Digital Radiography Image Quality: Image Processing and Display

Elizabeth A. Krupinski, PhD[a], Mark B. Williams, PhD[b], Katherine Andriole, PhD[c], Keith J. Strauss, MS[d], Kimberly Applegate, MD, MS[e], Margaret Wyatt[f], Sandra Bjork, RN, JD[f], J. Anthony Seibert, PhD[g]

This article on digital radiography image processing and display is the second of two articles written as part of an intersociety effort to establish image quality standards for digital and computed radiography. The topic of the other paper is digital radiography image acquisition. The articles were developed collaboratively by the ACR, the American Association of Physicists in Medicine, and the Society for Imaging Informatics in Medicine. Increasingly, medical imaging and patient information are being managed using digital data during acquisition, transmission, storage, display, interpretation, and consultation. The management of data during each of these operations may have an impact on the quality of patient care. These articles describe what is known to improve image quality for digital and computed radiography and to make recommendations on optimal acquisition, processing, and display. The practice of digital radiography is a rapidly evolving technology that will require timely revision of any guidelines and standards.

Key Words: Digital radiography, image quality, image display, soft-copy display, image processing, workstation

J Am Coll Radiol 2007;4:389-400. Copyright © 2007 American College of Radiology

INTRODUCTION AND OVERVIEW

Image quality is affected by a number of factors, beginning with the acquisition process and device and including the manner in which images are displayed. In digital systems, the functions of acquisition and display are clearly separable, so that the evaluation and optimization of image quality can take place at both ends of this imaging continuum. The analysis of image quality also depends on the particular type of imaging task [1-3]. Digital radiography is used in a wide variety of imaging tasks (eg, chest, musculoskeletal, genitourinary), but there are basic image-quality parameters that can be defined that are applicable to all of these tasks.

This paper on image processing and the display of digital radiography images, together with its companion paper on image acquisition, was developed with reference to information available in the peer-reviewed medical literature. The companion paper on image acquisition contains in its introduction a common definition of digital radiography that serves as a reference point for both articles. Briefly, in this guideline, the term *digital radiography* refers to all types of digital radiographic systems, including those historically termed *computed radiography* and those historically termed *digital radiography*. This guideline is applicable to the practice of cassette and cassetteless digital radiography.

It defines equipment guidelines, specifications of data manipulation and management, and quality control and quality improvement procedures for the use of digital radiography that should result in high-quality radiologic care. In all cases for which an ACR practice guideline or technical standard exists for the modality being used or the specific examination being performed, that guideline or standard will continue to apply when digital image data management systems are used. A glossary of commonly used terminology and a reference list are included.

[a]Department of Radiology, University of Arizona, Tucson, Ariz.

[b]Department of Radiology, University of Virginia, Charlottesville, Va.

[c]Department of Radiology, Brigham and Women's Hospital, Harvard Medical School, Boston, Mass.

[d]Department of Radiology, Children's Hospital, Harvard University, Boston, Mass.

[e]Department of Radiology, Indiana University, Indianapolis, Ind.

[f]American College of Radiology, Reston, Va.

[g]Department of Radiology, University of California, Davis, Sacramento, Calif.

Corresponding author and reprints: J. Anthony Seibert, PhD, University of California, Davis, Department of Radiology, 4860 Y Street, Suite 3100, Sacramento, CA 95817; e-mail: jaseibert@ucdavis.edu.

0091-2182/07/$32.00 • DOI 10.1016/j.jacr.2007.02.001

EQUIPMENT SPECIFICATIONS AND EXISTING STANDARDS

Specifications for equipment used in digital image data management will vary depending on the application and the individual facility's needs, but in all cases they should provide image quality and availability appropriate to the clinical needs, whether those needs be official interpretation or secondary review. Compliance with the current Digital Imaging and Communications in Medicine (DICOM) standard of the ACR and the National Electrical Manufacturers Association (especially part 14, on gray-scale displays) [4] is strongly recommended for all new equipment acquisitions, and consideration of periodic upgrades incorporating the expanding features of that standard should be part of ongoing quality control programs. Compliance with the Radiological Society of North America and the Healthcare Information and Management Society's Integrating the Healthcare Enterprise initiative [5], as embodied in the available technical frameworks, also is strongly recommended for all new equipment acquisitions.

Relevant standards for the soft-copy display of images have been summarized in the literature [6] and include Society of Motion Picture and Television Engineers (SMPTE) Recommended Practice 133-1991 [7,8], the National Electrical Manufacturers Association–DICOM standard (PS 3) [4], Deutsches Institut für Normung V 6868-57 [9], International Organization for Standardization 9241 and 13406 series [10,11], the Video Electronics Standards Association Flat Panel Display Measurements standard [12,13], American Association of Physicists in Medicine (AAPM) Task Group 18 Recommendations and Standards [14], and Integrating the Healthcare Enterprise Consistent Presentation of Images [15]. Each provides guidance and tools for the acceptance and quality testing of medical display devices and should be consulted if further detailed information is desired.

IMAGE DISPLAY TECHNOLOGY

Display device guidelines are currently divided according to two basic categories of digital image data set size when used for rendering an official interpretation: small matrix size (eg, computed tomography, magnetic resonance imaging, ultrasound, nuclear medicine, digital fluorography, and digital angiography) and large matrix size (eg, digital radiography, computed tomography, digitized radiographic films, and digital mammography). This guideline covers only the use of nonmammography large-matrix images. Specific guidelines for digital mammography can be found in the ACR's Practice Guideline for Determinants of Image Quality in Digital Mammography (proposed for 2007 [6,16]). The present guidelines also apply to primary displays or those used for diagnostic interpretation. Secondary displays (eg, those used by clinicians or technologists) for radiographic images do not need to adhere to these guidelines as long as the images are not used for primary interpretation purposes. A number of authors have reviewed the factors that contribute to image quality in soft-copy reading of radiographic images [17-19]. The minimum quality specifications are summarized here.

Matrix Size and Display Size

Soft-copy displays should render images with sufficient pixel density to allow viewing of the whole image with sufficient spatial detail at a normal viewing distance of approximately 30 to 60 cm (with eyeglasses specifically selected for this distance when required). Matrix size should be as close to the for-processing image data as possible, or attainable with magnification. A 5-megapixel (MP) (2,048 × 2,560 pixels) monitor (usually in portrait mode with a diagonal dimension of 54 cm [21 in]) exceeds the matrix size stipulated by the ACR's standard of a resolution of at least 2.5 lp/mm at the detector plane when acquiring a 35 × 43 cm image (equivalent to 14 × 17 in), and thus is sufficient for viewing all types of computed radiographic and digital radiographic images in a single view. Note that the US Food and Drug Administration recommends that only monitors that have been approved for digital mammography be used for interpreting digital mammography images [6,16].

A 1-MP (1,024 × 1,280 pixels), 2-MP (1,200 × 1,600 pixels), or 3-MP (1,536 × 2,048 pixels) monitor will not permit full simultaneous viewing of 35 × 43 cm images at a detector plane resolution of 2.5 lp/mm. For those images, zooming and roaming display functions are required to achieve a correspondence between the detector element matrix and the display pixel matrix so that the resolution of the display monitor does not limit the resolution of the partially displayed image. This is true for any size image for which the detector element matrix size exceeds the display pixel matrix size.

Luminance and Contrast

The luminance of a display can affect image quality significantly, so the appropriate range of luminance should be maintained. The ratio of maximum luminance to minimum luminance of a display device for images (other than for mammography) should be at least 100. The maximum luminance of gray-scale monitors used for viewing digital conventional radiographs should be at least 200 cd/m^2. Smaller ranges could lead to inadequate levels of contrast in displayed images, and larger values could lead to poor visualization of details at the extremes of the luminance range because of the limited range of the contrast sensitivity of the human eye. The contribution of ambient light reflected from the display surface should be included in luminance measurement considerations, because some level of ambient light is always present. Luminance should be as uniform as possible across the entire display.

The contrast response of a display should comply with the AAPM Task Group 18 recommendations [8]. A high display contrast ratio with a low minimum luminance level (0.5 cd/m^2) is most desirable. Contrast response should not deviate from the DICOM Grayscale Standard Display Function (GSDF) contrast values by more than 10% [4].

Bit Depth

It is necessary for a soft-copy display device to render image details with sufficient luminance quantification to prevent the loss of contrast details or the appearance of contour artifacts. Thus, a minimum of 8-bit luminance resolution (bit depth) is required. Nine-bit resolution or higher is recommended if the for-processing image data are greater than 8-bit. In general, the higher the luminance ratio of the display, the larger the bit-depth resolution that is recommended.

Display Calibration

All monitors and corresponding video graphics cards used for primary diagnosis or for image adjustment and evaluation (eg, a technologist review monitor) must provide a means to be calibrated to and conform to the current DICOM GSDF perceptual linearization methods [4,14]. The intent of the DICOM GSDF is to allow images transferred using the DICOM standard to be displayed on any DICOM-compatible display device with a consistent gray-scale appearance.

Additional factors to consider when characterizing a soft-copy display for interpreting medical images include the modulation transfer function and noise. The modulation transfer function at the Nyquist frequency of the display should be greater than 35%, as recommended by the AAPM Task Group 18 documents [14]. A display device also should not add more than a third of the noise of a typical image, limiting the display relative noise to 0.6% to 0.8%.

Desirable display calibration features include remote performance monitoring, calibration, and quality control. Monitor set matching of contrast ratio, brightness, and color are generally accomplished with the DICOM GSDF, although color does not have a standard calibration method to date.

Glare and Reflections

Veiling glare or the spread of light within the display can reduce contrast, so the glare ratio should be greater than 400 for primary displays. Reflections from ambient light sources should be kept at a minimum. Indirect and backlight incandescent lights with dimmer switches rather than fluorescent lights are recommended. Light-colored clothing and laboratory coats can increase reflections and glare. The intrinsic minimum luminance of a device should not be smaller than the ambient luminance (minimum luminance should be at least 2.5 times ambient light). Cathode ray tube (CRT) displays typically have antiglare coatings that can help reduce these effects, but not eliminate them. Protective shields on liquid crystal displays (LCDs) add to reflections and should not be used if possible.

Color Tint and Color Displays

Both monochrome and color displays have a color tint that is a function of where the manufacturer sets the white point. The tint of the display can affect the comfort of the user. The color tint of the display (blue, gray, yellow, etc) is based on user preference but should be uniform across the display area, and monitor pairs should be matched from the same manufacturing batch.

Currently, most color displays have lower luminance and thus lower contrast ratios than monochrome displays and are generally not recommended for viewing certain radiographic modalities (chest, bone, mammography). There are currently no accepted standards or guidelines available for calibrating color displays when viewing gray-scale radiographic images, so care should be taken. The DICOM GSDF can be applied to color displays but does not fully address this issue of calibration of color displays.

Technology-Specific Considerations

Both CRT displays and LCDs can be used as primary display devices. Both require about 30 minutes of warm-up time to reach maximum performance. Flat-surface displays (all LCDs and some CRT displays have flat surfaces) are preferred over those with curved surfaces (most CRT surfaces are curved). On-axis viewing is comparable for CRT displays and LCDs, but off-axis degradations in contrast are still possible with many LCDs and should be taken into account when viewing images on LCDs from nonorthogonal angles. If two displays are placed side by side for viewing images, it is recommended that they be tilted inward toward the viewer to minimize the impact of angular response variation. Angular performance should not lead to a deviation of the contrast response from the DICOM GSDF by more than 30% within the operating ranges of the viewing angles (usually $<30°$).

Secondary Displays

When the display systems are not used for the official interpretation, they need not meet all the characteristics listed above. If they are being used by a technologist to judge image quality during acquisition, consideration should be given to using a display as similar as possible to the diagnostic one in terms of maximum and minimum luminance, contrast ratio, and conformance to the DICOM GSDF. The display resolution need not be the same as long as zoom and pan (roaming) are easily available to the user so that the full intrinsic resolution of the image can be viewed.

IMAGE PRESENTATION AND PROCESSING CONSIDERATIONS

Display workstations used for the official interpretation of large-matrix systems should be capable of the following: bringing an image up on the workstation in 3 seconds or less; selection of image sequence and display format; flexible hanging protocols tailored to user preferences, with proper labeling and orientation of images; fast and easy navigation between new and old studies; rotating or flipping the images, provided that the labeling of patient orientation is preserved; and accurately associating the patient and study demographic information with the images of the study.

The total number of images acquired in a study needs to be accessible during interpretation. Although they need not all be displayed simultaneously, the use of dual monitors to display as many as possible is desirable. Clinically relevant technical parameters of the acquired image data should be accessible (eg, milliamperes, kilovolts, bit depth, exposure time, and matrix size). It is imperative that the exposure value be displayed on the picture archiving and communication system image to assess technique for dose, quality, and feedback to technologists.

Window and level adjustment tools must be available, because the full dynamic range of most images cannot be viewed on display devices with optimal contrast in all regions. Preset window and level settings (eg, bone or lung windows using set lookup-table transformations) are recommended to increase the speed of user interaction with the display device. It is recommended that the prior application of an irreversible compression ratio, processing, or cropping be noted in the image record.

Zoom (magnification) and pan (roaming) functions capable of meeting guidelines for display at the originally acquired spatial resolutions should be used rather than the user moving closer to the display. Calculating and displaying accurate linear measurements and pixel value determinations (mean and standard deviation) in values appropriate for the modality (eg, Hounsfield units for computed tomographic [CT] images) should be calculated and displayed if those data are available and can be calibrated to the acquisition device.

Most manufacturers apply processing algorithms (which are often proprietary) to optimize image quality, so it is necessary that the nature of these processing steps be made clear to users. It also is necessary to define what is considered for-processing (ie, raw image data before proprietary processing) vs for-presentation (ie, after some processing has been applied) data. Once the image data are transferred to the viewing workstation, they can be further processed using such tools as edge enhancement, histogram equalization, and other grayscale adjustments. Whether these tools actually improve diagnostic accuracy or simply improve the subjective appearance of images deserves further study.

Computer-aided detection (CAD) and computer-aided diagnostic tools for a variety of images and modalities (eg, nodule detection in computed radiographic and CT chest images, polyp detection in CT colonoscopy) are increasingly being approved by the Food and Drug Administration for routine clinical use. In general, these tools have been shown to enhance the performance of radiologists, although the effect may be lower for more experienced and specialized radiologists than for generalists. It is recommended that all CAD and computer-aided diagnostic algorithms begin with the for-processing data rather than the for-presentation data, because many of the algorithms already do a significant amount of image processing. The for-presentation data may alter the effectiveness of the CAD algorithms. It is recommended that radiologists using CAD understand what the CAD and computer-aided diagnostic tools are capable of doing, particularly with reference to their sensitivity and specificity, so that they can better judge the validity of the CAD prompts.

DIGITAL IMAGING READING ENVIRONMENT

The design of the digital reading room can generally influence not only the comfort and fatigue levels of radiologists but also interpretation accuracy [20]. Viewing conditions should be optimized by controlling reading room lighting to eliminate reflections on the monitor and lowering the ambient lighting level as much as feasible. Ambient lights should not be turned off completely nor turned up completely. About 25 to 40 lux is generally sufficient to avoid most reflections and still provide sufficient light for the visual system to adapt to the surrounding environment and the displays [21]. Incandescent lights with dimmer switches are recommended, especially those with natural filters. Fluorescent lights are not recommended. A combination of backlighting with desk side lighting with focused or shielded light (eg, for taking notes) is recommended. If view boxes and film are still being used in the room with soft-copy displays, it is recommended that partitions be put up between them to minimize reflections and glare. If this is not possible, the soft-copy displays should be positioned at 90° angles from the view boxes whenever possible.

With digital displays and their associated computers, it is necessary to ensure adequate airflow, optimal temperature, and humidity controls. It may be necessary, depending on the particular environment, to have direct ventilation for each workstation that is controllable by each user for personal comfort. Water-cooled computers should be considered. Avoid placing monitors in the same area as light boxes or alternators. If necessary, place them at 90° rather that 180° to avoid reflections. Separate each display workstation from others with partitions that can be moved or reconfigured depending on consultation needs.

Noise considerations (computers, fans, etc) are also important to minimize with digital workstations. Water-cooled computers should be considered because they are quieter than fan-cooled computers. Proper shielding (eg, via movable walls) should be considered, especially to isolate dictation systems from each other.

Proper chairs with lumbar support and adjustable height controls (including armrests) are recommended to avoid injuries and excessive fatigue. The workstation table should be height adjustable, and the keyboard, mouse, and monitors should be designed to maximize comfort and efficiency. Dictation tools, Internet access, and other reference tools should be readily accessible and easy to use during image interpretation. Consider ergonomically designed input devices and alternatives to the more traditional mouse and trackball interfaces.

DISPLAY PERFORMANCE AND QUALITY MONITORING

Performance monitoring must be done on each digital radiography device. Performance testing and monitoring of digital display equipment should be maintained in accordance with the equipment manufacturer specifications, applicable industry guidelines, and state and federal regulations. In the absence of adequate manufacturer procedures, guidelines, or standards, the recommendations for the performance evaluation of display devices testing methods and frequencies contained in the AAPM Task Group 18 report, "Assessment of Display Performance for Medical Imaging Systems," [14] should be followed. It should be noted that CRT and LCD devices tend to have different characteristics and may not degrade in the same ways or at the same rates. The same holds true for color vs gray-scale devices. Devices from different manufacturers may also degrade at different rates. In all cases, it is necessary to monitor the display parameters on a regular basis (at least once per month, possibly more frequently as the displays get older, because they tend to drift more with age.) Regular visual inspection also needs to be done on a monthly basis to check for dead pixels, which automatic quality assurance systems do not do.

As a minimum quality check for display devices, a test image, such as the SMPTE [8,22,23] test pattern or the AAPM Task Group 18 pattern, should be captured, transmitted, archived, retrieved, and displayed at appropriate intervals, to test the overall operation of the system under normal operating conditions. As a spatial resolution test, at least 2.5 lp/mm resolution should be confirmed.

As a test of the display fidelity, SMPTE pattern data files should be sized to occupy the full area used to display images. The overall SMPTE image appearance should be inspected to ensure the absence of gross artifacts (eg, blurring or bleeding of bright display areas into dark areas or aliasing of spatial resolution patterns). All display monitors used for primary interpretation should be tested at least monthly. As a dynamic range test, both the 5% and the 95% areas should be seen as distinct from the respective adjacent 0% and 100% areas.

IMAGE TRANSMISSION, RETRIEVAL, AND ARCHIVING

Compression

Data compression may be performed to facilitate transmission and storage. The type of medical image, modality, and the objective of the study will determine the degree of acceptable compression [24-26]. Several methods, including both reversible and irreversible techniques (*lossless* and *lossy* are also common terms), may be used under the direction of a qualified physician or practitioner, with minimal if any reduction in clinical diagnostic image quality. If compression is used, algorithms accepted by the DICOM standard, including wavelet compression methods such as JPEG-2000, are generally recommended. The types and ratios of compression used for different imaging studies transmitted and stored by the system should be selected and periodically reviewed by the responsible physician to ensure appropriate clinical image quality. Regulary bodies may require that the compression ratio be indicated on the compressed image. (See the *ACR's Practice Guideline for Electronic Medical Information Privacy and Security* [27]).

Transmission

The environment in which the studies are to be transmitted will determine the type and specifications of the transmission devices used. In all cases, for official interpretation, the digital data received at the receiving end of any transmission must have minimal, if any, loss of clinically significant information. The transmission system shall have adequate error-checking capability. (See the Practice Guideline for Electronic Medical Information Privacy and Security [27]).

The DICOM Transmission and Storage Standard [28] should be referred to for best practice implementation, especially the DICOM DX Image Information Object Definition. Optimally, all vendors should use the DX object.

Archiving and Retrieval

Digital imaging data management systems should provide storage capacity capable of complying with all facility, state, and federal regulations regarding medical record retention. Images stored at either a transmitting or receiving site should meet the jurisdictional requirements of the acquisition and transmitting site. Images interpreted off site need not be stored at the receiving facility, provided they are stored at the transmitting site. However, if the images are retained at the receiving site, the retention period of that jurisdiction must be met as well. The policy on record retention must be in writing.

Each examination data file must have an accurate corresponding patient and examination database record that includes patient name, identification number, accession number, examination date, type of examination, and facility at which the examination was performed. It is desirable that space be available for a brief clinical history.

Prior examinations must be retrievable from archives in a time frame appropriate to the clinical needs of the facility and medical staff. Each facility should have policies and procedures for archiving digital image data equivalent to the policies for the protection of hard-copy storage media.

The exchange of imaging information should be conducted in accordance with the Integrating the Healthcare Enterprise initiative [5] through the use of current standards by DICOM [28] and Health Level 7 [29].

Security

Medical images are subject to US privacy laws such as the Health Insurance Portability and Accountability Act of 1996 [30] and applicable state privacy requirements. Digital image data management systems should provide network and software security protocols to protect the confidentiality of patients' identification and imaging data as well as appropriate user accessibility and authentication. There should be measures to safeguard the data and to ensure data integrity against intentional or unintentional corruption. For teleradiology purposes, additional software and hardware devices such as virtual private networks may be required to maintain patient privacy. (See the *ACR's Practice Guideline for Electronic Medical Information Privacy and Security* [27]).

Reliability and Redundancy

For facilities practicing electronic radiology, quality patient care depends on the stability and reliability of the digital image data management system. Written policies and procedures must be in place to ensure the continuity of care at a level consistent with those for hard-copy imaging studies and medical records within a facility or institution. This should include internal redundancy systems, backup telecommunication links, and a disaster plan.

SUMMARY: OBSERVATIONS AND CHALLENGES

Digital radiology encompasses a number of modalities and image interpretation tasks. The images are acquired at different resolutions, bit depths, and matrix sizes. The task of a radiologist can vary depending on the nature of the imaging request. This makes the development of a set of guidelines for the whole practice of digital radiology both a necessity and a challenge. The minimum set of guidelines outlined in this document address image quality from a technical perspective. These technical measurements are generally easy to make and comply with the majority of digital radiology reading rooms. Numerous studies have demonstrated clear connections between these types of technical measurements and clinical interpretation performance. The optimized reading environment improves diagnostic accuracy and also may improve the efficiency with which a radiologist interprets images.

One of the main challenges that radiology is currently facing in terms of image quality of displays for interpreting medical images is the widespread availability and relatively low cost of off-the-shelf displays. There are a number of nonmedical commercial displays that are starting to rival the performance of dedicated, high-performance medical displays in terms of resolution and luminance. They are, however, color displays that are not optimized for gray-scale images. Color displays typically have lower contrast ratios (the black levels are not as black as with monochrome displays) and higher noise levels than high-performance medical-grade displays. Both of these parameters have the potential to degrade image quality and hence interpretation accuracy. Further studies are needed in this area.

The appeal of color displays goes beyond low cost. In addition to color Doppler sonography, many radiologic imaging applications are starting to incorporate color. Three-dimensional color renderings of CT and magnetic resonance imaging data are becoming more useful and more popular not only with surgeons but with radiologists. Few studies, however, have been done to demonstrate the influence of these displays on reader accuracy or reader efficiency (workflow). The 3-D renderings also have given rise to the possibility of true stereo color displays being used in radiology interpretation. Radiologists are very efficient at interpreting 3-D information from 2-D images, but these new displays (which do not require shuttered eyeglasses, unlike older stereo displays) may change dramatically the way that information is presented to radiologists. Again, whether these new displays and display techniques can improve reader performance has yet to be studied.

Digital radiography will continue to go through a number of changes in the future, as it has in the past. The ways to display these digital images will continue to change as well. The key point of this document is to raise awareness about the need to maintain high standards of image quality. Even as display technologies change, the need to follow the guidelines outlined in this document will continue. The parameters that we identified and provided minimum standards for are likely to remain the same basic set of parameters that will be important with any type of display. As new display technologies are developed, however, it will be necessary to evaluate them and determine how well they comply with these guidelines.

GLOSSARY

Analog signal. A form of information transmission in which the signal varies in a continuous manner and is not limited to discrete values.

Archive. A repository for digital medical images in a picture archiving and communications system, typically with a specific purpose of providing either short-term or long-term (permanent) storage and subsequent retrieval of images. Erasable or nonerasable media may be used in an archive.

Baud. The number of events processed in one second, usually expressed in bits per second or kilobits per second. Typical telephone rates are 14.4 kBps, 28.8 kBps, and 56 kBps. Digital subscriber line connections have maximum bandwidth of 1.5 MBps, cable modems from 3 to 15 MBps, and Ethernet connections from 10 MBps to several gigabits per second.

Bit (binary digit). The smallest unit of digital information that a computing device handles. It represents one of two possible states: off or on (0 or 1). All data in computing devices are processed as bits or strings of bits.

Bit depth. The number of bits used to encode the signal intensity (grayscale) of each pixel of an image.

Bits per second. See *baud, throughput.*

Byte. A grouping of 8 bits used to represent a character or numeric value.

Candela. A Système Internationale unit of luminance intensity, typically expressed as candelas per square meter.

Carrier. See *data carrier.*

Cathode ray tube (CRT). One type of monitor or display device in digital radiology systems. A cathode ray tube works by moving an electron beam across the back of the screen, lighting up phosphor dots on the inside of the glass tube, and illuminating the active portions of the screen. Successive lines from the top to the bottom create the entire image of the screen.

Central processing unit (CPU). The device in a computer that performs the calculations. It executes instructions (the program) and performs operations on data.

Charge-coupled device (CCD). A photoelectric device that converts light information into electronic information. Charge-coupled devices are commonly used in television cameras and image scanners and consist of an array of sensors that collect and store light as a buildup of electrical charge. The resulting electrical signal can be converted into digital values and processed in a computer to form an image.

Charge-coupled device scanner. A device that uses a charge-coupled device sensor to convert film images into electronic data.

Clock. A component in a computer's processor that supplies an oscillating signal used for timing command execution and information handling.

Clock speed. The rate at which the clock oscillates or cycles. Clock speed is expressed in megahertz, equal to millions of clock cycles per second, or gigahertz, which equals thousands of megahertz.

Complementary metal oxide semiconductor (CMOS). A photosensitive device consisting of an array of individual picture elements (pixels) etched on a crystalline silicon wafer and manufactured using the standard random access memory production process. Light falling on the array produces a proportional charge that is stored in each element. Interconnections between pixels allow for direct addressing, digitization of the accumulated charge, and refreshing the array for the next image capture event.

Compression ratio. The ratio of the size of an original image file to a compressed image file. For example, a compression ratio of 2:1 would correspond to a compressed image half the file size of the original.

Computed radiography (CR). An imaging system that uses a storage phosphor plate instead of film as the image detector contained in the cassette. A laser beam scans the latent image on the exposed storage plate to produce the digital data that is then converted into an image.

Consultation system. A teleradiology system used to determine the completeness of examinations, to discuss findings with other physicians, or for other applications with the knowledge that the original images will serve as the basis for the final official interpretation rendered at some later time by the physician responsible for that report.

Contrast ratio. The ratio of the luminosity of the brightest and darkest luminance signals from a digital display device.

Coprocessor. A device in a computer to which specialized processing operations are delegated, such as mathematical computation or video display. The advantage of a coprocessor is that it significantly increases processing speed.

Data carrier. The signal that is used to transmit data. If this signal is not present, there can be no data communication between modems.

Data communication. All forms of computer information exchange. Data communication may take place between two computers in the same building via a local-area network, across the country via telephone, or elsewhere via a wide-area network.

Data compression. Methods to reduce the data volume by encoding it in a more efficient manner, thus reducing the image processing and transmission times and storage space required. These methods may be reversible or irreversible.

Data transfer rate. The maximum speed at which information is transferred between devices, such as a scanner and a computer; between components within a device, such as between storage and memory in a computer; or between teleradiology stations.

Dedicated line. A telephone line that is reserved for the exclusive use of one customer. It can be used 24 hours a day and usually offers better quality than a standard dial-up telephone line but may not significantly increase the performance of data communication.

Del (detector element). The smallest area of a digital detector discrete array over which a signal is measured. The dimension of the del "aperture" is rectangular (usually square). In some detectors, the active area is a smaller fraction of the total area of the del because of the placement of necessary data lines and charge storage devices that result in lost signal. The ratio of the active area to the total area of the del is known as the "fill factor."

Detective quantum efficiency (DQE). A term used to describe the effectiveness of an imaging system in maintaining the signal-to-noise ratio during the imaging process. It can be interpreted loosely as the ratio of the image quality divided by the dose. Some digital radiographic systems have significantly higher detective quantum efficiency than screen-film systems, resulting in lower patient doses or improved image quality.

Digital Imaging and Communications in Medicine (DICOM). A standard for the interconnection of medical digital imaging devices, developed and sponsored by the ACR and the National Electrical Manufacturers Association, consisting of a standard image file format and a standard communications protocol.

Digital signal. A form of information transmission in which the signal varies in discrete steps, not in a continuous manner.

Digitization. The process by which analog (continuous-value) information is converted into digital (discrete-value) information. This process is a necessary function for computer imaging applications because visual information is inherently in analog format, and most computers can use information only in a digital form. Digitization consists of two steps: sampling in space, which affects the spatial resolution, and quantization in signal intensity, which affects the grayscale bit depth and may give rise to quantization noise.

Direct image capture. Known as digital radiography, the capture or acquisition of digital image data in digital format, requiring no separate laser scanner or film processor.

Diskette drive. A device on a computer that can read and write to small magnetic diskettes. It is used to import and export data using removable media. Other common removable media devices include memory sticks, compact discs, digital videodiscs, and tape, which require CD, DVD, and tape drives, respectively.

Dots per inch (dpi). In conventional radiography, resolution is commonly expressed in line pairs per millimeter, and film digitizer resolution is commonly expressed using units of dots (pixels) per inch.

Dynamic range. The difference in signal intensity, or frequency, between the largest and smallest signals a system can process or display. The optical density is the difference between the lightest and darkest useful regions of the image. Increasing the number of bits per pixel in a digital image increases the dynamic range of the image.

Exposure class. Similar to the term *speed* used with screen-film systems. Exposure class is used to describe the nominal radiation exposure required to obtain a proper radiograph. The new term is used instead of *speed* to reflect the significantly different energy response that digital detectors have compared with screen-film systems.

Exposure value estimate. A quantitative method to estimate the nominal incident radiation exposure required to obtain a proper radiograph. This is a manufacturer-dependent value. Fuji computed radiography uses the sensitivity number, a value that is similar to screen-film speed and inversely related to incident exposure. Agfa computed radiography uses the log of the median exposure determined from the segmented area on the imaging plate, which is a relative logarithmically varying value that is directly related to incident exposure. Kodak computed radiography uses the exposure index, a value that represents the relative measure of the x-ray exposure in the segmented, anatomic regions of the image and is logarithmically varying and directly related to the digital values in the image. Konica computed radiography uses the sensitivity value, a value similar to the sensitivity number, with similar relationships to incident exposure, but estimated and calculated in a different manner than used by Fuji. Imaging Dynamics (a digital radiographic company) uses the f-number, a relative value based on the same concept as in photography in describing relative light intensity ranges; in this situation, negative values represent lower exposure and positive values represent higher exposures than the desired nominal exposure. Other manufacturers have their own exposure value estimates. Users of a particular digital system must understand the meaning of the incident exposure index to be able to make a determination that the exposure was appropriate. The manner in which a vendor identifies the parts of an image that have received direct x-ray exposure or that are collimated has an effect on the calculated exposure index and may lead to errors.

File. A set of digital data that have a common purpose, such as an image, a program, or a database.

Fill factor. The ratio of the active charge collection area to the total physical space occupied by the detector element. Digital flat-panel detectors with better resolution (smaller del dimension) often have lower fill factors and poorer charge collection efficiency.

Floppy diskette. A removable media data storage device made of metal-coated plastic that can store computer information and can be physically transported from one place to another. The storage capacity of floppy diskettes is usually in the range of 360 kB to 1.5 MB, which is too small to be of use in imaging applications.

Giga (G). A prefix that stands for the number 1 billion. It is used primarily when referring to computer storage capacities; for example, 1 GB = 1 billion bytes or 1,000 MB.

Gray-scale. The number of different shades of gray that can be stored and displayed by a computer system related to the number of bits used in digitization. Each bit is binary, composed of a 0 or 1, so the total number of gray levels is the bit depth raised to the power of two: 8 bits = 2^8 = 256 gray levels, 10 bits = 1,024 gray levels, and 12 bits = 4,096 gray levels.

Gray-scale monitor. A black-to-white display with varying shades of gray, ranging from several shades to thousands, thus being suitable for use in imaging. This type of monitor also may be referred to as a monochrome display. (See *monochrome monitor*.)

Grayscale Standard Display Function (GSDF). Described in part 14 of the DICOM standard, which defines a gray-scale display function for monochrome image display device, based on perceptual linearization and defined for the luminance range of 0.05 to 4,000 cd/m^2. It was developed in part to facilitate similarity in gray-scale between different image display devices independent of luminance.

Hard disk drive. An internal computer device used for the storage of data.

Hardware. A collective term used to describe the physical components that form a computer. The monitor, central processing unit, disk drives, memory, modem, and other components are all considered hardware. If you can touch it, it is hardware.

Hospital information system (HIS). An integrated computer-based system to store and retrieve patient information, including laboratory and demographic information, billing data, and radiology reports.

Image management and communication system (IMACS). Systems that acquire, store, transmit, and display medical images, as well as coordinate image data with relevant patient and exam data.

Image. A computer's digital representation of a physical object. In projection radiography, the image represents a 2-D matrix of discrete values resulting from x-rays transmitted through the patient and incident on the detector that generate digital values proportional to the generated signal intensity in corresponding locations. The displayed image is created from the brightness and contrast modulation of the digital values synchronized to the display device.

Image compression. The reduction of the amount of data used to represent an image. Encoding the spatial and contrast information more efficiently or discarding some nonessential or redundant information or both accomplish this.

Integrated device electronics (IDE). A type of interface used for hard disk drives that integrates the control electronics for the interface on the drive itself. Its purpose is to increase the speed at which information can be transferred between the hard disk and the rest of the computer.

Integrated services digital network (ISDN). A switched network with end-to-end digital connection enabling copper wiring to perform functions such as high-speed transmission, which frequently requires higher capacity fiber-optic cable.

Interface. The connection between two computers or parts of computers. It consists mainly of electronic circuitry.

Irreversible compression. Compression that results in some permanent alteration of digital image data. This is sometimes referred to as lossy or non-bit-preserving compression.

Kilo (K). A prefix that stands for the number 1,000 (eg, 1 kilometer = 1,000 meters). In the context of digital imaging, it is used as part of binary arithmetic and stands for 2^{10} = 1,024 (eg, 1 KB = 1,024 bytes).

Laser film scanner. A device that uses a laser beam to convert an image on film into digital image data.

Leased line. See *dedicated line*.

Liquid crystal display (LCD). One type of monitor or display device in digital radiology systems. Liquid crystal displays use two sheets of polarizing material with a liquid crystal solution between them. An electric current passes through the liquid causing the crystals to align so that light can or cannot pass through them.

Local-area network (LAN). Computers in a limited area linked by cables that allow the exchange of data.

Lookup table (LUT). A table used to map image index numbers to output display values on a digital device.

Lossless. See *reversible compression*.

Lossy. See *irreversible compression*.

Luminance. A photometric measure describing the amount of light passing through or emitted from a particular surface (eg, a monitor or display device) that falls within a given solid angle. The Système Internationale unit for luminance is candelas per square meter.

Matrix size. Small: defined as images from computed tomography, magnetic resonance, ultrasound, nuclear medicine, and digital fluorography. Large: defined as images from digital radiography and digitized radiographic films.

Mega (M). A prefix that stands for the number 1 million (eg, 1 MHz = 1 million hertz).

Memory. Electronic circuitry within a computer that stores information.

Modem. A device that converts digital signals from a computer to pulse-tone signals for transmission over telephone lines; cable modems use fiber-optic cables.

Modulation transfer function (MTF). The spatial frequency response of an imaging system or component. It is expressed as a graph of the percentage of available contrast versus the spatial frequency.

Monochrome monitor. A computer display in which an image is presented as different shades of gray from black to white. (See *gray-scale monitor*.)

Mouse. An input device that allows a computer user to point to objects on the screen and execute commands.

Noise power spectrum (NPS). The frequency response of an imaging system to noise. In computed radiography and digital radiography, the noise spectrum is not white (uniform) because of aliasing and other noise sources. As a result, it is important to measure the noise frequency response of an imaging system.

Operating system. Software that allocates and manages the resources available within a computer system. Unix, Linux, Mac-OS, and Windows are examples of operating systems.

Optical disk. A computer data storage disk that uses optical devices such as a laser to write digital data to the disk.

Peripheral. A device that is connected to a computer and performs a function. Scanners, mouse pointers, printers, keyboards, and monitors are examples of peripherals.

Phosphor. The coating on the inside of a CRT or monitor that produces light when it is struck by an electron beam.

Picture archiving and communication system (PACS). A network of computers, monitors, and network equipment to store, transmit, and display digital radiographs.

Pixel (picture element). The smallest piece of information that can be displayed on a CRT or LCD monitor. It is represented by a numerical code within the computer and displayed on the monitor as a dot of a specific color or intensity. An image is composed of a large array of pixels of differing intensities or colors.

Protocol. A set of guidelines by which two different computer devices communicate with each other.

Radiology information system (RIS). System used to store, manipulate, and distribute patient data and image study reports. The RIS is generally comprised of patient registration, patient tracking, results entry, and reporting and can include appointment scheduling, facsimile/email of reports, interface with the PACS, and billing information.

Random-access memory (RAM). A type of temporary memory in a computer in which programs are run, images are processed, and information is stored. The amount of random-access memory that a computer requires varies widely depending on the specific application. Information stored in random-access memory is lost when the power is shut off.

Read-only memory (ROM). Permanent memory that is an integral part of a computer. Programs and information stored in read-only memory are not lost when the power is removed.

Resolution. Spatial resolution is the ability to distinguish small objects at high contrast. It is affected by sampling and limited by the pixel size. Contrast (gray-scale) resolution is the ability of a system to distinguish between objects of different signal intensity. It is affected by quantization and limited by bit depth.

Reversible compression. No alteration of original image information on reconstruction. This is sometimes referred to as lossless or bit-preserving compression.

Secondary image capture. The capture in digital format of image data that originally existed in another primary format (eg, a digital image data file on a CT scanner, a screen-film radiographic film) through the process of video capture or film digitization.

Small computer systems interface (SCSI). An interface protocol that is used to link dissimilar computer devices so that they can exchange data. Small computer systems interfaces are most common in image scanners and mass storage devices. This type of interface is well suited for imaging applications.

Society of Motion Picture and Television Engineers (SMPTE) Patterns. Society of Motion Picture and Television Engineers patterns can be used for monitor quality assurance evaluations. Many vendors have them available on their computers.

Software. The programs or sets of programs that are executed on a computer.

Tera (T). A prefix that stands for the number 1 trillion (eg, 1 THz = 1 trillion Hz). In the context of digital imaging, it is used as part of binary arithmetic and stands for $2^{40} = 1.09951 \times 10^{12}$ (eg, 1 TB = 1,048,576 MB = 1.09951×10^{12} bytes).

Throughput. A measure of the amount of data actually being communicated, usually expressed in bits per second. It is related to the nominal baud rate but is usually somewhat less in value because of nonideal circumstances. Typically, devices with higher baud rates or bandwidth can attain higher throughput.

Veiling glare. Diffuse scattering of light within various parts of a display device and electron scattering in the vacuum side of the tube in a CRT device. It reduces contrast in an image in the same manner as scatter reduces subject contrast.

Video capture. The process by which images are digitized directly from the video display console of a modality, such as computed tomography, magnetic resonance imaging, or ultrasound. The video signal is converted into a digital signal. This process is more efficient and produces better-quality images than scanning films that are produced by the same equipment but are of lesser quality than direct DICOM capture because video capture is normally limited to 8-bit gray-scale.

Voxel (volume element). A 3-D version of a pixel. Voxels are generated by 3-D computer-based imaging systems, such as computed tomography and magnetic resonance imaging.

Wide-area network (WAN). A communication system that extends over large distances (covering more than a metropolitan area), often using multiple communication link technologies, such as copper wire, coaxial cable, and fiber-optic links.

Write once, read many times (WORM). A peripheral memory device that stores information permanently, by burning a pit on a CD mirror surface, for example.

Zoom and pan. The ability to magnify and roam through a region in the display.

ACKNOWLEDGMENTS

This paper was written collaboratively by the ACR, the AAPM, and the Society for Imaging Informatics in Medicine according to the process described in the ACR's *Practice Guidelines and Technical Standards* book.

REFERENCES

1. International Commission on Radiation Units and Measurements. ICRU report 54, medical imaging—the assessment of image quality. Bethesda, Md: International Commission on Radiation Units and Measurements; 1996.
2. Beutel J, Kundel HL, Van Metter RL, eds. Handbook of medical imaging, vol 1: physics and psychophysics. Bellingham, WA: SPIE Press; 2000.
3. Kim Y, Horii SC, eds. Handbook of medical imaging, vol 3: display and PACS. Bellingham, WA: SPIE Press; 2000.
4. Digital Imaging and Communications in Medicine (DICOM) Part 14; grayscale standard display function. Available at: http://medical.nema.org/dicom/2003/03_14PU.pdf. Accessed May 9, 2007.
5. Integrating the healthcare enterprise: technical framework. Healthcare Information and Management Systems Society Web site. Available at: http://www.himss.org/ASP/topics_ihe.asp. Accessed May 9, 2007.
6. Siegel E, Krupinski E, Samei E, et al. Digital mammography image quality: image display. J Am Coll Radiol 2006;3:615-27.
7. Society for Motion Picture and Television Engineers. Specifications for medical diagnostic imaging test pattern for television monitors and hard-copy recording cameras. New York, NY: Society of Motion Picture and Television Engineers; 1991.
8. Gray JE. Use of the SMPTE test pattern in picture archiving and communication systems. J Digit Imaging 1992;5:54-8.
9. Deutsches Institut für Normung. Image quality assurance in x-ray diagnostics, acceptance testing for image display devices: DIN 6868-57-2000. Munich, Germany: Deutsches Institut für Normung; 2001.
10. International Organization for Standardization. Ergonomic requirements for office work with visual display terminals, part 3: visual display requirements (ISO 9241-3). Geneva, Switzerland: International Organization for Standardization; 1992.
11. International Organization for Standardization. Ergonomic requirements for office work with visual display terminals, part 2: ergonomic requirements for flat panel displays (ISO 13406-2). Geneva, Switzerland: International Organization for Standardization; 2001.
12. Video Electronics Standards Association. Flat panel display measurements standard (FPDM), version 1.0. Milpitas, CA: Video Electronics Standards Association; 1998.
13. Video Electronics Standards Association. Video signal standard, version 1, revision 1, draft 4. Milpitas, CA: Video Electronics Standards Association; 2000.
14. Samei E, Badano A, Chakraborty D, et al. Assessment of display performance for medical imaging systems. Report of the American Association of Physicists in Medicine (AAPM). Task Group 18, Medical Physics Publishing. Madison, WI: American Association of Physicists in Medicine; 2005.
15. Integration profiles: the key to integrated systems. Integrating the Healthcare Enterprise Web site. Available at: http://www.ihe.net/resources/ihe_integration_profiles.cfm#cpi. Accessed May 9, 2007.
16. Williams MB, Yaffe MJ, Maidment ADA, Martin MC, Seibert JA, Pisano ED. Image quality in digital mammography: image acquisition. J Am Coll Radiol 2006;3:589-608.
17. Samei E. New developments in display quality control. Quality assurance: meeting the challenge in the digital medical enterprise. In: Reiner BI, Siegel EL, Carrino JA, eds. Great Falls, VA: Society for Computer Applications in Radiology; 2002:71-81.
18. Roehrig H. The monochrome cathode ray tube display and its performance. In: Kim Y, Horii SC, eds. Handbook of medical imaging, vol 3: display and PACS. Bellingham, WA: SPIE Press; 2000:155-220.
19. Badano A, Flynn MJ. High fidelity medical imaging displays. Bellingham, WA: SPIE Press; 2004.

20. Nagy P, Siegel E, Hanson T, Kreiner L, Johnson K, Reiner B. PACS reading room design. Semin Roentgenol 2003;38:244-55.
21. McEntee M, Brennan M, Evanoff M, Phillips P, O'Connor WT, Manning D. Optimum ambient lighting conditions for the viewing of softcopy radiological images. Proc SPIE Med Imaging 2006;6146: 61460W.
22. Society for Motion Picture and Television Engineers. SMPTE image quality patterns. Available at: http://www.smpte.org.
23. Gray JF, Lisk KG, Haddick DH, Harshbarger JH, Oosterhof A, Schwenker R. Test pattern for video displays and hard copy cameras. Radiology 1985;154:519-27.
24. Erickson BJ. Irreversible compression of medical images. J Digit Imaging 2002;15:5-14.
25. Kalyanpur A, Neklesa VP, Taylor CR, Daftary AR, Brink JA. Evaluation of JPEG and wavelet compression of body CT images for direct digital teleradiologic transmission. Radiology 2000;217:772-9.
26. Maldjian JA, Liu WC, Hirschorn D, Murthy R, Semanczuk W. Wavelet transform based image compression for transmission of MR data. AJR Am J Roentgenol 1997;169:23-6.
27. Practice guideline for electronic medical information privacy and security. American College of Radiology Web site. Available at: http://www.acr.org/s_acr/sec.asp?CID=1073&DID=17773&Doc=FILE.PDF. Accessed May 9, 2007.
28. Digital Imaging and Communications in Medicine. Transmission and storage standard. Available at: http://medical.nema.org.
29. Health Level 7 (HL7). Home page. Available at: http://www.hl7.org.
30. Health Insurance Portability and Accountability Act. Available at: http://www.hhs.gov/ocr/hipaa/. Accessed May 9, 2007.