that that the patterns are displayed as one display pixel per image pixel, as any digital magnification will hide the actual response. Most image viewers have function to accomplish this display mode. In order not to be limited by the MTF of the eye, use of a magnifying glass is recommended. Using the TG18-QC pattern and a magnifier, the examiner should inspect the displayed Cx patterns at the center and four corners of the display area and score the appearance using the provided scoring scale. The line-pair patterns at Nyquist and half-Nyquist frequencies in the horizontal and vertical directions should also be evaluated in terms of visibility of the lines. The average brightness of the patterns should also be evaluated using the grayscale step pattern as a reference. The difference in visibility of test patterns between horizontal and vertical patterns should be noted. The relative width of the black and white lines in these patches should also be examined using a magnifier. The resolution uniformity may be ascertained across the display area using the TG18-CX test pattern and a magnifier in the same way that the Cx elements in the TG18-QC pattern are evaluated.

Alternatively, the resolution response can be visually assessed using the TG18-PX test pattern. The pattern should be displayed so that each image pixel is mapped to one display pixel. Using a magnifier with a reticule, the physical shape and size of a few pixels in different areas of the pattern at the center and the corners are evaluated. The size of the maximum-brightness pixels should be measured at approximately 50% and 5% of luminance profile (Figure 4c). The resolution-addressability ratio (RAR) is assessed as the ratio of the 50% size (FWHM) and the nominal display pixel size. If notable astigmatism is present at the corners of the active display area, the astigmatism ratio, or the ratio of the large versus short axis of the spot ellipse should be measured. It should be noted that this method of resolution measurement requires experience to achieve consistent results.

4.5.3.2 Expected Response

In the visual inspection of the TG18-QC and TG18-CX patterns on primary class display systems, the Cx elements should be scored between 0 and 4 at all locations. This limit coincides with RAR ≤ 1.15 (Table III.9). For secondary class displays, the Cx scores should be between 0 and 6 (RAR ≤ 1.47). For both classes, the horizontal and vertical line-pair patterns at Nyquist frequency should be discernable at all locations and for all directions.

In CRTs, it is normal for the performance at the center to be better than that at any corner due to natural deflection distortions. Also, the horizontal line-pair patterns at Nyquist frequency usually appear overall slightly brighter than the vertical patterns because the vertical patterns contain a higher percentage of rise/fall time per pixel, delivering less beam energy to the phosphor screen. At the Nyquist frequency, the difference in the average luminance should be less than 30%. A difference more than 50% indicates a slow video amplifier not well suited for the matrix size. The vertical and horizontal line-pair patterns at half-Nyquist frequency should show less of a luminance difference since the vertical patterns contain two pixels per line, providing more dwell time for the electronic beam. A significant difference between the thicknesses of the black and white lines is also indicative of a poorly shaped pixel with excessive spread of the pixel, which diminishes the black content.

In evaluating the display resolution using the TG18-PX test pattern on CRTs, the pixel shapes should be nearly round, indicating a close match of the optics and video bandwidth. The pixel should show a near-Gaussian distribution of luminance, indicating symmetrical rise and fall times. Improper damping of the video amplifier or overshoot phenomena cause distortions that can be described as crescent-shaped echoes and/or comet tails following the intended pixel. The size of the pixel profile at 50% of the maximum should compare closely to manufacturer's specification. The 5% size should be about twice the 50% size (Figure 4). Larger 5% sizes cause notable display resolution loss due to the increase in pixel overlap. The RAR should be between 0.9 and 1.1 for primary class displays (Muka et al. 1997). This range provides a balance between a structured appearance (e.g., raster lines visible) and an excessive resolution loss. The maximum astigmatism ratio should be less than 1.5 over the display area for primary class displays. For LCDs, the pixel intensity should not extend beyond the nominal pixel area.

4.5.4 Quantitative Evaluation of Display Resolution

4.5.4.1 Assessment Method

4.5.4.1.1 MTF Method. Quantification of the MTF requires the use of a displayed-image digitizing system, such as a digital camera, to digitally capture a portion of the display and to analyze the resulting images, as described in section 3.1.2. The lens of the camera should be set to a high f-number in order to reduce the flare of the camera lens. The flare should also be further reduced with the aid of a cone or funnel device. The magnification of the lens should result in oversampling of the display. At least 64 camera pixels should cover one display pixel (i.e., 8×8 recorded pixels per displayed pixel). The camera needs to be well focused on the screen of the display under test. This is best done when the lens aperture is opened to its maximum level. In this position, the depth of focus is small and the line width is very sensitive to the focus control. Afterward, the lens aperture is set to its smallest level in order to achieve a large depth of focus and minimum flare. Large depth of focus is particularly important in view of the thickness nonuniformities of the CRT's faceplate.

The TG18-RV, TG18-RH, and TG18-NS patterns provide line inputs as target patterns for the MTF measurements. These patterns allow the assessment of MTF in the horizontal and vertical directions at three luminance levels and five locations on the display area. At each location, the camera should be securely positioned in the normal direction in front of the target area of the display and focused on the line. The magnification should be determined in accordance with the display pixel size, camera matrix size, and the desired oversampling. The camera field of view should include the pixel markers in the pattern. While the camera should be placed in a normal direction with respect to the faceplate, it needs to be rotated parallel to the faceplate such that the camera pixel array is angled at 2° to 5° with respect to the displayed image, in order to provide appropriate oversampling. After the camera is properly positioned and focused, images from all six patterns should be captured before moving the camera to the next location. The exposure time should be selected such that the digital signal of the camera exceeds the dark signal by a factor of 100. Furthermore, the exposure time should be long enough to permit integration over multiple display frames, but short enough with respect to instabilities of the scanning and deflection circuits. Ultimately the integration time should be appropriate with respect to the integration time of the human eye, for which the experiments are conducted. Integration times between 0.2 s and 1 s are appropriate to use. The measurements should be made in a darkened room.

The 30 images should be acquired without any image compression. The data should be transferred to a computer for data processing. The captured line patterns should be reduced to orthogonal MTFs using Fourier analysis. There are several processing steps in the calculations, and the results are expected to vary slightly with the methods. For standardization and simplicity the following steps are suggested:

1. Determine the size that the image pixels represent in terms of the spatial dimension on the display using the known physical distance of the pixel markers on the patterns and the measured pixel distance of the markers in the captured images.
2. Linearize the image data with respect to display luminance using the luminance response of the display (characterized in section 4.3).
3. Add the mean value of the image from the TG18-NS to that of the TG18-RV (or TG18-RH) pattern, and subtract the TG18-NS image pixel by pixel from the TG18-RV (or TG18-RH) image in order to remove display pixel structure. Averages of multiple images may be used for more complete removal of structured noise. The subtracted image is used for further processing.
4. Identify a rectangular square region of interest (ROI) extending along the image of the line.
5. Determine the angle of the line.
6. Reproject the two-dimensional data within the ROI along the direction of the line into subpixel bins to obtain the composite line spread function (LSF).
7. Smooth the LSF if it expresses excessive noise.
8. Find the Fourier transform of the LSF, and normalize the resulting MTF.
9. Divide the MTF by the sinc function associated with the width of the LSF subpixel bins, and correct for the previously characterized MTF of the camera system (see section 3.1.2).

Note that in some cases the LSF might be asymmetric. In those cases, each side of the LSF is used to form two symmetric LSFs. The resultant MTFs are reported along with their average as representative of the display resolution.

4.5.4.1.2 Luminance Method. Particular to CRTs, another more limited but simpler method to quantitatively characterize the resolution of a display system is based on luminance measurements performed on the line-pair patterns of the TG18-QC test pattern. The method does not provide absolute measures of luminance; rather it provides the resolution differences in the orthogonal directions. Using a telescopic luminance meter focusing on the entire central patch with the 100% modulation horizontal line-pair pattern, measure the average luminance of the patch. Repeat the measurement on the adjacent vertical line-pair patch, and calculate the percent difference between the two luminance values relative to the maximum measured luminance value. Repeat the procedure for all four corners. The values are indicative of the CRT's resolution characteristics, i.e., inadequacy of the rise and fall times that define the pixels in the horizontal direction.

4.5.4.2 Expected Response

Acceptable responses are delineated for each one of the quantitative methods described above. Measured responses outside the acceptable range should prompt corrective actions in the form of focus adjustments, repair, or replacement of the device.

4.5.4.2.1 MTF Method. Values of the measured MTF at the Nyquist frequency should be at least 35% for primary display devices and 25% for secondary devices. More comprehensive quantitative criteria for the MTF are expected to be determined from future clinical experience.

4.5.4.2.1 Luminance Method. In assessing the resolution of a display device using the luminance method, the percent luminance difference at the center should be less than 30% for primary class display systems and 50% for secondary class systems. The corners always yield lower values than the center, as the extent of the corner pixels are influenced by the spread in the electron energy due to a nonperpendicular beam-landing angle.

4.5.5 Advanced Evaluation of Display Resolution

4.5.5.1 Assessment Method

As an advanced method, the MTF of a display system can be assessed using the other measurement methods mentioned in section 4.5.2. The following is a brief summary of these methods. The interested readers should consult the stated references.

In the square-wave response method, small-amplitude square waves of different spatial frequencies are displayed in the horizontal and vertical directions and their responses are recorded. The MTF or sine-wave response is found from the square-wave response by Fourier series analysis. Finding the MTF from the square wave is practically like finding it point by point, frequency by frequency from the ratio of the output modulation (peak-to-peak amplitude) to the input modulation. The advantage of using square-waves comes from the fact that (1) it is difficult to make good sine waves digitally, and (2) square waves are composed of a multitude of sine waves, so one can take advantage of the multitude of harmonics.

The line response method is described above for positive single-line profiles, where a single line is displayed on an otherwise darker background. The same method can be applied to negative single-line profiles, where a single line is displayed at a low luminance value on an otherwise uniformly bright background (Weibrecht et al. 1997). The small signal requirement should still be met. The profiles of single lines are determined and the MTF is found from the one-dimensional Fourier transform of the line profiles.

The MTF can also be determined from the edge-spread function (ESF) of the system. The ESF is not spatially limited and truncation errors occur if the discrete Fourier transform (DFT) is directly applied to it. To make the ESF spatially limited, it is typically differentiated to obtain the LSF and the MTF, deduced by Fourier transform methods. Unlike the line response method, which provides the average MTF of the system, the edge response method can quantify the MTFs for asymmetrical LSF. However, the edge response method requires a spatial-derivative operation, which accentuates noise in the analysis. This noise may be reduced if the MTF is obtained using multiple edge images. The small signal requirement should still be met.

In the single-pixel response method, images of single positive (or negative) pixel profiles against otherwise dark (or bright) backgrounds are captured via a digital camera (Weibrecht et al. 1997). The MTF is found from the two-dimensional Fourier transform of captured pixel profiles. Note that for the case of single-line and single-pixel profiles, the results are different depending on the polarity of the signal contrast applied because of the differing relative contribution of multiple pixels as well as the display's veiling glare.

In the broadband response method, the display system's response to white stochastic signals is assessed. This method can be implemented only under conditions of a linear approximation, i.e., small signal amplitudes, since the energy of the stochastic signals can be spread over large measurement areas. Furthermore, stochastic signals may be a convenient close representation of real medical images. The basic idea of the stochastic approach makes use of the fact that the signal power spectrum (SPS) found at the output of a linear, noise-free system, $\Phi_{out}(f)$, is the signal power spectrum of the input signal, $\Phi_{in}(f)$, weighted by the squared magnitude of the transfer function, $|H(f)^2|$ (Gaskill 1978) as

$$\Phi_{out}(f) = |H(f)|^2 \, \Phi_{in}(f) \ . \tag{15}$$

Thus, the MTF is given by the normalized square root of the ratio of the output SPS and the input SPS. This ratio is also called the *broadband response*. The broadband response technique is perhaps the most cumbersome, yet precise method for measuring the spatial resolution of a display system.

4.5.5.2 Expected Response

The expected requirements for the advanced measurements of display resolution characteristics have not yet been established.

4.6 Display Noise

4.6.1 Description of Display Noise

The detectability of small objects and objects of low contrast in medical images depends not only on their size and contrast but also on the superimposed noise and noise in the immediate surroundings. Noise in the context of this report is defined as any high-frequency fluctuations/patterns (< 1 cm) that interfere with the detection of the true signal. Note that not only do the frequency components of the noise that occur below the display's Nyquist frequency deteriorate the image quality, but higher frequency components up to the human visual system resolution limit also contribute to the noise impression. In this definition of noise, very low frequency fluctuations (> 1 cm) are excluded, as they are usually perceived as non-uniformity rather than as noise and are classified under luminance non-uniformity, discussed in section 4.4.

CRT displays have several noise sources such as electronic noise, stochastic noise in the conversion of the video signal to photons, and structured noise. Thus, CRT display system noise has both temporal and spatial components. The temporal component behaves similar to quantum noise and appears to be determined by random fluctuations in the number of luminescence photons detected by the human eye (Roehrig et al. 1990). Spatial noise is a fixed-pattern noise that stems from the granular structure of the CRT phosphor screen. Typically, temporal noise is small compared to spatial noise, except at the lowest luminance levels. The signal-to-noise ratio (SNR) of spatial noise is usually independent of the luminance level. P45 screens usually add less noise to a displayed image than P4 or P104 screens as discussed in sections 2.3.1.1 and 2.4.8.

Noise also exists in flat-panel displays. Noise in flat-panel AMLCDs, both temporal and spatial, can arise from variations in luminance within the active area of the pixel. Such variations can be from non-uniformities in the applied electrical field due to electrode fabrication methodology and physical placement, and from unwanted variations in the input signal due to voltage fluctuations and electronic noise. They can also be caused by the intentional specification of subpixels driven at slightly different luminance levels to achieve a greater number of gray values. Three subpixels are commonly used and individually addressable, so three regions of luminance differences may exist within one full pixel's active area. Furthermore, in order to achieve a uniform thickness of LC material with AMLCD (needed in order to ensure consistent optical properties), inert glass beads are often, but not always, placed between the front and back glass panels. These beads normally transmit light and generate small spots of light in a dark screen for normally black displays. Their impact is small and may be generally discounted.

Noise can also be caused by variations in uniformity of luminance, taking into account the pixel structure. Each AMLCD pixel has a surrounding inactive area, which causes a structured pattern in the active display. The pattern can take many forms depending on the size, shape, and architecture of the pixels. Regardless of the source of noise in flat panels, the specification of its presence and assessments of its impact are similar to those for CRT devices.

4.6.2 Quantification of Display Noise

Spatial noise of a display system can be described by the normalized noise power spectrum (NPS) of the system. The noise power is derived from the discrete Fourier transform of displayed uniform images, $I(i,k)$,

$$n(u,v) = \sum_{j=0}^{m-1}\sum_{k=0}^{n-1} I(j,k)\cdot e^{2i\pi ju/m}\cdot e^{2i\pi kv/n}, \qquad (16)$$

where j and k are pixel indices, m and n are the number of samples representing the image in horizontal and vertical directions, and n(u,v) is the noise amplitude for the frequency components u and v. The noise power spectrum is defined as

$$NPS(u,v) = \frac{1}{mn}E\{|n(u,v)|^2\}\ , \qquad (17)$$

where $E\{|n(u,v)|^2\}$ is the expectation value of the function $|n(u,v)|^2$, determined by averaging the noise spectra from different areas of the screen image (Gaskill 1978, Dainty and Shaw 1974). The NPS is normalized by the respective signal power. Noise power is presented by a two-dimensional graph or a plot of one-dimensional slices of the two-dimensional data along a particular direction. Noise power is often expressed in square millimeters by multiplying the normalized NPS by the area of individual samples.

While temporal noise can be characterized with the aid of a photomultiplier or a detector with a time response relevant to the human visual system (i.e., 8 Hz) (Roehrig et al. 1990b, 1993), it has not been shown to be of great concern in medical display devices and, thus, is not addressed in this report.

4.6.3 Visual Evaluation of Display Noise

4.6.3.1 Assessment Method

The visual method to quantify the spatial noise of a display system is based on the method to determine just noticeable luminance differences as a function of size using the TG18-AFC test pattern. Each quadrant of the test pattern contains a large number of regions with varying target position. In each quadrant, the contrast and size of the target are constant. The contrast-size values for the four quadrants are 20-2, 30-3, 40-4, and 60-6. The observer views the patterns from a viewing distance of 30 cm. The quadrants can be subjectively evaluated to establish the contrast-size relationships for which the observer can confidently place the position of all targets. The target visibility in each of the target regions may also be quantified by counting the number of targets readily visible in each of the quadrants and computing the percent correct.

4.6.3.2 Expected Response

The visual evaluation should render all the targets except the smallest one visible for primary class displays and the two largest sizes visible for secondary class displays. Since the mean value and the standard deviation of the background are each linearly dependent on the luminance, their ratio (i.e., SNR) remains independent of luminance (Roehrig et al. 1990b, 1993). Therefore, the results of the noise evaluation are independent of the absolute luminance value of the pattern's background. However, the failure of a device in this test can also be an indication of an improper luminance response, the possibility of which can be eliminated by first verifying the proper luminance response of the device.

4.6.4 Quantitative Evaluation of Display Noise

4.6.4.1 Assessment Method

Spatial noise of a display system can be quantified by either single-pixel signal-to-noise ratios or by the normalized NPS. Both methods require the use of a scientific-grade digital camera (see section 3.1.2.1) to capture an image of a uniform pattern displayed on the device. The camera lens should be set to a high f-number in order to reduce veiling glare in the camera. Also, the magnification of the lens should result in oversampling of the display in a way that allows sampling of spatial frequencies up to 40 cycles per degree, which is the resolution limit of the human visual system at the maximum luminance of most electronic displays (Rose 1974). As an example, when evaluating a 21-in. display with a matrix size of 1726×2304 at 250 mm distance, the

Nyquist frequency corresponds to about 12.4 cycles/deg. Evaluation of noise up to this limit requires sampling frequencies to at least 40/12.4 = 3.2 times the Nyquist frequency of the display. To achieve this, at least 16 camera pixels should cover one display pixel. The camera images should also be flat-field corrected, compensated for gain variations, and restored for the degradation of the MTF of the camera optics based on the prior performance evaluation of the camera system, noted earlier.

The central region of the TG18-NS test patterns can be used as the target uniform pattern for both measurements at three luminance levels. The camera should be securely positioned in front of the target area of the display and focused. The field of view should include the pixel markers in the pattern. The magnification should be determined in accordance with the display pixel size, the camera matrix size, and the desired oversampling. After the camera is properly positioned and focused, images from all three TG18-NS patterns will be captured. To eliminate the effects of temporal fluctuations in the luminance output, images should be captured with an integration time of about 1 s. The measurements should be performed in a darkened room. The images should be transferred uncompressed to a computer for data processing.

4.6.4.1.1 Single-Pixel SNR. The quantification of the display noise by the single-pixel SNR follows the concepts of information theory (Roehrig et al. 1990b). The quantity is determined by processing each captured image using the following steps:

1. Determine the size that the image pixels represent in terms of the spatial dimension on the display using the known physical distance of the pixel markers on the pattern and the measured pixel distance of the markers in the captured image.
2. Linearize the image data with respect to display luminance.
3. Utilizing only the central 1/4 area of the image, apply a sampling aperture of $n \times n$ camera pixels, where n is the number of camera pixels representing one display pixel.
4. Calculate the SNR as the ratio of the mean to standard deviation in the sampled image.
5. Correct for the camera noise. Based on the assumption that the camera noise and the display spatial noise are uncorrelated, the SNR based on the mean and standard deviation of sampled camera images without exposure using the same integration time may be subtracted from the SNR value computed in step 4 to determine the SNR independent of the camera.

4.6.4.1.2 Noise Power Spectrum. The captured uniform patterns are processed to acquire the NPS at three luminance levels using Fourier analysis. Multiple processing steps are involved, and the methods can vary the results slightly. For standardization and simplicity, the following steps are suggested for processing each captured image:

1. Determine the size that the image pixels represent in terms of the spatial dimension on the display using the known physical distance of the pixel markers on the pattern and the measured pixel distance of the markers in the captured image.
2. Linearize the image data with respect to display luminance.
3. Divide the central 1/4 region of the captured image into multiple, nonoverlapping regions, 128×128 or 256×256 in size. The size of these regions determine the sampling interval of the resulting NPS. Depending on the exact level of magnification (oversampling) and the matrix size of the camera, between 9 to 64 regions may be identified. It is recommended that at least 20 regions be used for the assessment of the NPS. To

achieve this, it might be necessary to acquire multiple images from the central patch of the TG18-NS pattern by orienting the camera toward another, nonoverlapping area of the central area of the displayed pattern.

4. Apply a two-dimensional fast Fourier transform on each region to yield the two-dimensional NPS.
5. Average the two-dimensional NPS from all regions.
6. Correct for the camera noise. Based on the assumption that the camera noise and the display spatial noise are uncorrelated, the NPS based on sampled camera images without exposure using the same integration time may be subtracted from the results.
7. Derive the orthogonal NPS from the calculated two-dimensional NPS by band averaging, excluding the data on the orthogonal axes.

It should be pointed out that the NPS measurements could also be performed first by defocusing of the electron beams, thus removing the raster lines. This method is not recommended, as it will measure system performance in a condition that is not used clinically. The two approaches generate different results. Depending on whether the raster lines are visible or have been defocused and are not visible, the measured noise is different by almost a factor of 2 (Figure 50).

4.6.4.2 Expected Response

Since there are only a few examples of actual SNR and NPS measurements at this point, and since no correlation of the measurements and diagnostic accuracy is ascertained, no fixed

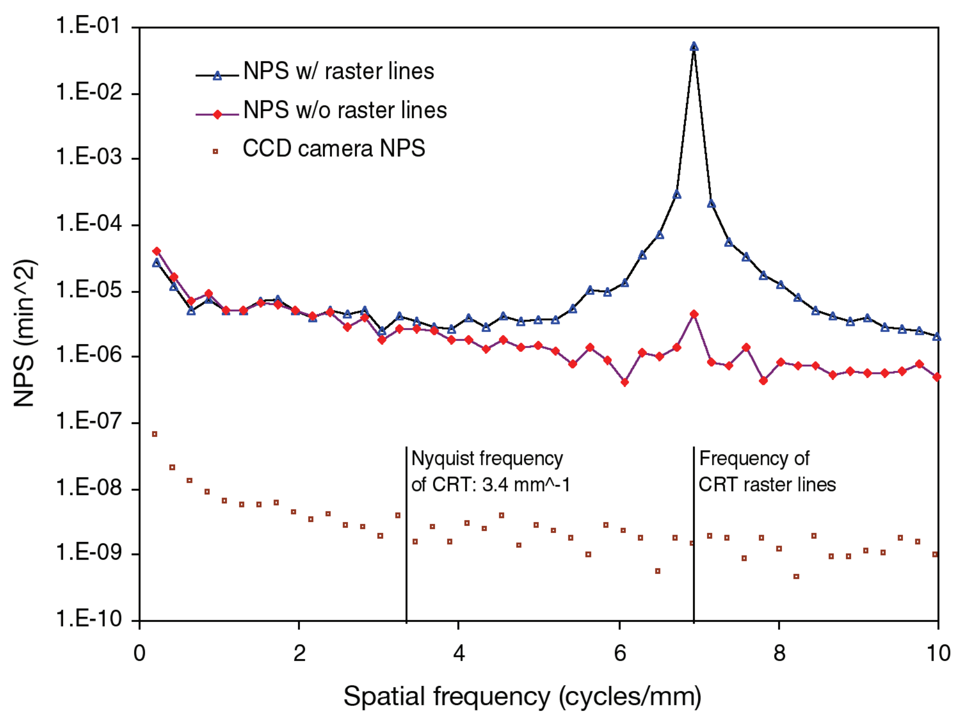


Figure 50. Examples of noise power spectra (NPS) in the vertical direction due to phosphor noise for a luminance value resulting from an 8-bit command level (pixel value) of 127 for the two situations in which the raster lines are visible, and the other in which they have been defocused and are not visible.

criteria are recommended at this time. However, noise values associated with the display device should not exceed those of typical radiological images that are viewed with the system.

4.6.5 Advanced Evaluation of Display Noise

4.6.5.1 Assessment Method

As an advanced evaluation, the spatial noise characteristics of display, SNR and NPS, can be ascertained at five locations on the display using the center and corner areas of the TG18-NS test patterns. Additionally, the temporal noise characteristics of the display can be ascertained. The measurements can be performed by assessing the noise characteristics across an ensemble of images acquired at 8 Hz, corresponding to the integration time of the human eye.

4.6.5.2 Expected Response

The expected requirements for the advanced measurements of display noise characteristics have not yet been established.

4.7 Veiling Glare

4.7.1 Description of Veiling Glare

Light scattering in display devices induces a diffuse luminance that veils the intended image. In this report, the term *flare* is used to describe diffuse scattering of light in a photographic lens, while the term *glare* is used for display devices. Veiling glare is also different from reflection, covered in section 4.2, in that reflection refers to the response of a display device to incident ambient lighting conditions, while glare is an internal display property.

In monochrome CRT display devices, three physical attributes contribute to veiling glare. They are internal reflections of the electrons from the aluminum layer inside the CRT (Figure 51), generation of secondary electrons in the phosphor and aluminum layer of the CRT, and light scattering in the glass faceplate. The last attribute, which is dominant, is due to scattering of the light in the thick glass plate of the emissive structure by specular reflections from the exit surface and diffuse reflections from the phosphor layer (Badano and Flynn 2000). The amount of veiling glare can be reduced by using darkened glass.

In color CRT devices, the veiling glare has a substantial electronic component caused by backscattering of the electrons from the edges of the shadow mask or aperture grill openings. These backscattered electrons reenter the mask or the grill opening at different locations causing a low-frequency spread of displayed luminance. The electronic component of veiling glare has different spatial extent for shadow mask and aperture grill designs. The shadow mask designs typically have more electron backscattering than grill designs (Oekel 1995).

For most flat-panel devices, no light is reflected internally, nor are secondary electrons created, and light is attenuated in short distances such that the diffuse component of veiling glare is minimal. However, short-range scattering can still cause local glare, which is noticed around bright characters on a black background.

The luminance distribution of an image scene acts as a source for the production of veiling glare. Since light transport is typically a linear process, the veiling-glare component of an image can be determined by convolving the image with the point spread function describing the veiling glare (Badano and Flynn 2000). The displayed image is then the linear sum of the primary

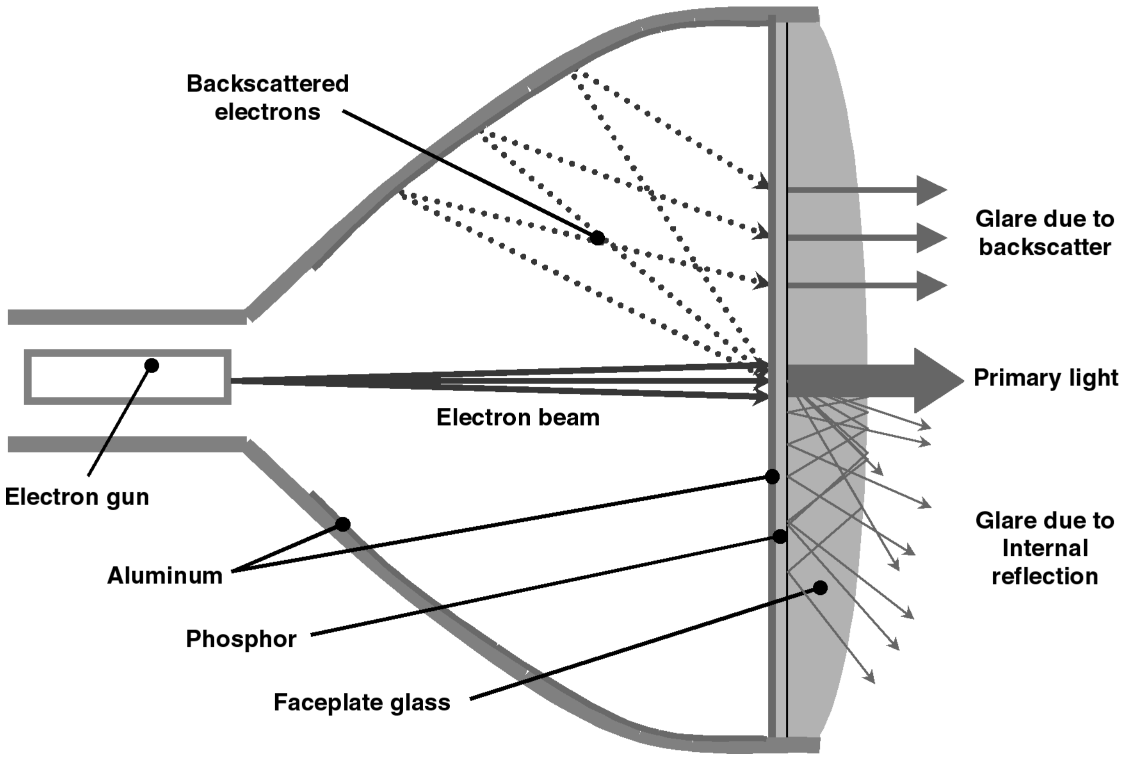


Figure 51. Electronic and optical components of veiling glare in CRTs. A white area on the CRT's surface causes reflections of electrons on its internal aluminum layer and scattering of optical photons in its thick faceplate, increasing the luminance of the black areas.

image and the diffuse secondary image associated with veiling glare. The addition of this diffuse secondary component has the overall effect of reducing contrast in a manner similar to contrast reduction from scattered x-rays in radiography. This contrast reduction is most severe in the dark regions of the primary image.

The human eye has flare characteristics better than most optical lens recording systems and is capable of perceiving low-contrast objects in dark regions surrounded by bright image scenes. Display devices with very low veiling glare are thus needed to present images with good contrast in these dark regions. Conventional trans-illuminated film has essentially no veiling glare. Conventional color CRTs have substantial veiling glare which make them unsuitable as primary class medical display devices.

4.7.2 Quantification of Veiling Glare

Veiling glare is measured using a test pattern with a dark region surrounded by a bright field. For image intensifiers, a central dark circle with a diameter equal to 10% of the diameter of the recorded field is specified by NEMA. There have been only a few published standards for the test pattern and method to be used for the measurement of veiling glare in display devices. NIST has reported results using black squares of varying size on a white background (Boynton and Kelley 1997). However, a radially symmetric pattern consisting of a circular dark spot surrounded by a circular bright area can provide experimental results that can be related to ring response functions and point response functions (Badano and Flynn 2000, Badano et al. 1999).

For a particular test pattern, the veiling glare can be quantified by the ratio of the maximum luminance to the minimum luminance, referred to as the *glare ratio*. The glare luminance measurements require the observation of a dark region surrounded by a very bright field. Thus, a low-flare luminance meter device that shields the observation from the bright region is required. The measurements can be performed using either a custom-made or a telescopic luminance meter with a baffled funnel at one end, as described in sections 3.1.1.1 and 3.1.3.

It is recommended that veiling glare be assessed using a test pattern with a black background and a central white region 20 cm in diameter. In the center of the bright circle should be a black region 1 cm in diameter. A set of glare test patterns in a standard image format can be used to establish a variety of conditions needed to complete a glare test. Alternatively, graphics software for generating test patterns can be used to generate the patterns on demand (see section 3.1.3).

4.7.3 Visual Evaluation of Veiling Glare

4.7.3.1 Assessment Method

The visual assessment of veiling glare can be accomplished using the TG18-GV and TG18-GVN test patterns. The display size must be adjusted so that the diameter of the white region is 20 cm. The observer should discern the visibility of the low-contrast objects in sequential viewing of the TG18-GVN and TG18-GV patterns with the bright region masked from view. Alternatively, a test pattern generator of the type described in section 3.3.1 may be used. This gives one the ability to adjust the contrast (via pattern modification) of a single target at the center of a 1-cm-diameter dark circle until the target is just visible under the conditions of presence and absence of a 20-cm-diameter 100% bright surround. Because the human visual system will change adaptation if it views the bright field, it is imperative that the bright field is fully blocked from view and that no reflected light from the bright field be observable. This may be accomplished by the use of a mask or cone, which shields the human eye from the surround luminance of the pattern.

4.7.3.2 Expected Response

No significant reduction in the contrast of the target objects should be observed between the two patterns, one with and one without the bright field. This test is sensitive to the perceived contrast of the target with a black surrounding region. If this is exactly at the just noticeable threshold, then any reduction in contrast due to the presence of the bright field will render the targets not visible. A target contrast of about 4 times the just noticeable $\Delta L/L$ is appropriate for this test in primary class display devices. For a system with 1024 DDLs and a calibrated display device with a luminance range of 1 to 250 cd/m^2, this target contrast corresponds to a change of four DDLs, which produces a $\Delta L/L$ of 0.03. Thus, at least three objects should be readily visible in either pattern for primary class display devices. The corresponding object for secondary class display devices is at least one target.

4.7.4 Quantitative Evaluation of Veiling Glare

4.7.4.1 Assessment Method

The quantitative evaluation of veiling glare is accomplished using a highly collimated luminance meter and the TG18-GQ, TG18-GQB, and TG18-GQN test patterns. It is important to assure that the patterns are displayed at the specified size. The display size must be adjusted so that the diameter of the white region is 20 cm. Furthermore, as described in section 3.1.3, the bright luminance surrounding the central measurement point at the center of the test patterns should be blocked, using either a baffled luminance meter or a telescopic luminance meter with a light-blocking baffled funnel or cone. Using either of these devices, the luminance in the center of the central dark region of the TG18-GQ pattern, L, the white luminance in the center of the white region of the TG18-GQB pattern, L_B, and the background luminance value in the center of the TG18-GQN pattern, L_N, are recorded. The glare ratio for the display is then computed as

$$\mathrm{GR} = (L_B - L_N)/(L - L_N)\ . \tag{18}$$

4.7.4.2 Expected Response

The veiling glare for a high-fidelity display system should not change the contrast of a target pattern by more than 20% with and without a bright surrounding. Thus, the luminance from veiling glare should not be more than 25% of the minimum luminance for the normal operating settings of the display. Since the ratio of the maximum luminance to the minimum luminance should be about 250 (Flynn and Badano 1999), this implies a glare ratio of 1000, which is typical of measurements made for transilluminated film. However, the recommended test pattern presents a scene with significantly more veiling glare in the target region than is encountered in medical imaging scenes. Though not as strict criteria, which may not be achievable by certain display technologies, this report recommends that the primary class displays have a glare ratio of greater than 400 and secondary class displays have a glare ratio greater than 400 (Flynn et al. 1999). Glare ratio results for specific medical imaging systems are reported in the literature (Badano et al. 2002).

4.7.5 Advanced Evaluation of Veiling Glare

4.7.5.1 Assessment Method

Using the quantitative test method described above, a more complete characterization of veiling glare can be made by measuring the glare ratio as a function of the black region diameter. It is important to assure that the patterns are displayed at the specified size. The display size must be adjusted so that the diameter of the white region is 20 cm. If the veiling glare point response function is shift invariant and radially symmetric, the glare ratio data, G_i, at various radii, r_i, can be reduced as an estimate of the veiling glare ring response function, $R(r)$ (Badano and Flynn 2000, Badano et al. 1999) using

$$\begin{gathered} 1/G_i - 1/G_{i+1} = \int_{r_i}^{r_{i+1}} R(r)dr \\ R^i(r) = \Delta(1/G_i)/\Delta r \end{gathered} \quad . \tag{19}$$

Typically, measurements are made of radii from 5 to 30 mm, with finer spacing at smaller radii, using the TG18-GA test patterns.

4.7.5.2 Expected Response

Measurement of the veiling-glare ring response function provides information regarding the spatial extent of the luminance spread. The shape of this curve is different for monochrome CRT devices, color CRT devices, and flat-panel devices (Badano et al. 1999). Anti-reflective (AR) coatings alter the shape of the ring response function. The ring response function is particularly useful for comparing and understanding differences among display devices. However, this information would typically not be used to establish display requirements.

4.8 Display Chromaticity

4.8.1 Description of Display Chromaticity

Measurement of display color tint is important as it pertains to matching the color of multiple grayscale displays that might be used in a single workstation. In inherently color displays, the color tint is affected by the balance of the three primary colors forming a grayscale image. In monochrome displays, the color tint is either affected by the phosphor type, in the case of CRTs, or the spectrum of the backlight, in the case of AMLCDs. In LCDs, color tint is further affected by the viewing angle. Display color matching has been found to be an important factor in PACS workstation acceptability, and the ability to measure color has proven beneficial during acceptance testing of new multihead display systems (Fetterly et al. 1998). To date, no significant clinical impacts of color mismatching have been observed.

4.8.2 Quantification of Display Chromaticity

The recommended color measurement system is the 1976 CIE (Commission Internationale de l'Eclairage), CIELUV, uniform chromaticity scale. The 1976 CIELUV system was developed to address limitations in a CIE chromaticity system that was initially published in 1931 (IEC 1986, Keller 1997). The 1931 system allowed any color visible to a human observer to be specified by a pair of coordinates in a two-dimensional color space. The coordinates were dubbed x and y. All visible colors occupy a horseshoe-shaped region in the x-y plane. The 1931 color space could be used, for example, to determine what color would result from mixing different proportions of two colors by drawing a line between the source colors and moving proportionally along the line. Because of the nonlinear nature of the human visual system (HVS), equal distances in the 1931 color space did not represent equally perceivable color changes. This was a principal drawback addressed in the 1976 CIELUV color system. In the CIELUV system, the 1931 color space was linearly warped so that equal distances anywhere in the new color space represented equal perceived color differences. This modification did, however, introduce a limitation for color mixture analysis, such as mentioned above. The CIELUV system is based on two new coordinates, u' and v', that can be related back to the original 1931 coordinates x and y via fractional linear transformation.

To quantify color uniformity, a colorimeter is used to measure the system coordinates u' and v' for all display devices attached to a workstation. The distance between pairs of (u',v') points is linearly proportional to the perceived color difference expressed in terms of just-noticeable-difference (JND) index. Once (u',v') are measured for each display device, a color uniformity parameter is computed as the maximum distance between any possible pair of (u',v') points. Distance (D) between two points (u_1',v_1') and (u_2',v_2') is calculated using $D = [(u_1' - u_2')^2 + (v_1' - v_2')^2]^{1/2}$. The distance represented by the color uniformity parameter is equivalent to the diameter of the smallest circle in the color space that can encompass all of the (u',v') points.

In this report, color uniformity is specified by the $\Delta(u',v')$ metric and not by other metrics for a number of reasons. First, $\Delta(u',v')$ is part of the ISO, VESA, and IEC standards. Secondly, it offers a luminance-independent metric for screen uniformity. Finally, it is proven to be an effective measure of color uniformity and is much less complicated than other metrics.

4.8.3 Visual Evaluation of Display Chromaticity

4.8.3.1 Assessment Method

The visual assessment of color uniformity is performed using the TG18-UN80 test pattern. The pattern is displayed on all the display devices associated with a workstation. The relative color uniformity of the displayed pattern across the display area of each display device and across different display devices is then discerned.

4.8.3.2 Expected Response

No significantly perceivable color differences should be present among display devices and across the display area of each device for primary class devices. No requirements are specified for secondary class displays.

4.8.4 Quantitative Evaluation of Display Chromaticity

4.8.4.1 Assessment Method

The TG18-UNL80 test pattern is displayed on all the display devices associated with a workstation. A colorimeter is then used to measure the (u',v') color coordinates at the center and at the four corners of the display area of each display device, and these coordinates averaged to produce a mean (u',v') chromaticity measurement for the display device. The measurements on all display devices are used to compute the color uniformity index as the maximum distance in u'-v' space between any possible pair of average (u',v') points using $D = [(u_1' - u_2')^2 + (v_1' - v_2')^2]^{1/2}$. If the colorimeter used outputs the color coordinate in the older (x,y) space, the values can be converted to (u',v') space using the following transformations:

$$u' = 4x \,/\, (-2x + 12y + 3), \qquad v' = 9y \,/\, (-2x + 12y + 3)\;;$$
$$x = 27u' \,/\, (18u' - 48v' + 36), \qquad y = 12v' \,/\, (18u' - 48v' + 36)\,. \tag{20}$$

4.8.4.2 Expected Response

Based on clinical experience, a color uniformity parameter of 0.01 or less is necessary to assure acceptable color matching of primary class grayscale display devices of a workstation (Fetterly et al. 1998). The distance between any pair of color coordinates across the display area of each device should also not exceed this limit. No quantitative requirements are specified for secondary class displays.

4.8.5 Advanced Evaluation of Display Chromaticity

4.8.5.1 Assessment Method

Some display devices may demonstrate a color shift as a function of viewing angle, particularly for certain types of flat-panel devices. Advanced tests may be used to evaluate the chromaticity as a function of viewing angle. This can be done with collimated or focused colorimeter probes or CCD test devices specifically equipped to measure color over the full field of an image. For these advanced tests, color coordinates should be measured for uniform fields with low, medium and high luminance.

4.8.5.2 Expected Response

For advanced measurements, the color uniformity parameter for primary class displays should not exceed 0.01 for all viewing angles within the useable viewing angle range and for all luminance values tested. No advanced requirements are specified for secondary class displays.

4.9 Miscellaneous Tests

In addition to the primary display attributes described above, there are a number of secondary attributes that may need to be addressed in a full display performance evaluation. Brief descriptions and assessment methods for these characteristics are outlined below.

4.9.1 CRT Displays

4.9.1.1 Artifacts

4.9.1.1.1 Description. CRT devices are prone to a number of video artifacts. Ghosting or shadowing appears as a sort of shadow or mirror image around structures, particularly characters. It is usually caused by an impedance mismatch, often in the video cable or in the termination within the display device itself. When multiple display devices are configured into a workstation, such a mismatch can also be induced by using cables of varying lengths or inadequate shielding. Smearing is a bright to dim shadow easily seen trailing to the right from a bright area, such as the test patches on the TG18-QC pattern. Like ghosting, the cause can be either an internal or external (i.e., video cable connection) impedance mismatch, or a defective cable or controller card. Jitter and swim are two other artifacts that can appear at fixed or random locations. They are most visible at the edge of the display area and are due to instability in the video card sync output or the display itself.

Yoke ringing, or simply ringing, is the term used to describe a number of vertical white lines at the left edge of the screen. They are typically visible in the first few centimeters of a new raster line. The source of this artifact is a cross talk between the deflection yoke's horizontal and vertical windings, inductance resulting from the fields collapsing during retrace. From the time of the horizontal synchronization pulse until the next video line starts, there needs to be a design-dependent damping period that permits the cross talk to be fully damped. Fixed-frequency displays will normally state specific timing capabilities that provide for the damping.

Multifrequency displays covering a broad range of horizontal timings also have a minimum time period. Low cost, commercial video controllers using lower cost DACs do not always provide sufficient damping periods, resulting in instabilities and horizontal jitter. This problem also causes an inability to center the video signal within the display area. In a system with a sufficient damping period, there are overscans, i.e., the raster is larger than the usable display area. If the active video drifts into this blanked area, ringing artifacts may appear, which would require a readjustment of the device. Such readjustments are often made by a service engineers.

Breathing or pulsing of the video is caused by poor or failing high-voltage regulation. The appearance can be deceiving to the observer. The video area is actually expanding in size as the high-voltage is lowered during a transition from a dark screen to a bright screen. The opposite occurs when the transition is from a bright screen to a dark screen. Non-regulated high-voltage circuits are more typical of commercial color displays. Medical displays should have either a regulated high-voltage supply independent of the horizontal circuits, or a regulated fly-back. In extreme cases, a high-voltage supply that cannot recover during horizontal retrace, but does on vertical retrace, will have a luminance non-uniformity with the upper left corner being the brightest and values falling as the scan progresses to the bottom.

4.9.1.1.2 Evaluation Method. Examine the white-to-black and black-to-white signal changes in the appropriate portions of the TG18-QC test pattern. The pattern should be examined from a viewing distance of 30 cm. The transitions should be abrupt, with little to no evidence of a slow transition or "tail," overshoot, shadowing, or ghosting. The pattern overall should be free of any artifacts.

4.9.1.2 Moiré Patterns

4.9.1.2.1 Description. Color displays exhibit moiré patterns when the addressable pixel format is not matched with the shadow mask or aperture grill dot pitch. The aliasing is a periodic pattern seen as a rainbow of colors floating in the glass. Most commercial color displays have adjustments for both vertical and horizontal moiré. The approaches taken by the manufacturers have been either to adjust the phase of both axes or modify the focus values to diminish moiré.

Monochrome displays can also exhibit moiré caused by invisible artifacts in the glass that beat with the scan rate. In this case, selecting a slower or faster refresh rate on the video card will usually remove the problem.

4.9.1.2.2 Evaluation Method. Moiré patterns are most noticeable when the displayed pixel size approaches the spacing or pitch of the color phosphor trio. Regular patterns of alternating on-off-on-off pixels such as checkerboards or grilles tend to enhance the visibility of moiré patterns. Alternating pixel patterns displayed at low luminance levels may exhibit increased moiré if the pixel size decreases with beam current, as is typically the case for CRTs. It is usually sufficient to use alternating pixel patterns to visually inspect for the presence of objectionable moiré and to evaluate the effectiveness of moiré cancellation circuits. Moiré cancellation methods often introduce negative side effects such as defocused spots and/or jitter. It is important to determine whether such side effects noticeably degrade the image.

4.9.1.3 Color Artifacts

4.9.1.3.1 Description. Color convergence in color CRTs is a factory setting performed in the alignment procedures for the yoke and guns that must function as a matched set. Color CRTs are purchased by display manufacturers as pre-aligned assemblies and may not be adjustable in the field. In medical applications using color display devices to display grayscale images, color misconvergence often appears as a colored ghost or shadow, usually around sharp edges and characters.

Poor color purity also occurs because of poor color registration, whereby a percentage of one gun is landing on another color phosphor. Degaussing circuits automatically activate when the CRT display device is powered on to demagnetize the shadow mask so as to negate any ambient magnetic field which may otherwise disrupt the registration between the individual beams and their respective red, green, and blue phosphors on the screen.

Another potential cause of color errors is mismatched video amplifiers, in that the rise and fall time on one does not track with the other two. Again, ghosting of one color will be noticed on either the leading or trailing edge (or both) of characters. In addition, when one or more of the video amplifiers is overdriven, it may become saturated, causing a visible horizontal streak (sometimes called bleed) from the trailing edge of a displayed object or character. This condition is often avoided by reducing L_{max} using the contrast control.

It should be noted that color purity can be mistaken with misconvergence if it is not localized. Misconvergence refers to any separation between individual beams at the screen. Some displays provide a dynamic adjustment for convergence and are user correctable.

4.9.1.3.2 Evaluation Method. Convergence is evaluated by inspecting a crosshatch pattern consisting of two or more primary colors. Handheld optical devices (e.g., Klein gauge) provide a quantitative measure of the misconvergence. Advanced photometric measurements require the use of a digital camera to locate the centroids of individual red, green, and blue spots.

Color registration errors are assessed the same as luminance uniformity on monochrome displays, except individual red, green, and blue primaries are evaluated. For full-screen white, the CIE color coordinates are recorded in addition to the luminance. Color bleeding (streaking) is assessed for white and individual red, green, and blue primaries in the same way as are video artifacts in monochrome displays.

4.9.1.4 Physical Defects

4.9.1.4.1 Description. Defects in the screen of a CRT can be categorized as either glass or phosphor blemishes. Manufacturers screen for phosphor defects such as voids and particle contamination and reject the display device according to the size and position of the defect(s). On-site physical damage to the phosphor is rare but not impossible. Phosphor burn is still a real possibility in spite of the universal use of screen savers. Hours of use reading one type of image or displaying a menu bar will ultimately affect the phosphor.

Glass defects occur when the faceplate is formed. Very small particles in the glass may appear as dark specks but may also disappear when the display is turned on. Occlusions are caused by trapped gas during forming and are voids in the glass. Visually they appear like cracks because of the opposing surfaces reflecting light.

4.9.1.4.2 Evaluation Method. Display artifacts can be evaluated using a uniform test pattern, TG18-UN80. The pattern should appear uniform without any of the defects described above.

4.9.1.5 Flicker

4.9.1.5.1 Description. While not an artifact per se, flicker is one of the more distracting and disturbing characteristics of a soft-copy display. Flicker is a description of the human perception of the vertical refresh as well as the interference of the refresh rate with other periodic sources of illumination. We see flicker more at high luminance levels and lower refresh rates under 65 Hz. Peripheral vision is also more sensitive to flicker.

Interference from fluorescent lights is the most common cause of the perception of flicker. At refresh rates above 72 Hz most people will not be significantly bothered, and at rates over 80 Hz very few people will perceive any flicker. CRT displays operating at or near 60-Hz refresh rates should be avoided. LCD displays typically exhibit no flicker even at refresh rates as low as 20 Hz.

Phosphor decay is the performance characteristic that causes flicker. The proper matching of refresh rates and phosphor will minimize flicker. The two dominant medical phosphors, P104 and P45, at or above a 72-Hz refresh rate will satisfy a majority of the general population.

4.9.1.5.2 Evaluation Method. The presence of flicker can be visually ascertained using the TG18-UN80 test pattern at a viewing distance of 30 cm. The flicker should be evaluated for both foveal and peripheral visions. For quantitative assessment of flicker, VESA standards can be consulted (VESA 2001).

4.9.2 Liquid Crystal Displays

The image quality of flat-panel LCDs is affected by the specific way these devices generate the image for the viewer. The significant differences with respect to the CRT merit a separate discussion introducing the factors that have to be considered when assessing the performance of a LCD, and the artifacts that can be found in displaying medical images. In this section, we describe two factors that affect the image quality of flat-panel displays in displaying static images, electronic cross talk, and pixel defects. Other aspects that are not covered here are angular variations in the luminance (covered in section 4.4), temperature effect (particularly important in LCDs), and mura patterns (visible non-uniformity due to imperfections in the display pixel matrix surface).

4.9.2.1 Electronic Cross Talk

4.9.2.1.1 Description. Of particular importance to high-resolution display devices with large numbers of gray levels is the scene-dependent, undesired artifact caused by cross talk in the active matrix array circuitry. Cross talk is primarily an electronic term designating unwanted coupling between adjacent or nearby circuits. In AMLCDs, cross talk is associated with the modification of the intended voltage across the LC cell that results in an undesired alteration of the pixel luminance. The artifact is caused by incomplete pixel charging, by currents through the thin-film transistor, and by displacement currents determined by parasitic capacitive coupling. Display cross talk is more important for large-sized panels having higher resolution and grayscales (Libsch and Lien 1998). Although having different origins, cross-talk artifacts have also been studied for passive-matrix polymer light-emitting displays. Even for medium-resolution display devices, cross talk can affect the level of a centrally located small target by as much as 1% (Badano and Flynn 2000).

Careful material selection, improved driving schema, precision in the fabrication process, and device design optimization have been used to reduce cross-talk artifacts. The use of low-capacitance design and the selection of higher-conductivity metals, such as copper, for the scan lines reduce occurrences of incomplete pixel charging. In addition, integrating a black matrix acting as a light shield for the a-Si:H TFT reduces photo-generated leakage currents.

Measurements of cross talk involve the use of bar patterns where a small target within the bar is at a different luminance level than the rest of the bar. Patterns with horizontal and vertical bars are useful since cross talk can be present along both directions, depending on the display device architecture. The variations of target gray level when the background level changes can be recorded with a luminance meter. An advanced test should use a luminance meter that records target luminance without contamination from the background gray level, as described in section 3.1.1.1 (Badano and Flynn 2000, Wright et al. 1999, VESA 2001).

As a visual test, the cross talk element of the TG18-QC test pattern may be used. When examined with the surround regions masked from view, the central low contrast vertical target of the element should exhibit constant contrast along its length. Significant variations are indicative of objectionable cross talk in the horizontal direction. The pattern should also be examined with 90° rotation for evaluating the presence of cross talk in the vertical direction.

4.9.2.2 Pixel Defects

4.9.2.2.1 Description. Defective pixels are pixels that operate improperly when addressed with a proper signal. Pixel defects can be classified as stuck pixel (never change state), intermittent pixel (change state independently of addressing signal), and defective pixel (state does not correspond with addressing signal). Off pixels are pixels that remain black for all signals, while partial pixels are pixels that have defective subpixels. Most frequently for LCDs with subpixels, the pixels are only partially defective.

4.9.2.2.2 Evaluation Methods. The number of pixel defects in a matrix-addressed display should be assessed visually on a frequent basis and compared with a given tolerance. They should also be characterized in terms of proximity or clustering in the display area. Quantitative methods have been proposed both in ISO standards (ISO 13406-2) and in the Flat Panel Display Measurements Standard (VESA 2001) for such measurements.

4.10 Overall Evaluations

In addition to the testing a display device for a specific performance characteristic, the overall quality of a system can be assessed using a comprehensive visual/quantitative approach. Overall assessment can be based on any of the TG18-recommended multipurpose test patterns. Each pattern should be displayed with one display pixel representing each image pixel and examined from a viewing distance of 30 cm. The findings can be correlated with the results of more focused testing methods specified above and serve as a basis for quality control assessments. The frequency of such an evaluation is discussed in section 6.

4.10.1 Evaluations Using TG18-QC Pattern

The appearance of the elements in the TG18-QC test pattern can be used to assess the overall performance of display systems. The following are recommended:

1. General image quality and artifacts: Evaluate the overall appearance of the pattern. Note any non-uniformities or artifacts, especially at black-to-white and white-to-black transitions. Verify that the ramp bars appear continuous without any contour lines.
2. Geometric distortion: Verify that the borders and lines of the pattern are visible and straight and that the pattern appears to be centered in the active area of the display device. If desired, measure any distortions (see section 4.1.3.2).
3. Luminance, reflection, noise, and glare: Verify that all 16 luminance patches are distinctly visible. Measure their luminance using a luminance meter, if desired, and evaluate the results in comparison to GSDF (section 4.3.3.2). Verify that the 5% and 95% patches are visible. Evaluate the appearance of low-contrast letters and the targets at the corners of all luminance patches with and without ambient lighting.
4. Resolution: Evaluate the Cx patterns at the center and corners of the pattern and grade them compared to the reference score (see section 4.5.3.1). Also verify the visibility of the line-pair patterns at the Nyquist frequency at the center and corners of the pattern, and if desired, measure the luminance difference between the vertical and horizontal high-modulation patterns (see section 4.5.3.1).

4.10.2 Evaluations Using TG18-BR Pattern

In using the TG18-BR pattern the viewer assesses the checkerboard patterns to discern the smallest checkerboard that can be distinguished in each panel of a quadrant. Quadrants are read clockwise from upper left to lower left. Within each quadrant, the panels are also read clockwise. A magnifier can be used for reading the smallest checkerboards. Refer to section 3.2.1.4 for specific details on checker/checkerboard sizes and scoring.

A display with sufficient bandwidth and proper setup will have a balanced response from the darkest to the brightest panel with equal perception of the checkerboards. On primary class display systems, the B-60 checkerboard should be easily observed in all panels and quadrants. Displays with balanced response characteristics can be read up to B-90 in the third and fourth quadrants, B-80 in the second quadrant, and B-60 in the first quadrant. Performance above this level is exceptional. This level of performance is indicative of a high-quality 1600×1200, 21 in., monochrome CRT.

4.10.3 Evaluations Using TG18-PQC Pattern

While this report is intended for the assessment of electronic display devices, the images displayed on such devices are often printed on transparent film for interpretation on an illuminator. The TG18-PQC is a multipurpose test pattern primarily designed to insure that the appearance of printed images is similar to that of electronic display devices. Using the central column of the pattern, the film optical density of the 18 marked regions should be recorded. Secondly, the average luminance of the illuminator used for viewing films should be measured. The luminance of the 18 regions should then be computed from the optical density and illuminator luminance measurements. These luminance values should be evaluated to establish that the print device is properly set up to yield a luminance response consistent with the grayscale display standard. As described in section 4.3.4.2.2, this is best done by evaluating the contrast response.

Modern film printers that are properly maintained will generally not exhibit problems with resolution, distortion, or noise. A quick visual test of resolution can be done using the bar patterns at the top and bottom of the TG18-PQC test pattern. For this, the size of the test pattern should be matched to the size of the print matrix for the printer being used so that there is a one-to-one correspondence between image pixels and printer pixels. At each luminance step, a set of low contrast bars of varying size and contrast can be examined to determine whether the prints have aberrant noise. Finally, the ramp pattern at the right and left of the TG18-PQC pattern should be examined to determine whether any contrast artifacts are present.

4.10.4 Evaluations Using TG18-LP Patterns

The TG18-LP test patterns can be used to visually establish whether the resolution of a display device is acceptable. The low-luminance test pattern should be displayed first for both the horizontal and vertical bar patterns. Using a consistent viewing condition, the patterns should be examined to establish that the pattern of one line pair for every two pixels can be seen in all regions of the display. Any region where the pattern is not visible is indicative of a device with aberrant resolution at that position. Since high-performance devices have very small pixels, a large field of view magnifying glass in convenient for evaluating this test pattern.

If the performance at low brightness is satisfactory, the performance should be similarly evaluated with the mid- and the high-luminance horizontal and vertical test patterns. Again, any indication that the line-pair pattern is not visible in all regions is an indication of improper resolution performance.

4.10.5 Evaluations Using Anatomical Images

A radiologist should evaluate the overall clinical image quality of the display using patient images. The TG18 report suggests four specific anatomical images for this purpose: TG18-CH, TG18-KN, TG18-MM1, and TG18-MM2. These correspond to a chest radiograph, a knee radiograph, and two digital mammograms. Clinical criteria for evaluating these images are given in Table 6. The images may be scored according to these criteria corresponding to the different image features. The radiologist who wishes to evaluate his/her display should independently rate the image features according to the criteria in Table 6, and then compare their ratings to those obtained with a high-quality transilluminated film print of the patterns. Significant discrepancies need to be brought to the attention of the responsible medical physicist or service engineer.

Table 6. Criteria for evaluating the TG18 anatomical images.

Test Pattern	Evaluation Criteria
TG18-CH	Degree of difficulty for exam
	Overall contrast
	Overall sharpness
	Symmetrical reproduction of the thorax, as shown by the central position of a spinous process between the medial ends of the clavicles
	Medial border of the scapulae
	Reproduction of the whole rib cage above the diaphragm
	Visually sharp reproduction of the vascular pattern of the lungs, particularly the peripheral vessels
	Sharp reproduction of the trachea and proximal bronchi
	Sharp reproduction of the borders of the heart and the aorta
	Sharp reproduction of the diaphragm
	Visibility of the retrocardiac lung and the mediastinum
	Visibility of the subdiaphragmatic features
	Visibility of the spine through the heart shadow
	Visibility of small details in the whole lung, including the retrocardiac areas
	Visibility of linear and reticular details out to the lung periphery
TG18-KN	Degree of difficulty for exam
	Overall contrast
	Overall sharpness
	Reproduction of trabecular detail
	Reproduction of bony and soft tissue
TG18-MM1 and TG18-MM2	Degree of difficulty for exam
	Overall contrast and brightness
	Overall sharpness (no blur)
	Sharp appearance of Cooper's ligaments
	Structure of the clip and the presence of the gap at its apex (TG18-MM1 only)
	Appearance and visibility of subtle microcalcifications (TG18-MM1 only)
	Visibility of structures at the margins of the breast (TG18-MM1 only)

5 ACCEPTANCE TESTING OF A DISPLAY SYSTEM

Previous sections described the methods for assessing the performance of a display system. In this section, we specifically outline the recommended tests to be performed as a part of an acceptance testing procedure with references back to detailed tests and equipment in sections 3 and 4.

5.1 Prerequisites for Acceptance Testing

As in any acceptance testing initiative, the display acceptance testing is justified and meaningful only if it is directly linked to the contract between the user and the vendor, commonly in the form of a Request for Proposal (RFP) or Request for Quotation (RFQ). In the contract, the user must specifically delineate the engineering specification for the display device, acceptance testing procedures, definitive acceptance criteria, and the actions to be taken should noncompliance be identified. Other prerequisites for acceptance testing of a display device are described below.

5.1.1 Personnel

The acceptance testing of a display system must be performed by an individual(s) having appropriate technical and clinical competencies. Even though the vendor is expected to perform some testing before turning a display system over to the user, the user must independently test the system(s). Medical physicists trained in display performance assessments should perform the tests. Other staff including biomedical engineers, in-house service electronic technicians, or trained x-ray technologists can perform most of the tests described herein; however, the medical physicist should accept oversight responsibilities, both for the training of support staff and for final approval of the results.

5.1.2 Preliminary Communications

Preliminary communication with the vendor is essential for understanding how the system is intended to be operated and how the test patterns of interest can be loaded on the system. Some systems come with dedicated QC utilities. The details and usage of these utilities must be fully documented and understood beforehand. Any recommended service and/or calibration schedule, including the services provided, tests performed, and the service/calibration intervals, must be obtained from the manufacturer, ideally as part of the purchasing process.

5.1.3 Component Inventory

Prior to acceptance testing, the characteristics of the display systems delivered should be verified against those specified in the purchase agreement. A database should be established which includes information such as display type, size, resolution, manufacturer, model, serial number, manufacture date, room number, display ID (if applicable), associated display hardware (e.g., display controller), and test patterns available on the systems.

5.1.4 Initial Steps

The following procedures are recommended prior to acceptance testing of the display device:

1. Review all delivered documentation from the vendor. Especially note the quality testing results performed in the factory.
2. Verify the availability of desired tools (see sections 3.4.1 and 5.2 and Table 7).
3. Check display placement (see section 3.4.2).
4. Follow the start-up procedures (see section 3.4.3).
5. Document the ambient lighting level (see section 3.4.4).
6. Calibrate/verify the L_{max} and L_{min}, and brightness and contrast settings (see section 3.4.5).
7. If applicable, verify/perform a DICOM luminance calibration (see section 3.4.6).

5.2 Tests and Criteria

Table 7 provides a list of the tests to be performed at acceptance testing, the required tools, and the expected performance. In addition to the tests specified in Table 7, other miscellaneous tests as described in section 4.9 and some of the overall assessment tests as specified in section 4.10 can be used to establish baseline performance for future quality control tests. Depending on the interest and resources, additional advanced tests are further encouraged as a part of acceptance testing. The use of worksheets and checklists will help in recording the results and performing the desired calculations. Note that all the visual tests should be performed from a viewing distance in the range of 30 cm unless otherwise noted in the testing procedures.

Table 7. Tests, tools, and acceptance criteria for acceptance testing of electronic display systems.

Test	Major Required Tools		Procedure	Acceptance Criteria (for two classes of displays)		Suggested Action (if unacceptable)
	Equipment	Patterns		Primary	Secondary	
Geometric distortions	Flexible ruler or transparent template	TG18-QC	See section 4.1.4	Deviation ≤ 2%	Deviation ≤ 5%	Readjustment, repair or replacement for repeated failures
Reflection[a]	Measuring ruler, light sources, luminance and illuminance meters, illuminator	TG18-AD	See sections 4.2.3 and 4.2.4	$L_{min} \geq 1.5\ L_{amb}$ (ideally $\geq 4\ L_{amb}$)	$L_{min} \geq 1.5\ L_{amb}$ (ideally $\geq 4\ L_{amb}$)	Results are used to adjust the level of ambient lighting
Luminance response	Luminance and illuminance meters	TG18-LN TG18-CT TG18-MP	See sections 4.3.4 and 4.3.3	$L'_{max} \geq 170$ cd/m^2 $LR' \geq 250$ $\Delta L'_{max} \leq 10\%$ $k_\delta \leq 10\%$	$L'_{max} \geq 100$ cd/m^2 $LR' \geq 100$ $\Delta L_{max} \leq 10\%$ $k_\delta \leq 20\%$	Readjustment, recalibration, repair or replacement for repeated failures
Luminance dependencies	luminance-meter, Luminance angular response measurement tool	TG18-UNL TG18-LN TG18-CT	See sections 4.4.3 and 4.4.4	Non-unif. ≤30% $LR'_{\delta,\theta} \geq 175$ $k_{\delta,\theta} \leq 30\%$	Non-unif. ≤30% $LR'_{\delta,\theta} \geq 70$ $k_{\delta,\theta} \leq 60\%$	Readjustment, repair or replacement for repeated failures; Angular results used to define acceptable viewing angle cone
Resolution[b]	luminance-meter Magnifier	TG18-QC TG18-CX TG18-PX	See sections 4.5.3 and 4.5.4.1.2	0 ≤ Cx ≤ 4 $\Delta L \leq 30\%$ RAR=0.9–1.1 AR ≤ 1.5	0 ≤ Cx ≤ 6 $\Delta L \leq 50\%$	Focus adjustment, repair or replacement for repeated failures
Noise[b]	None	TG18-AFC	See section 4.6.3	All targets visible except the smallest	Two largest sizes visible	Reverification of Luminance response, otherwise replacement
Veiling glare	Baffled funnel, telescopic photometer	TG18-GV TG18-GVN TG18-GQs	See sections 4.7.3 and 4.7.4	≥ 3 targets visible, GR ≥ 400	≥ 1 target visible, GR ≥ 150	Reverification of Luminance response, otherwise replacement
Chromaticity	Colorimeter	TG18-UNL80	See section 4.8.4	$\Delta(u',v') \leq 0.01$	None	Replacement

[a] In the absence of illumination devices, this acceptance testing can be performed only visually, using TG18-AD and the method described in section 4.2.3.1.

[b] More objective resolution and noise measurements can be performed as described in sections 4.5.4 and 4.6.4, using a digital camera.

6 QUALITY CONTROL OF A DISPLAY SYSTEM

Previous sections described in detail the methods for assessing the performance of a display system. In this section, we specifically outline the recommended tests to be performed as a part of a QC program with references back to sections 3 and 4 for detailed description of the tests and equipment.

6.1 Prerequisites for Quality Control

The performance of electronic display systems needs to be tested on a periodic basis as outlined below. There is some flexibility is the required periodicity of the QC tests, as hardware features and reproducible performance can reduce the need for very frequent testing. It is recommended that initial testing be done more frequently and an assessment made on the results. If stability is maintained, a determination can be made to decrease the frequency of testing, based on validated results. Additionally, some manufacturers offer automated software tools that facilitate the QC tests. These software tools are acceptable for use, as long as they are validated against standard methods described in this report.

6.1.1 Personnel

The QC procedures must be performed by individuals with appropriate technical and clinical competencies. The daily QC of a display system should be performed by the operator/user of the system. Radiology staff using electronic displays should be familiar with the daily testing procedure and expected results. For less frequent tests, designation of responsible personnel will ensure that these individuals develop and maintain familiarity with the tests, reducing variability in the QC data and in the interpretation of the results. These individuals should be under the supervision of a medical physicist. The annual QC evaluation should be performed by a qualified medical physicist or by a QC technologist working under the close supervision of a qualified medical physicist. All personnel responsible for performing QC tests will require initial training specific to their level of responsibility, and periodic retraining and mentoring by medical physics staff.

6.1.2 Availability of Prior Evaluations

The initial acceptance testing data are used to establish and maintain expected performance. Data acquired during routine QC testing must be compared to the limits established around the baseline values. It is also essential to utilize the same pattern for repeat evaluations of a given display device. The use of worksheets and checklists will help in establishing and monitoring the baselines. It is strongly recommended to record and maintain this information in electronic databases. Most commercial calibration packages support automated recording, tracking, and analysis.

6.1.3 Initial Steps

The following procedure should be followed before performing any QC tests except for daily QC.

1. Review the results of previous QC tests.
2. Verify the availability of desired tools (see sections 3.4.1 and 6.2 and Table 8).

3. Check display placement (see section 3.4.2).
4. Follow the start-up procedures (see section 3.4.3).
5. Document the ambient lighting level (see section 3.4.4).
6. Calibrate/verify the L_{max} and L_{min}, and brightness and contrast settings (see section 3.4.5).
7. If applicable, verify/perform a DICOM GSDF luminance calibration (see section 3.4.6).

6.2 Tests and Criteria

Table 8a–c provides an outline of the tests to be performed as a part of a routine QC program, the required tools, and the expected performance. In addition to the stated tests, other overall assessment tests as specified in section 4.10 can be used as a part of a routine QC program. Note that all the visual tests should be performed from a viewing distance in the range of 30 cm unless otherwise noted in the testing procedures.

Table 8a. Tests for daily QC of electronic display system, performed by the display user.

Test	Major Required Tools		Procedure	Acceptance Criteria (for two classes of displays)		Suggested Action (if unacceptable)
	Equipment	Patterns		Primary	Secondary	
Overall visual assessment	None	TG18-QC or anat. images	See sections 4.10.1 or 4.10.6	See sections 4.10.1/ 4.10.6	See sections 4.10.1/ 4.10.6	Further/closer evaluation

Table 8b. Tests for monthly/quarterly QC of electronic display systems performed by a medical physicist, or by a QC technologist under the supervision of a medical physicist.

Test	Major Required Tools		Procedure	Acceptance Criteria (for two classes of displays)		Suggested Action (if unacceptable)
	Equipment	Patterns		Primary	Secondary	
Geometric distortions	None	TG18-QC	See section 4.1.3.1	See section 4.1.3.2	See section 4.1.3.2	Further/closer evaluation
Reflection	Luminance and illuminance meters	TG18-AD	See sections 4.2.3 and 4.2.4	$L_{min} \geq 1.5\ L_{amb}$ (ideally $\geq 4\ L_{amb}$)	$L_{min} \geq 1.5\ L_{amb}$ (ideally $\geq 4\ L_{amb}$)	Readjust the level of ambient lighting
Luminance response	Luminance and illuminance meters	TG18-LN TG18-CT TG18-MP	See sections 4.3.4 and 4.3.3	$L'_{max} \geq 170$ cd/m^2 $LR' \geq 250$ $\Delta L'_{max} \leq 10\%$ $k_\delta \leq 10\%$	$L'_{max} \geq 100$ cd/m^2 $LR' \geq 100$ $\Delta L'_{max} \leq 10\%$ $k_\delta \leq 20\%$	Readjustment, recalibration, repair, or replacement for repeated failures
Luminance dependencies	Luminance meter	TG18-UN TG18-UNL	See sections 4.4.3 and 4.4.4	Non-unif. ≤ 30%	Non-unif. ≤ 30%	Readjustment, repair, or replacement for repeated failures
Resolution	Magnifier	TG18-QC TG18-CX	See sections 4.5.3	$0 \leq Cx \leq 4$	$0 \leq Cx \leq 6$	Focus adjustment, repair, or replacement for repeated failures

Table 8c. Tests for annual quality control of electronic display systems performed by a medical physicist.

Test	Major Required Tools		Procedure	Acceptance Criteria (for two classes of displays)		Suggested Action (if unacceptable)
	Equipment	Patterns		Primary	Secondary	
Geometric distortions	Flexible ruler	TG18-QC	See section 4.1.4	Deviation ≤ 2%	Deviation ≤ 5%	Readjustment, repair, or replacement for repeated failures
Reflection	Luminance and illuminance meters	TG18-AD	See sections 4.2.3 and 4.2.4	$L_{min} \geq 1.5\ L_{amb}$ (ideally $\geq 4\ L_{amb}$)	$L_{min} \geq 1.5\ L_{amb}$ (ideally $\geq 4\ L_{amb}$)	Readjust the level of ambient lighting
Luminance response	Luminance and illuminance meters	TG18-LN TG18-CT TG18-MP	See sections 4.3.4 and 4.3.3	$L'_{max} \geq 170$ cd/m^2 $LR' \geq 250$ $\Delta L_{max} \leq 10\%$ $k_\delta \leq 10\%$	$L'_{max} \geq 100$ cd/m^2 $LR' \geq 100$ $\Delta L_{max} \leq 10\%$ $k_\delta \leq 20\%$	Readjustment, recalibration, repair, or replacement for repeated failures
Luminance dependencies	Luminance meter	TG18-UNL	See section 4.4.4	Non-unif. ≤ 30%	Non-unif. ≤ 30%	Readjustment, repair, or replacement for repeated failures
Resolution[a]	Luminance meter, magnifier	TG18-QC TG18-CX TG18-PX	See sections 4.5.3 and 4.5.4.1.2	0 ≤ Cx ≤ 4 $\Delta L \leq 30\%$ RAR=0.9-1.1 AR ≤ 1.5	0 ≤ Cx ≤ 6 $\Delta L \leq 50\%$	Focus adjustment, repair, or replacement for repeated failures
Noise	None	TG18-AFC	See section 4.6.3	All targets visible except the smallest	Two largest sizes visible	Reverification of luminance response, otherwise replacement
Veiling glare	Baffled funnel, telescopic photometer	TG18-GV TG18-GVN TG18-GQs	See sections 4.7.3 and 4.7.4	≥3 targets visible, GR ≥ 400	≥1 target visible, GR ≥ 150	Reverification of luminance response, otherwise replacement
Chromaticity	Colorimeter	TG18-UNL80	See section 4.8.4	$\Delta(u',v') \leq 0.01$	None	Replacement

[a]More objective resolution measurements can be performed as described in section 4.5.4, using a digital camera.

APPENDIX I. EVALUATION OF “CLOSED” DISPLAY SYSTEMS

This report focuses primarily on “open” systems. An open system is one that allows user-introduced digital test patterns to be retrieved from a PACS or local archive and displayed for the purposes of monitor evaluation and calibration. These monitors are primarily used for display of diagnostic images residing in a PACS.

In diagnostic imaging today, the some clinical display systems are not open systems. Those may include display devices dedicated to one system intended to display only images obtained on that system (e.g., a fluoroscopy system or a CT scanner). Typically, the only controls available to the operator of such systems are contrast and brightness. There may be no way to calibrate the grayscale display function, no way to display a TG18 test pattern, and no tools present for image manipulation. The manufacturers of these systems may provide test patterns of their own design, but in most cases these are inadequate to meet the display assessment requirements of this report. These systems are referred to as closed systems.

Because the capabilities of closed systems vary considerably among manufacturers, recommendations for QC on closed systems cannot be uniformly established. This appendix establishes general QC methodology, which should be adapted wherever feasible. Manufacturers are strongly encouraged to migrate toward open systems for all of their displays in order to facilitate clear specification and fair evaluation in a standardized environment. This will include the development of systems that allow the introduction of user-defined DICOM-compliant images into the local image database. This is most easily accomplished with systems that are capable of performing DICOM Query/Retrieve from any DICOM-compliant PACS.

I.1 General Considerations

I.1.1 Preliminary Communications

Prior to purchase, it is important to include specifications of the size of the active area, the resolution or number of scan lines, color/spectral luminance, monochrome vs. color display, dynamic range, and magnetic shielding. These requirements will vary depending upon the intended use of the system, such as fluoroscopy, CT, US, MRI, digital spot imaging, etc. A service and/or calibration schedule including the services to be provided, tests to be performed, and the service/calibration intervals will need to be agreed upon prior to purchase.

I.1.2 Component Inventory

At acceptance testing, verify the characteristics of the monitors delivered against those specified in the purchase agreement. Keep a log of the monitors and display devices in use. Record information such as monitor type, size, resolution, manufacturer, model, serial number, manufacture date, room number, monitor ID (if applicable), type of test pattern used, etc. It may not be possible to use the same test pattern source for all monitors in the department. However, it is essential to utilize the same pattern for repeat evaluations of a given monitor.

I.2 Preparation for Evaluation

I.2.1 Instrumentation Needed

A variety of special tools are needed for acceptance and QC testing of monitors. The following instrumentation is recommended:

1. Digital test pattern images from the system, or from digital distribution media. Short of availability of TG18 test patterns, SMPTE or other multipurpose test patterns stored on the imaging system may be used. The same pattern(s) should be utilized whenever a test is initiated. In the absence of any suitable test pattern on the system, a video test-pattern generator (equipped with TG18-QC, SMPTE, or other multipurpose test patterns) will need to be utilized. The video signal from the pattern generator should have the same peak voltage, refresh rate, and line rate as that from the image source.
2. Calibrated luminance-meter (see section 3.1.1.1).
3. Calibrated illuminance meter (see section 3.1.1.2).
4. Calibrated colorimeter (see section 3.1.1.3).
5. Glass-cleaning solution and lint-free cloth or paper.
6. Flexible ruler or small tape measure.
7. Screwdriver (for accessing rear panel).
8. Mask (for accurate positioning of instruments), if desired. If a mask is used, it must be used in every subsequent evaluation of the display device.

I.2.2 Initial Steps

Follow the initial steps as outlined in section 5.1.4, keeping in mind that DICOM calibration may not be applicable to many closed systems.

I.2.2.1 Special Considerations for Operator Console Displays

Console display devices are used in one of two ways: without and with operator adjustment of brightness and contrast settings. The QC procedures for these devices vary, depending upon which of these operations is used.

As an example of the first kind, many CT departments utilize preprogrammed brightness and contrast settings for hard-copy production. This is possible because the CT number associated with a particular type of tissue varies insignificantly assuming correct CT calibration and the use of consistent kV. The operator makes no adjustments to the image density or contrast. In this case, the QC program should guarantee that, for a given data set with window width (WW) and level (WL) set in a prescribed manner, the contrast and brightness of the hard-copy image are constant from copy to copy over time. If multiple CT devices are in use, the same dataset from any scanner, having WW and WL set in the prescribed manner, should also result in the same hard-copy image density and contrast from scanner to scanner. The appearance of the CT image on the control console monitor has no bearing on the contrast and density of the final hard-copy image. This is an example of a system operated without adjustment of the image by the operator. Calibration of these monitors may be performed without reference to the corresponding hard-copy image. For such systems, the maximum and minimum luminance values are adjusted according to the guidelines provided in section 4.2 or to the manufacturer's recommendations. A test pattern (SMPTE or preferably TG18-QC) containing luminance patches that are larger than the luminance meter's detector head (electronic magnification may be used, if necessary) may be used for this purpose.

Other modalities do not lend themselves to the use of prescribed WW and WL settings. For example, in MRI the signal strength associated with a glioma may not be reproducible from scan to scan even on the same patient. In order to properly record the pathology of interest, operator adjustment of WW and WL is essential. These adjustments are made by viewing the data set at a video monitor with the expectation that the resulting hard copy will match the image on the monitor. Therefore, it is essential that the contrast and brightness settings on the monitor be adjusted such that the contrast transfer function (CTF) of the monitor closely approximates that of the printer. For such systems, the brightness and contrast settings should be adjusted to match the appearance of images on the operator consoles and hard-copy prints. This is a challenging task, as equivalent appearance depends on factors such as the ambient light level at the console and the response of the operator's visual system, which will vary among individuals. Initially, the calibration of the hard-copy printer should be verified. The adjustment of the console is best performed by setting up the display with several operators present. Generate a print of a test pattern (SMPTE or preferably TG18-QC). With the test pattern displayed on the monitor, adjust the brightness and contrast settings on the monitor to match the hard copy as closely as possible. When all observers agree that the monitor accurately reflects (or resembles as closely as possible) the contrast seen in the hard-copy image, the monitor is considered calibrated. Measure the luminance levels of the maximum, minimum, and two or three intermediary brightness patches of the displayed test pattern, and record these for future reference.

I.3 Display Evaluation Procedures

Ideally, as many as possible of the tests outlined in sections 5 and 6 should be performed on "closed" systems. Displays used for diagnosis of medical images (exam room monitors) should conform to primary specifications. Operator's console displays should conform to secondary specifications (see Tables 7 and 8). As a minimum, the display visual evaluation procedures contained in section 4.10.1 or 4.10.2 should be followed using the TG18-QC or SMPTE test patterns. The test pattern from a video test pattern generator can be simultaneously displayed on two or more monitors by attaching an RG59U video cable from the output of the first monitor to the input of the second (daisy-chain). Check to ensure that both monitors are properly terminated (75 Ω total impedance) and that the test-pattern generator is set to the appropriate peak voltage, refresh rate, and line rate.

The QC procedure should be repeated on a monthly basis for the first quarter of operation and then quarterly thereafter, if the system is proved to be stable enough over time. The tests should also be repeated after any change to the monitor's brightness and contrast settings to maintain constancy. The image appearance should also be compared to that of the hard copy on a quarterly or annual basis. Furthermore, for display systems with more than one display monitor, the performance of various monitors should be benchmarked with respect to each other.

APPENDIX II. EQUIVALENT APPEARANCE IN MONOCHROME IMAGE DISPLAY

Throughout a single institution, the same image data is often presented on multiple display devices. These devices may be laser-printed films, diagnostic workstation monitors, or referring physician workstation monitors. This appendix considers how equivalent appearance of the same image can be achieved on different displays.

Section 4.3 describes two requirements for obtaining equivalent image appearance on multiple display devices. The first requirement is that the devices be calibrated using the same luminance response standard. The DICOM Grayscale Display Function (GSDF), specified in DICOM 3.14 (NEMA 2000), is the model selected for the standardized luminance response. The GSDF provides a well-defined rendering aim so that acquisition modalities can produce image code values with the expectation that the intrinsic response of display workstations and laser-film printers has been calibrated to render image code values to the standard. The second requirement is that the devices have the same luminance ratio, L'_{max}/L'_{min}. When viewing an image, the human visual system adapts to contrast within a limited range of luminance. After adaptation to the overall brightness of an image, the visual system has reduced contrast in brighter and darker regions (see Figure 43, section 4.3). An image viewed on a device with a large luminance ratio (i.e., a film with an optical density range of 0.15 to 3.0 and LR = 708) will have poor contrast in bright and dark regions when compared with the same image display on a device with a small luminance ratio (e.g., a secondary class display with LR = 100). Thus, equivalent appearance requires that images be displayed on GSDF-calibrated devices with the same luminance ratio.

It is notable that equivalent appearance can be achieved with devices having different L'_{max}. While visual perception has poor sensitivity in dark regions, the GSDF increases the contrast between display controller input states, p-values, at low luminance levels. The value of a bright display device is that L'_{min} is large for the same luminance ratio, and therefore higher values of L_{amb} can be tolerated. Bright displays can thus be used in clinical locations where it is impractical to reduce ambient light levels.

Most modern film printers and primary class display devices can be calibrated to the DICOM GSDF. Secondary class display devices can usually be set up to approximate the GSDF. Significant differences in appearance are thus often due to differences in luminance ratio. This is particularly true in medical centers for which imaging systems were originally set up with the expectation that interpretations would be made on printed films. In these circumstances, application grayscale transformations and presentation window and level values are often set up for films printed with high maximum film density (i.e., 2.80 to 3.10), and image values of interest are set to appear in a well visualized range of film densities (i.e., 0.10 to 2.10). For radiographic images, image values printed at higher film densities are then viewed with high brightness spot illuminators. Electronic display devices typically have a lower L'max than film, and ambient lighting restricts the luminance ratio to about 250. This luminance ratio provides good contrast visualization over the full range of image values. However, an image with an application grayscale transformation and presentation window and level intended for film viewing will appear significantly different when viewed on an electronic display with a lower luminance ratio.

When an image needs to be presented on a display with a different luminance ratio, an adjustment in window and level can provide equivalent contrast appearance. The adjustment requires knowledge of the *intended* L'_{max} and L'_{max}/L'_{min} and the *alternative* L'_{max} and L'_{max}/L'_{min}. For an alternative luminance ratio that is less than an intended luminance ratio, a reduced p-value range for presentation of the image is computed by considering the DICOM calibration curve of the intended device and the calibration curve for the alternative device. As illustrated in Figure II.1, the ratio of the JND indices associated with the alternative L'_{max}/L'_{min} to JND indices associated with the intended L'_{max}/L'_{min} (i.e., the ratio of A to B in Figure II.1) is used to narrow the window width. The window level is otherwise set to place the upper level at the maximum p-value. Similar methods are applied when the alternative luminance range is larger than the intended and the window width needs to be adjusted to a larger value. In either case, knowledge of the intended and alternative L'_{max} is required only to properly compute the JNDs associated with both devices (i.e., the length of the lines labeled "A" and "B" in Figure II.1). This can be done using the polynomial expressions or tables published in DICOM 3.14.

Ideally, the intended L_{max} and L_{max}/L_{min} should be included in an appropriate data element of the image object. When a remote display device displays this image, the window width and level may be automatically adjusted to account for differences in L_{max}/L_{min} relative to the intended value stored in the image object. If the luminance range of the alternative device is the same as the intended device, the full range of p-values is displayed even if the L_{max} of the alternative device is different. If the luminance range is different, then a change in the range of displayed p-values is required. It should be noted that there is no standard method for communicating the intended L_{max} and L_{max}/L_{min} for an image. However, this is presently being considered as an addition to the DICOM standards for image presentation. In the absence of an automated implementation, present window and level settings for different image object types can be used to make the needed adjustment.

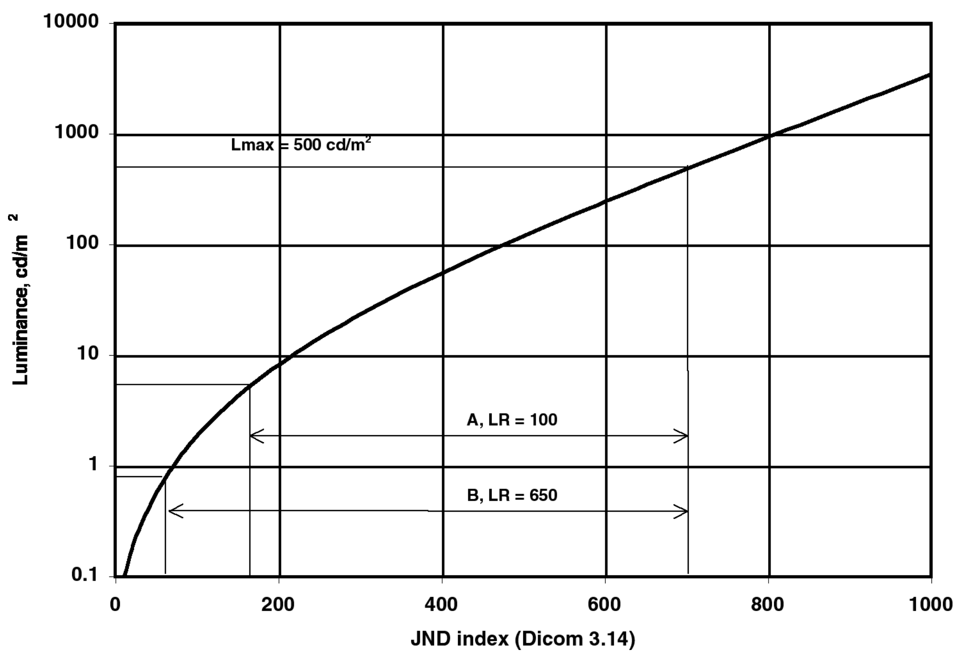


Figure II.1. The window width and level of an alternative display is adjusted to reflect the reduced range of JND indices associated with a reduced luminance range. This is illustrated by comparing the length A to the length B. The upper display level remains the same but the lower display level is increased.

Factors other than contrast may cause the appearance of images displayed on various devices to be different. The size of the presented images will affect the perceived spatial frequency of image features in cycles per millimeter. Since the human visual contrast sensitivity is strongly dependant on perceived spatial frequency, a difference in the size of presented images will cause a difference in contrast perception. Resolution, noise, and ambient reflection may otherwise cause a difference in appearance not related to image contrast.

APPENDIX III. DESCRIPTION OF TG18 TEST PATTERNS

Medical physicists, investigators, vendors, or other users can utilize the authentic copyrighted TG18 patterns supplied in conjunction with this report for any professional, investigational, educational, or commercial purposes. However, the patterns may not be altered in any form or fashion, and their labels may not be removed. Alternatively, with the aid of the descriptions provided in section 3 and appendix III and with the exception of anatomical test patterns, the users may generate patterns similar to the TG18 patterns. To do so, four requirements should be observed:

1. The original reference should be acknowledged.
2. The generated pattern may not duplicate the original TG18 label.
3. The generated pattern should include a label indicating that it is a synthetic pattern based on the description provided in the TG18 report.
4. If the pattern is scaled (e.g., a new 1.5k × 2k pattern versus the original 1k and 2k patterns), all the specified elements of the original pattern should be present, and the label should indicate that it is a scaled pattern.

In using the patterns, for most patterns, it is essential to have a one-on-one relationship between the image pixels and the display pixels, unless indicated otherwise in the test procedures in section 4. Patterns in DICOM and 16-bit TIFF formats should be displayed with a window and level set to cover the range from 0 to 4095 (WW = 4096, WL = 2048), except for the TG18-PQC, TG18-LN, and TG18-AFC patterns, where a WW of 4080 and WL of 2040 should be used. For 8-bit patterns, the displayed range should be from 0 to 255 (WW = 256, WL = 128).

Table III.1. Description of multipurpose test patterns.

Test Pattern/Features	Pixel Dimensions and Location (1k [2k] size)	Pixel Values (8-bit [12-bit])
TG18-QC		
Background	1024 × 1024 [2048 × 2048]	128 [2048]
Crosshatch	Spacing: 102 × 102 [204 × 204] Width: 1 [1]; 3 [3] around central region.	191 [3071]
Luminance patches: - 16 levels, equally spaced	102 × 102 [204 × 204]; clockwise increasing luminance in central region (see Table III.8).	8, 24, …, 248 [128, 384, …, 3968]
- Low contrast corners	10 × 10 [20 × 20]; in corners of 16 uniform patches.	+4 [64] in upper left-lower right –4 [64] in lower left-upper right
- Min/Max levels	102 × 102 [204 × 204]; lower central region.	0 [0] and 255 [4095]
- Contrast at Min/Max levels	51 × 51 [102 × 102]; centered in Min/Max patches.	Min: 0/13 [0/205] Max: 242/255 [3890/4095]
Line pairs (horizontal and vertical grilles)	46 × 46 [92 × 92]; Nyquist (1 on, 1 off) and half-Nyquist (2 on, 2 off) frequencies; at center and four corners of pattern.	High contrast: 0,255 [0,4095] Low contrast: 128,130 [2048,2088]
Cx patterns: - Measurement set	46 × 46 [92 × 92]; at center and four corners of pattern.	Background: 0 [0] Cx: 255, 191, 128, 64 [4095, 3071, 2048, 1024]
- Fiducial marker set, 12 levels of defocus	95 × 95 [190 × 190]; clockwise increasing underfocus; numbered –2, –1, 0, 1, …, 9 (see Tables III.8 and III.9).	Maximum contrast input; defocus determined by Kohm et al. (2001)
Luminance ramps	512 × 64 [1024 × 128] aligned vertically on left/right sides of the pattern. Number of lines at constant pixel value: 2 [4] for 8-bit, 1 [1] for 12-bit.	1k: 0, 1, …, 255 [0, 8, …, 4088] 2k: 0, 1, …, 255 [0, 4, …, 4092]
White/Black windows - Outer windows - Inner windows	815 × 25 [1629 × 50]; above central region. 407 × 25 [813 × 50]; above central region.	
Cross talk bars	576 × 86 [1152 × 172]; along top of pattern. Bar lengths: 256, 128, …, 1 [512, 256, …, 1] Bar height: 3 [6] Central vertical bar 6 × 86 [12 × 172]	13/242 [205/3890]

Table III.1. (continued)

Test Pattern/Features	Pixel Dimensions and Location (1k [2k] size)	Pixel Values (8-bit [12-bit])
Low-contrast letters: "QUALITY CONTROL"	Bold capital letters, 23 [46] pixels high; in uniform background areas below central region.	Maximum contrast: 0/255 [0/4095] –6 [–96] and +6 [+96] at the upper and lower portions. Backgrounds: 0, 128, 255 [0, 2048, 4095]. Letters at +1 to +14 [16 to 224] above background.
Border	Width: 3 [3]. Inset: 10 [20].	191 [3071]
TG18-BR		
Test Pattern #4	See references (Briggs 1979, 1987).	
TG18-PQC		
Right luminance ramp	87 × 1024 [174 × 2048] Center 29 [58] columns.	255-0 [4080-0] ramp, last 7 rows at 0 [0] modulated by 0 [0], 0 [+8], 0 [+12], 0 [+8], 0 [0], 0 [-8], 0 [-12], 0 [-8], … cyclically for sequential rows.
Left luminance ramp	87 × 1024 [174 × 2048] Center 29 [58] columns.	0-255 [0-4080] ramp, last 7 rows at 255 [4080] modulated by 0 [0], 0 [+8], 0 [+12], 0 [+8], 0 [0], 0 [-8], 0 [-12], 0 [-8], … cyclically for sequential rows.
Top section	850 × 62 [1700 × 124]	Alternating rows changing between 0 [0] and 255 [4080]
Bottom section	850 × 62 [1700 × 124]	Alternating rows changing between 0 [0] and 255 [4080]
18 horizontal steps of 850 × 50	Mean values of 0 [0], 15 [240], [1700 × 100]. Each horizontal step modulated differently for each of 17 50 × 50 [100 × 100] squares.	30 [480], … 255 [4080]
Mid section	Central squares have constant value with the borders marked with high contrast.	The inner 4 squares are modulated by ±1 [16] (0.4%) except for the first and last steps with the max and min values that have modulation of +2 [32] or –2 [32].
	Left 8 squares have horizontal square wave modulation with two groups having line widths of 2, 3, 5, and 8 pixels.	The outer 4 squares are modulated by ±5 [80] (2%) except for the first and last steps with the max and min values that have modulation of +10 [160] or –10 [160]
	Right 8 squares identical to the left ones except for orientation of patterns (vertical)	Same as above.

Table III.2. Description of luminance test patterns.

Test Pattern/Features	Pixel Dimensions and Location	Pixel Values (8-bit [12-bit])
TG18-CT		
Background	1024 × 1024	128 [2048]
Luminance patches: - 16 levels, equally spaced	102 × 102, separated by 51; ordered in 4 × 4 matrix, diagonal zigzag increment, centered in pattern.	8, 24, …, 248 [128, 384, …, 3968]
- Low contrast corners	10 × 10; in four corners of each luminance patch.	+4 [64] in upper left-lower right –4 [64] in lower left-upper right
- Low contrast central disk (half moon)	Diameter: 34	±2 [32] + on right half, – on left half
TG18-LN{8,12}-nn		
Background	1024 × 1024	153 [2457] (~20% of peak luminance)
Luminance measurement areas: nn = 01 to 18	324 × 324 (10% of full area); centered in background.	0, 15, … , 255 [0, 240, … , 4080]
TG18-UN{10,80}		
Background	1024 × 1024	26 [410] or 204 [3276]
TG18-UNL{10,80}		
Background	1024 × 1024	26 [410] or 204 [3276]
Borders of measurement areas	324 × 324 (10% of full area), 1 pixel wide; at center and four corners of pattern.	128 [2048]
TG18-AD		
Background	1024 × 1024	0 [0]
Horizontal line pairs	60 × 60 blocks; half-Nyquist frequency (2 on, 2 off); in 7 × 7 block array, centered in pattern.	Bright lines at pixel value = C+7R, where C is column number (1 to 7) and R is row number (0 to 6). For 12-bit, multiply pixel values by 4.
Grid	Spacing: 60 × 60. Width: 2.	50 [200]
TG18-MP		
Background	1024 × 1024	16 [256]
Vertical ramps	16 768 × 48 ramps	Each ramp:48 [3] horizontal lines per pixel value.
Border	770 × 770, pixel-wide bordering the ramp area.	Pixel value = 32 [512]
Markers	1 × 3 and 1 × 5 markers for various bit transitions.	4 1 × 3 markers per 8 bit transition [1 × 3 markers for 10 bit and 1 × 5 markers for 8 bit transitions]. Pixel value = pixel value of the adjacent lines +16 [256] (left half) and –16 [256] (right half).

Table III.3. Description of resolution test patterns.

Test Pattern/Features	Pixel Dimensions and Location	Pixel Values (8-bit [12-bit])
TG18-R{H,V}{10,50,89}		
Background	1024 × 1024 [2048 × 2048]	51 [819]
Measurement areas	324 × 324 [648 × 648] (10% of full area); at center and four corners of pattern.	26, 128, 228 [410, 2048, 3656]
Horizontal or vertical line	Length: 324 [648]. Width: 1 [1]. Centered in each measurement area.	+12% pixel value contrast: 29, 143, 255 [459, 2293, 4095]
Position markers	Four single pixels at corners of square, 60 [120] pixels wide, centered in each measurement area.	128, 26, 128 [2048, 410, 2048]
TG18-PX		
Background	1024 × 1024 [2048 × 2048]	0 [0]
Array of single pixels	Single pixels on 100 × 100 [200 × 200] grid; reduced contrast arrays offset by 25 [50].	255, 191, 128, 64 [4095, 3071, 2048, 1024]
TG18-CX		
Background	1024 × 1024 [2048 × 2048]	0 [0]
Cx patterns: - Measurement set	7 × 7 Cx repeated with 90° rotations over entire pattern.	255, 191, 128, 64 [4095, 3071, 2048, 1024]
- Fiducial marker set, 12 levels of defocus	95 × 95 [190 × 190] patches; clockwise increasing underfocus around central region; numbered -2, -1, 0, 1, … , 9 (see Tables III.8 and III.9).	Maximum contrast input; defocus determined by Kohm et al. (2001).
TG18-LP{H,V}{10,50,89}		
Background	1024 × 1024 [2048 × 2048]	26, 128, 228 [410, 2048, 3656]
Line pairs: Horizontal or vertical	Nyquist frequency (1 on, 1 off) over entire pattern.	+12% contrast: 29, 143, 255 [459, 2293, 4095]

Table III.4. Description of noise test patterns.

Test Pattern/Features	Pixel Dimensions and Location	Pixel Values (8-bit [12-bit])
TG18-AFC		
Background	1024 × 1024 size Divided into quadrants with 4 pixel wide lines. Each quadrant divided into an 8 × 8 set of square boxes by 2 pixel wide lines.	128 [2040] Line values = 143 [2280]
Center and four quadrants	128 × 128 regions containing 16 small square low contrast object arranged in a 4 × 4 pattern. Size of the objects from top to bottom with square dimensions, of 2, 3, 4, and 6 pixels.	Objects values from left to right, background plus 2, 3, 4, and 6 [32, 48, 64, and 96] (contrasts 0.8%, 1.2%, 1.6%, 2.4%).
	In each small box filling the quadrants, a small square low contrast object randomly placed in one of four subquadrants of the box. upper left quadrant: size = 2 upper right quadrant: size = 3 lower left quadrant: size = 4 lower right quadrant: size = 6	Values = background + upper left quadrant, 2 [32] upper right quadrant, 3 [48] lower left quadrant, 4 [64] lower right quadrant, 6 [96]
TG18-NS{10,50,89}		
Background	1024 × 1024	51 [819]
Measurement areas	324 × 324 (10% of full area); at center and four corners of pattern.	26, 128, 228 [410, 2048, 3656]
Position markers	Four single pixels at corners of 60-pixel square, centered in each measurement area.	128, 26, 128 [2048, 410, 2048]

Table III.5. Description of glare test patterns.

Test Pattern/Features	Pixel Dimensions and Location	Pixel Values (8-bit [12-bit])
TG18-GV		
Background	1024 × 1024	0 [0]
White annulus	Inner, outer radii: 15, 300. Centered in pattern.	255 [4095]
Low-contrast disks	Diameter: 9. Five disks, equally spaced inside inner radius of white annulus.	2, 4, 6, 8, 10 [32, 64, 96, 128, 160]
TG18-GVN		
Same as TG18-GV but *without* white annulus.		
TG18-GQ		
Background	1024 × 1024	0 [0]
White annulus	Inner, outer radii: 15, 300. Centered in pattern.	255 [4095]
TG18-GQN		
Same as TG18-GQ but *without* white annulus.		
TG18-GQB		
Same as TG18-GQ but with white disk replacing annulus	Radius: 300. Centered in pattern.	255 [4095]
TG18-GAr		
Background	1024 × 1024	0 [0]
White annulus	Outer radius: 300. Centered in pattern. Inner radius, r: 3, 5, 8, 10, 15, 20, 25, or 30.	255 [4095]

Table III.6. Description of anatomical test patterns.

Test Pattern/Features	Pixel Dimensions and Location	Pixel Values (8-bit [12-bit])
TG18-CH	PA chest test pattern (see 3.2.6.1). 2048 × 2048	12-bit range: 8 to 3944
TG18-KN	Knee test pattern (see 3.2.6.2) 2048 × 2048	12-bit range: 2 to 3902
TG18-MM1	Mammogram test pattern 1 (see 3.2.6.4). 2048 × 2048	12-bit range: 0 to 4095
TG18-MM2	Mammogram test pattern 1 (see 3.2.6.4). 2048 × 2048	12-bit range: 0 to 4095

Table III.7. Pixel values used in TG18 test patterns.

Percent of Maximum Pixel Value	8-bit Pixel Value	12-bit Pixel Value
0	0	0
1	3	41
5	13	205
10	26	410
11.2	29	459
20	51	819
25	64	1024
50	128	2048
51	130	2088
56	143	2293
60	153	2457
75	191	3071
80	204	3276
89.3	228	3656
95	242	3890
100	255	4095

Table III.8. TG18-QC pattern: luminance levels with 8-bit and [12-bit] pixel values and Cx ratings.

Level 6 88 [1408]	**Level 7** 104 [1664]	**Level 8** 120 [1920]	**Level 9** 136 [2176]	**Level 10** 152 [2432]	**Level 11** 168 [2688]
Level 5 72 [1152]	**Cx 2**	**Cx 3**	**Cx 4**	**Cx 5**	**Level 12** 184 [2944]
Level 4 56 [896]	**Cx 1**			**Cx 6**	**Level 13** 200 [3200]
Level 3 40 [640]	**Cx 0**			**Cx 7**	**Level 14** 216 [3456]
Level 2 24 [384]	**Cx -1**	**Cx -2**	**Cx 9**	**Cx 8**	**Level 15** 232 [3712]
Level 1 8 [128]	**0 / 5%** 0 / 13 [0 / 205]			**100 / 95%** 255 / 242 [4095 / 3890]	**Level 16** 248 [3968]

Table III.9. The blurring characteristics of the Cx reference set utilized in TG18-QC and TG18-CX test patterns (Kohm et al. 2001).

Ref No.	Standard Deviation of blurring in pixels	Corresponding RAR
–2	$0.35\sigma_1$, $0.875\sigma_2$*	NA
–1	$0.3\sigma_1$, $0.99\sigma_2$*	NA
0	0	1 (perfect)
1	0.339	0.80
2	0.383	0.90
3	0.432	1.02
4	0.488	1.15
5	0.551	1.30
6	0.622	1.47
7	0.703	1.65
8	0.794	1.87
9	0.896	2.11

*Profile = 0.85 $N(\sigma_1)$ + 0.15 $N(\sigma_2)$, where N is Gaussian distribution.

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