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PRACTICE GUIDELINE FOR DETERMINANTS OF IMAGE QUALITY IN DIGITAL MAMMOGRAPHY

PREAMBLE

These guidelines are an educational tool designed to assist practitioners in providing appropriate radiologic care for patients. They are not inflexible rules or requirements of practice and are not intended, nor should they be used, to establish a legal standard of care. For these reasons and those set forth below, the American College of Radiology cautions against the use of these guidelines in litigation in which the clinical decisions of a practitioner are called into question.

The ultimate judgment regarding the propriety of any specific procedure or course of action must be made by the physician or medical physicist in light of all the circumstances presented. Thus, an approach that differs from the guidelines, standing alone, does not necessarily imply that the approach was below the standard of care. To the contrary, a conscientious practitioner may responsibly adopt a course of action different from that set forth in the guidelines when, in the reasonable judgment of the practitioner, such course of action is indicated by the condition of the patient, limitations on available resources, or advances in knowledge or technology subsequent to publication of the guidelines. However, a practitioner who employs an approach substantially different from these guidelines is advised to document in the patient record information sufficient to explain the approach taken.

The practice of medicine involves not only the science, but also the art of dealing with the prevention, diagnosis, alleviation, and treatment of disease. The variety and complexity of human conditions make it impossible to always reach the most appropriate diagnosis or to predict with certainty a particular response to treatment.

Therefore, it should be recognized that adherence to these guidelines will not assure an accurate diagnosis or a successful outcome. All that should be expected is that the practitioner will follow a reasonable course of action based on current knowledge, available resources, and the needs of the patient to deliver effective and safe medical care. The sole purpose of these guidelines is to assist practitioners in achieving this objective.

I. INTRODUCTION

This guideline was developed collaboratively by individuals with recognized expertise in breast imaging and medical physics representing the American College of Radiology (ACR), the American Association of Physicists in Medicine (AAPM), and the Society for Imaging Informatics in Medicine (SIIM) primarily for technical guidance. It is based on a review of the clinical and physics literature on digital mammography and the experience of experts and publications from the Image Quality Collaborative Workgroup [1-3].

In many parts of this guideline, the level of technical detail regarding the determinants of image quality for digital mammography is advanced, and is intended to provide radiologists, medical physicists, regulators, and other support personnel directly involved in clinical implementation and oversight an expanded in-depth knowledge of the issues pertinent to assessing and maintaining digital mammography image quality from the acquisition, display, and storage aspects of the process. Basic clinical guidelines are a subset, and all interested individuals are encouraged to review the information with this in mind. Additionally, this guideline includes the input from industry, radiologists and other interested parties in an attempt to represent the consensus of the

broader community. It was further informed by input from another working group of Integrating the Healthcare Enterprise (IHE) Initiative [4]. Furthermore, the ACR Subcommittee on Digital Mammography is developing a Quality Control Manual for Digital Mammography.

Analysis of image quality has meaning only in the context of a particular imaging task [5]. This guideline has been developed with reference to specific imaging tasks required by mammography, utilizing the information available in the peer-reviewed medical literature regarding digital mammography acquisition and image display, storage, transmission, and retrieval. Specifically, the imaging tasks unique to mammography that determine the essential characteristics of a high quality mammogram are its ability to visualize the following features of breast cancer:

1. The characteristic morphology of a mass.
2. The shape and spatial configuration of calcifications.
3. Distortion of the normal architecture of the breast tissue.
4. Asymmetry between images of the left and right breast.
5. The development of anatomically definable new densities when compared to prior studies.

The primary goal of mammography is to accurately visualize these features if they exist. At the same time, it is important that these signs not be falsely identified if they are not actually present in the breast. Two aspects of digital image quality can be distinguished: technical and clinical. It is relatively easy to make technical measurements describing the above attributes, and reasonable to infer a connection between these technical measures and clinical image quality. The extent to which these features are rendered optimally with a digital mammography system using current technology depends on several factors and is the major focus of this guideline.

II. QUALIFICATIONS AND RESPONSIBILITIES OF PERSONNEL

Interpreting physicians, medical physicists, and radiological technologists who work in mammography must meet the requirements of the Mammography Quality Standards Act (MQSA) final rule as published by the Food and Drug Administration (FDA) [6]. Those personnel must have at least 8 hours of training in digital mammography before beginning to use that modality. See the [ACR Practice Guideline for the Performance of Screening Mammography](#).

III. DIGITAL MAMMOGRAPHY IMAGE ACQUISITION

In digital mammography, the processes of image acquisition, display, and storage are performed by separate systems, each of which can be optimized. The digital detector has a faithful response to the intensity of

incident X-rays over a very wide range. It can be designed to efficiently absorb X-rays, produce an electronic signal, digitize the signal, and store the results in computer memory. The output image is saved as a two-dimensional matrix, where each element represents the X-ray transmission corresponding to a particular path through the breast. This image can be digitally processed such that when it is displayed in softcopy form on a high-resolution monitor or printed on laser film, it will demonstrate the key features required for mammographic interpretation.

Details of image acquisition devices and specifications outlined in this section are available on request from the specific equipment manufacturers. Once a system has been purchased, calibrated, and acceptance tested, regularly scheduled quality control procedures performed by the technologist and annual testing (or as needed) by the qualified medical physicist are required to maintain compliance with the FDA. Currently, the responsibility for the testing procedures for the image acquisition system is the specific manufacturer of the device who maintains FDA approval.

There are a number of detector technologies for clinical digital mammography to which the following parameters apply:

1. Flat-panel thin-film-transistor (TFT) arrays of two types:
 - a. Indirect detection (X-ray absorption to light conversion to charge generation), and
 - b. Direct detection (X-ray absorption directly to charge generation).
2. Slot-scan charge-coupled device (CCD) array systems.
3. Cassette-based photostimulable storage phosphor (PSP) detection and readout (computed radiography (CR)).
4. Other (future) technologies including:
 - a. CCD large area detectors, and
 - b. Direct photon counting detectors.

Tissue coverage, spatial resolution, contrast, latitude or dynamic range, noise, and freedom from artifacts each contributes to the overall quality of the image and the high probability that relevant anatomical detail or pathology is displayed.

A. Tissue coverage depends on the chosen view (projection) and positioning of the breast. The goal is to project as much of the breast tissue as possible onto the image receptor to maximize breast cancer detection. The following items impact tissue coverage:

1. The geometrical relationship of the X-ray source, collimation, compression device, patient, and grid and image receptor requires the X-ray beam

to tangentially intercept the receptor at the point closest to the chest wall.

2. Inactive regions (front wall, edge of cassette) adjacent to the chest wall will result in missed tissue area, and should be no greater than 7 mm; typical digital units miss between 4 mm to 7 mm of tissue [7,8].
3. Clinical assessment of positioning match those required for screen-film and evaluates the retromammary aspects of the breast between the craniocaudal (CC) and mediolateral oblique (MLO) views. On the CC view, the posterior nipple line diameter of the breast (the distance between the nipple and the posterior edge of the image) should be no more than 1 cm less (approximately) than that on the MLO view (the distance between the nipple and the anterior edge of pectoralis muscle). The anterior edge of the MLO image of the pectoralis muscle should be convex, and the muscle should be seen at least down to no less than 1 cm above the level of the nipple. The posterior nipple line should be drawn at an angle, about 45 degrees on the MLO image.
4. Large breasts and inadequate field of view (FOV) require imaging of the breast in sections, particularly for small FOV detector areas. The resulting subimages must be tiled together to form the complete mammogram. Breast compression variations and direction of sub-images make sections difficult to match at the boundaries. An increase in radiation dose occurs to regions of the breast that are exposed to X-rays in more than one sub-image. Standard tiling methods that double expose the least possible amount of breast tissue should be used. A larger FOV lowers the need for multiple-section imaging.

B. Spatial resolution is the ability of an imaging system to allow two adjacent structures to be visualized as being separate, or the distinctness of an edge in the image (i.e., sharpness). Measurement is performed by qualitative or quantitative methods. Spatial resolution losses occur because of blurring caused by geometric factors (e.g., the size of the X-ray tube focal spot and the magnification of a given structure of interest), unsharpness due to light diffusion in the receptor phosphor screen, detector element effective aperture and pitch, and relative motion of the X-ray source, the breast or the image receptor during the exposure. Spatial resolution effects on clinical image quality are most easily observed when imaging fine detail in the breast such as spiculations radiating from a mass or microcalcifications. Detection, shape, and margins help differentiate a benign from a malignant process. However, one cannot isolate spatial resolution effects on clinical image quality from effects due to

quantum mottle and electronic noise under typical digital image acquisition conditions.

1. Qualitative measurement is achieved with a bar pattern of alternating radio-opaque “bars” and radiolucent “spaces” of equal width, imaged to determine limiting resolution in line pairs/distance. Intrinsic detector resolution measurement fixes the pattern to the receptor surface to eliminate motion and focal spot blurring. System resolution (including the focal spot) uses a bar pattern placed at a typical magnification factor. For digital systems, the resolution might be different in the row and column directions, often requiring separate evaluations. Limiting resolution is the frequency at which the lines can no longer be resolved.
2. Quantitative measurements by modulation transfer function (MTF) are obtained by measuring the transfer of signal amplitude (contrast) of sinusoidal patterns (of various frequencies) from incident X-rays to the output under high exposure conditions such that quantum mottle (noise) does not mask the signal transfer characteristics. It is determined by the product of the individual components along the signal chain. The system MTF can be measured by imaging a test object containing a narrow slit or a sharp edge. For clinically relevant, lower exposure conditions, the ability to transfer fine detail with higher frequency content (e.g., microcalcifications) with lower signal modulation can be limited by the X-ray quantum *and* electronic system noise associated with image acquisition. Thus, it is important to consider frequency dependent spatial resolution and system noise together (see Section III, D, 3 for more detail).
3. Geometric blurring is minimized by using a small focal spot for contact imaging (e.g., 0.3 nominal size) and an even smaller focal spot for magnification (e.g., 0.1 nominal size) [9], by reducing the object-to-image receptor distance as much as possible (e.g., contact), and by increasing the focal spot-to-object distance, (e.g., 60-65 cm). Causes of increased geometric blurring and variation include: a gap of 1 to 2 cm from the breast exit surface to the receptor due to the grid, an actual focal spot size that is larger than the nominal value (the National Electrical Manufacturers Association [NEMA] allows up to 1.5 times larger) [9], and variations of the effective apparent focal spot size over the detector plane (larger on chest wall side of the image).
4. Detector element (del) size – Array (TFT and CCD) detectors are constructed from a matrix of

discrete dels. Each del has an active area with dimension, d , surrounded by an area that is insensitive to the incident radiation. The center-to-center spacing between dels, known as the pitch, p , is typically greater than d .

- a. For square dels, the relative area of sensitivity, d^2/p^2 , is called the fill factor and in part determines the detector's geometric radiation efficiency.
 - b. The del represents the spatial resolution limit, since objects projected over a smaller area than d^2 are averaged. Smaller d results in less blurring and higher spatial resolution.
 - c. The MTF associated with the del falls to 0 at a spatial frequency of $1/d$ cycles/mm. A detector with 50 μm dels passes spatial frequencies up to 20 cycles/mm. Changes in signal intensity that occur over a distance less than the del pitch cannot be faithfully represented in the image, resulting in an artifactual appearance of high spatial frequency signals at low spatial frequencies, a phenomenon known as aliasing. To avoid aliasing, the highest spatial frequency in the image f_{max} projected to the detector plane (and before sampling) must be less than $1/(2p)$, the Nyquist frequency.
5. Spatial resolution, signal-to-noise ratio (SNR), radiation dose requirements, and manufacturing and economic considerations are all part of detector design issues. Improved dynamic range and SNR outweigh a loss of limiting spatial resolution. The del pitch of 100 μm results in a sampling frequency of 10 cycles/mm and a Nyquist frequency of 5 cycles/mm, while a del pitch of 50 μm results in a sampling frequency of 20 cycles/mm and a Nyquist frequency of 10 cycles/mm.
 6. The "presampling MTF" isolates the intrinsic blurring caused by the detector from the effects of sampling and is performed by imaging a sharp edge or narrow slit that is angled to a small degree with respect to the principal axes of the detector matrix [10].
 7. Detector-specific blurring occurs in the X-ray converter material.
 - a. For scintillator-based converters, the first source of blur is spreading of emitted light within the scintillator material. The spreading is determined by the material's thickness and by the design of the scintillator in terms of its crystal structure and its reflective and absorptive properties.
 - b. In direct flat panel detectors, the voltage or electric field across the direct conversion material must be adequate to ensure that there is negligible recombination or lateral spreading of the charge pairs in the material before they are collected at the electrodes.
 8. Motion blurring in digital mammography is caused by movement of the breast during exposure and is minimized by using a short exposure time and compressing the breast.
 - a. Tube voltage (kVp) may be increased for thick, dense breasts to allow reduction of exposure time. Image processing compensates for contrast losses to the extent allowed by the background noise and the image SNR.
 - b. Magnification techniques with small focal spots and lower tube current (mA) require longer exposure times. The amount of blurring depends on object motion speed, exposure duration, and degree of magnification.
 - c. For scanned slot charge-coupled device (SSCCD) systems, motion causes misregistration artifacts between the anatomy imaged before a motion occurs and that imaged after.
- C. Contrast resolution (radiographic contrast) refers to the magnitude of the signal difference between the structure of interest and its surroundings in the displayed image (typically evaluated for areas of 1 cm^2 or larger) and is influenced by subject contrast and display (image) contrast. Achieving high radiographic contrast is especially important due to subtle differences in soft-tissue density of normal and pathologic structures of the breast, the need to detect minute microcalcifications, and the marginal structural characteristics of soft-tissue masses.
1. Subject contrast is the relative difference in X-ray exposure at the entrance plane of the image receptor transmitted through one part of the breast and through an adjacent part resulting from X-ray attenuation properties. Attenuation is strongly dependent on the X-ray energies (spectrum) determined by the target material,

- kVp, and filtration (either inherent in the tube or added).
- a. Molybdenum (Mo) target X-ray units generate characteristic radiation at 17.9 and 19.5 keV. A Mo filter 0.025 mm - 0.03 mm thick strongly suppresses photon energies less than 15 keV and those greater than 20 keV, yielding high subject contrast and avoiding excess radiation dose for 2 to 5 cm breasts imaged at typical voltages of 25 to 28 kVp.
 - b. Higher effective energy incident X-ray beams are used for thicker and/or denser breasts (5 cm to 7 cm). These beams are achieved with higher voltage (>28 kVp) on a Mo target with either a Mo filter (0.030 mm) or a rhodium (Rh) filter (0.025 mm). For denser breasts, a Rh filter preferentially transmits energies from 15 to 23 keV, including Mo characteristic radiation.
 - c. A more penetrating beam is obtained with a Rh target emitting 20 and 23 keV characteristic X-rays combined with a Rh filter (0.025 mm), operated at 28 kVp or higher. For very dense, difficult-to-penetrate breasts, the resulting spectrum preserves subject contrast and reduces dose to a practical level.
 - d. Tungsten (W) target tubes are advantageous for short exposure times. Without useful characteristic radiation, the energy spectrum is optimized for mammography with Mo and Rh filters, typically of 0.05 mm thickness or greater. Greater filter thickness is necessary to attenuate useless L X-rays emanating from the W target. Careful choice of kVp and filter material can yield excellent results in terms of contrast and breast dose.
2. Image processing adjustment of display contrast potentially allows the use of higher energy X-ray beams 25 to 35 kVp and above for digital systems (compared to screen-film, where 22 to 32 kVp is more typical). Dose is reduced for the same image SNR, especially for large or dense breasts.
 3. X-ray scatter escaping the breast without useful anatomical information is recorded by the image receptor. The scatter to primary ratio, S/P, characterizes the amount of image contrast loss and apparent sharpness reduction. It is not unusual for S/P to be greater than 1.0 [11,12]. Scattered X-rays reduce subject contrast, “use up” some recording range (latitude), add noise to the image, and lower the SNR. Digital post-processing can partially recover radiographic contrast by selectively removing the low-frequency scatter contributions to the image and
 - rescaling pertinent digital image information over the full scale of the digital image range.
 4. Grids designed for mammography reduce scattered radiation and improve subject contrast at the cost of higher breast dose [13,14]. For all digital systems except the SSCCD system, grids are used for contact imaging to reduce noise contributed by scatter. With magnification studies, the increased air gap eliminates the need for the grid.
 - a. Linear grids consist of lead strips (septa) separated by spacers of radiolucent material and move during the X-ray exposure to blur the projection of the septa.
 - b. A two-dimensional focused rhombic cellular structure made of copper with an air interspace is an alternate device.
 - c. The exposure increase for digital detectors is chiefly due only to incomplete transmission of the primary radiation (unlike the screen-film detector, where scatter transmission is also an issue). Adjustment of radiographic technique to compensate for the presence of a grid should be based on maintaining SNR in the grid image versus non-grid image rather than on known grid Bucky factors that are determined using screen-film detectors. Any technique adjustments should be performed in consultation with and verified by the radiologist in charge of the digital mammography program.
 - d. The SSCCD system uses a narrow scanned beam of X-rays and does not require a grid. Dose can be reduced substantially relative to large-field-of-view (LFOV) screen-film mammography and LFOV digital mammography systems that use a grid.
 5. Breast compression is equally important for digital mammography as it is for screen-film. It contributes to digital image quality by immobilizing the breast (reducing motion unsharpness), producing a more uniform, thinner tissue (lower scattered radiation, more even penetration of X-rays, less magnification or geometric blurring, less anatomical superposition), and lowering radiation dose.
 6. Overall radiographic contrast depends on both the subject contrast and the display (image) contrast and is expressed in terms of the optical density difference between two areas on the processed laser film or as the relative brightness difference between the corresponding areas in an image displayed on a monitor.
 - a. The signal stored in digital form is directly (or logarithmically) proportional to the amount of radiation transmitted through the breast.

- b. With a properly designed image acquisition system, the dynamic range should be adequate to measure the entire range of intensities from that of the unattenuated beam outside the breast to that through the densest, thickest part of the breast. For this reason, the stored image reflects the inherent subject contrast very faithfully.
- c. Images corrected for detector blemishes and gain variations without postprocessing are the DICOM “for processing” images.
- d. Subsequent image processing, including contrast and spatial resolution enhancement applied to the “for processing” digital image produces the final DICOM “for presentation” image for interpretation either on hardcopy film or softcopy displays.

D. In digital mammography, it is not very meaningful to discuss contrast without also considering noise. Radiographic noise or mottle is the unwanted random (uncorrelated), nonrandom (correlated), or static (e.g., detector defect) variation in average digital signal level in a radiograph that has been given a uniform X-ray exposure [15-17].

1. Quantum mottle is the random spatial variation of the X-ray quanta absorbed in the image receptor. Using fewer quanta increases the noise (for a fixed signal) or decreases the SNR and reduces the visibility of subtle contrasts. Fine calcifications that can be the first sign of cancer may not be visible in a noisy (underexposed) image.
2. Noise can be quantified in terms of the standard deviation of the number of X-ray quanta recorded in a given area of the image receptor or the standard deviation in image signal (optical density or digital image value) over a given area (region of interest [ROI]). The spatial frequency characteristics of the noise are better described by the noise power spectrum (NPS(f)) of the image [18,19].
3. SNR is the ratio of the magnitude of the image signal to the noise. The SNR *transfer efficiency* is termed the detective quantum efficiency (DQE) [18,20-22] which describes the transfer of SNR from the X-ray pattern incident on the imaging system to its output, generally plotted versus spatial frequency. $DQE(f)$ is equal to the ratio of $SNR_{out}^2(f)/SNR_{in}^2(f)$, where $SNR_{out}^2(f)$ is the ratio of the signal power, $MTF^2(f)$, to the noise power, $NPS(f)$, and represents the *noise equivalent quanta*, $NEQ(f)$, and where $SNR_{in}^2(f)$ is the number of X-ray photons per unit area incident on the detector, Q . Quantitatively, $DQE(f) = k MTF^2(f)/(NPS(f) \times Q)$, where k is a scaling constant [18-21]. The value of $DQE(f)$ ranges from 1 (100%) to 0 (0%). High $DQE(f)$

indicates good information transfer, and as $DQE(f)$ approaches 0, incident X-ray information is lost. The exposure required for achieving a desired output SNR is inversely related to the DQE, and systems with high DQE are usually more dose efficient. “Appropriate” X-ray exposure depends on the system DQE, and requisite SNR as described below (parts 4-6) can be achieved with a calibrated automatic exposure control (AEC) system.

4. The signal difference-to-noise ratio (SDNR), a measure of the difference between a signal and its background divided by the noise, can be used as an indicator of reliably depicting a structure in the breast in the presence of noise. In a high quality digital mammography image the SDNR usually exceeds some threshold value, typically 5. This metric is useful for monitoring changes in image quality during periodic quality control (QC).
5. Quantum noise should be the principal contributor to the signal fluctuation seen in a uniformly exposed radiograph. Factors affecting the visibility of quantum mottle in mammography include X-ray interaction efficiency, efficiency of converting X-rays to light or electrons and collecting the signal, light diffusion in phosphors, and radiation quality.
6. Design and calibration of the detector and electronics for adequate dynamic range and number of bits of digitization are essential to precisely record the entire range of X-ray intensities transmitted by the breast. With proper acquisition techniques on a calibrated detector, the electronic image can be amplified as much as desired with no constraint on image brightness. Radiation dose depends on desired SDNR. Typically, systems that have a higher overall DQE over a specific frequency range can achieve higher SDNR for the same breast dose when all other factors are equal (e.g., grid, geometry kVp, image process).

E. With digital detectors there may be spatial variations in sensitivity of the receptor, causing the image to have structure that is unrelated to the tissues in the breast (i.e., detector artifacts).

1. Bad dels, typically aligned in columns and rows, occur during the manufacturing process. Such point and line defects are typically “mapped,” and adjacent neighbor response values are averaged as a substitute value. The number and proximity of detector defects that are allowable without affecting image quality remain to be specified.

2. Large area variations, nonuniform variations, and offsets that are temporally stable, known as “fixed pattern noise,” can be significantly reduced by imaging a uniform field of X-rays and using the low noise recorded image as a correction mask to make the image uniform.
3. “Flat-field correction” [23] should be performed according to manufacturers’ recommendations at a predetermined calibration frequency and after major repairs.

IV. DIGITAL MAMMOGRAPHIC IMAGE DISPLAY

Although it is possible to display digital images in a hardcopy format, the advantages of digital technology may not be fully realized without softcopy display of mammograms [24]. The quality of the display has a direct effect on radiologic interpretation. A faulty or inadequately calibrated or improperly set-up display device can compromise the overall quality of the diagnostic procedure [25,26].

As new features are added to enhance the radiologic interpretation process, choices in image display continue to expand. Although many aspects of display technologies and uniform practice have been addressed by standards-setting groups [27-32], similar to the situations for other digital imaging technologies, a well-codified set of recommendations would constitute a moving target. While emerging technologies may require modification in the display criteria, certain features should be in place at the present time. The challenge is to identify those areas of commonality in which durable and evidence-based criteria for image display quality can be elucidated. NEMA has recently published two new standards that include templates and describe a minimum set of QC tests that should be included as part of the quality assurance plan for displays and workstations [33] as well as hardcopy printing devices [34] for full-field digital mammography (FFDM).

A. Hardcopy Printing

Despite the move to digital acquisition of mammographic images, some are still printed to hardcopy for display and interpretation. Although it is likely that within the next decade increasing percentages of these studies will be viewed as softcopy on monitors, hardcopy mammographic image quality remains an important issue and must be included in any effort to address digital image quality in mammography. Although the FDA recommends that only printers specifically cleared for FFDM use by its Office of Device Evaluation (ODE) be used, the use of other printers is also legal under MQSA [35]. The ACR also strongly recommends that only FDA ODE-cleared printers be used for digital mammography. Quality assurance issues for hardcopy display have been set forth in a number of publications [34,36,37]. While

there are no recommendations regarding the use of hardcopy versus softcopy display for interpretation, the FDA requires the ability to print FFDM images of final interpretation quality to film if so requested by patients or their health care providers [35]. When FFDM images are printed to film, the manufacturer’s guidelines should be followed.

1. Printer operation recommendations
 - a. The printer to be used should be cleared for mammography applications by the FDA.
 - b. Spatial sampling should at least match the detector element (del) size, so the printing device should not be the limiting factor. Images should be printed to match the “true” size of the imaged anatomy [4].
 - c. Conformance to the Digital Imaging and Communications in Medicine (DICOM) Grayscale Standard Display Function (GSDF) standard is desirable.
 - d. No evidence suggests significant quality differences between dry and wet laser printers. When using either device, all FDA rules must be followed and QC procedures adhered to.
 - e. Laser printers are not required when printing FFDM images, but their use is highly encouraged. Existing recommendations for hardcopy printing should be used uniformly when printing digital images.
 - f. The FDA requires that all printers used with an FFDM unit comply with a quality assurance program that is substantially the same as that recommended by the FFDM image receptor manufacturer and that they pass the phantom and clinical image review process of the facility’s accreditation body. At the present time, no accreditation body reviews softcopy images, so the FDA recommends that the softcopy images be of such quality that if they were submitted, they would pass the phantom and clinical image review process of the facility’s accreditation body [35].
2. Lightbox considerations
 - a. Luminance: 3,000 candelas per square meter (cd/m^2) minimum is the standard for screen film [37]. The same guidelines should be used for digital images printed onto film. A bright light (focal or lightbox) will be of limited value for digital mammograms printed to film.
 - b. Uniformity: No specific standards address spatial uniformity of lightbox luminance nor of intra-lightbox luminance uniformity. Clearly, luminance variations should be kept to a minimum.
 - c. Shutters and masking: The FDA requires that masking materials be available for

interpreting physicians [6]. Viewscopes are allowed as long as the illuminated area can be limited to a region equal to or smaller than the exposed portion of the film. The average ambient light conditions should be adjusted relative to the average luminance of the displayed images (properly masked). Care should be taken to avoid any direct reflections on image surfaces. Darker images require a darker environment to interpret properly.

3. Presentation considerations and hanging protocols for printed film
 - a. Shiny vs. dull side: There is no specific recommendation regarding which side of the film should be facing out from the lightbox. Radiologist comfort with the hanging protocol is more important than hanging the films in a defined way.
 - b. Layout: The most common film size formats are 8 x 10 inches (18 × 24 cm) and 10 x 12 inches (24 × 30 cm). No specific recommendations address hanging protocols, and a broad range of personal preferences is acceptable.

B. Softcopy Display Monitors

Many factors contribute to image quality in softcopy radiographic and mammographic display [38-41]. Although the FDA recommends that monitors used for interpretation be specifically cleared for FFDM use by the FDA's ODE, the use of others is also legal under MQSA [35]. The ACR also strongly recommends that only FDA ODE-cleared monitors be used for digital mammography. In addition, softcopy displays for mammography should have minimum quality specifications for acquisition, interpretation, and review workstations. The AAPM Task Group 18 documentation on assessment of display performance for medical imaging systems provides test images [38], an executive summary of tests [42], and a complete overview [43] that is very useful for specifying and verifying performance for display of medical images, including mammography. Details for the majority of the display parameter specifications outlined below are available, often on request, from the display manufacturers. Once a display has been purchased and calibrated, it should be tested regularly by the medical physicist to maintain compliance.

1. Minimum and maximum luminance
 - a. Monitor luminance, L is characterized by minimum (L_{\min}) and maximum (L_{\max}) values. In the presence of reflected ambient luminance (L_{amb}), the monitor luminance is designated as L' . The ratio of the maximum luminance (L'_{\max}) to the minimum luminance (L'_{\min}) of a mammographic display device should range between 250 and 650 over a 30 degree viewing cone

whose principal axis is perpendicular to the image. Ideally, the maximum luminance should be 450 cd/m² or higher in order to avoid too low a value for minimum luminance (susceptible to ambient lighting) to maintain a desired luminance ratio.

- b. Smaller ranges might lead to an inadequate level of contrast in the displayed mammograms. The human eye is more sensitive to contrast and high spatial resolution details with increased luminance.
2. Contrast
 - a. Within the applicable luminance range of the mammographic display device, the device should render the image details with a consistent grayscale that should be measured and maintained over time. The contrast response of mammographic displays should comply with the AAPM Task Group 18 recommendations [42,43].
 - b. Contrast response of a display should not deviate from the DICOM GSDF contrast values by more than 10%.
 3. Lookup table transformation
 - a. Lookup tables (LUTs) facilitate the conversion of recorded intensities into levels of luminance for display on a video monitor.
 - b. LUTs can be controlled by the user, and, in the case of softcopy display, can be varied interactively by the radiologist to facilitate image interpretation.
 - c. An adequate number of bits of digitization must be used to ensure that there are no overriding limitations related to the characteristic curve of the receptor.
 - d. While the dynamic range of image acquisition is not considered a limiting factor, the dynamic range of the display device is much more restrictive, in part because of the limited luminance capability of electronic displays.
 - e. With softcopy display, the radiologist may need to perform some manipulation of the display parameters (e.g., digital window and level adjustments), as monitors are limited in displaying the full range of signal levels from the breast at optimal contrast.
 4. Bit depth
 - a. A display device must render mammographic details with sufficient luminance and grayscale range to prevent the loss of contrast details or the presence of contour artifacts.
 - b. A minimum of 8-bit output luminance resolution is required. At the time of publication, relatively few data have been reported in the literature to address possible

advantages with higher bit-depth display devices.

5. Digital image matrix size and display size

- a. Although a 3 megapixel monitor (1,500 x 2,000 pixel samples in the horizontal and vertical directions for portrait orientation) would probably be adequate for primary diagnosis, a 5 megapixel monitor (2,000 x 2,500 pixel samples in the horizontal and vertical directions for portrait orientation) requires less zoom/pan for image interpretation when the mammographer desires to view the full resolution image dataset.
- b. Mammographic displays should render images with a pixel density to enable viewing of a full or partial (50% or greater area of the breast image) mammogram with sufficient spatial detail at a normal viewing distance of 15-60 cm. Panning through a reduced subset of the entire image at full spatial resolution without excessive magnification should be easily available to the reader. Zoom/pan functions should be used rather than moving closer to the display to view details.
- c. A two-monitor portrait set up is recommended for minimizing head and shoulder rotation, keeping body and arms in ergonomic positions, and avoiding near vision deficits. Eyeglasses, when required, should be specifically selected for the viewing distance. The display monitor should present the images in portrait geometry, maintaining the original aspect ratio of the acquisition device.
- d. During the readout, all images should be viewed at 1:1 or 100% size. Routine viewing at 2:1 or (300% size increase) with zoom/pan function to examine the entire image may also be useful. When viewed at a size that is “fit to the viewport,” images are not necessarily reduced by a factor of 1:2 or 50%, and reduction will vary depending on the image size. Some displays scale the fit to viewport to maximize the scale of the mammogram. Hanging protocols and viewing modes for evaluation and comparison of longitudinal studies are important considerations in order to maintain consistent viewing conditions, particularly for mammograms from different acquisition devices. The IHE Mammography Image profile [4] should be consulted for recommendations and implementation of digital mammography image display for interpretation.
- e. At a 60 cm distance (arms-length), the human visual contrast sensitivity drops

significantly beyond ~2.5 cycles/mm and the peak sensitivity is ~0.5 cycles/mm, suggesting that the pixel size (or pitch) should be less than approximately 200 microns. Typical pixel sizes for 3 and 5 megapixel monochrome liquid crystal display (LCD) monitors (i.e., 1,500 x 2,000 and 2,000 x 2,500 pixels) are about 200 microns and 150 microns, respectively. This suggests that 3 megapixel displays may be adequate; however, more scientific evaluation is needed. Display device specifications should match as closely as possible the acquisition matrix size. Alternate display dimensions (e.g., larger than 55 cm diagonally) with 200 micron pixels may be a future consideration for display of digital mammography images.

6. Display resolution

- a. The resolution performance of a display should enable the discrimination of small spatial patterns associated with breast cancer without the need for excessive magnification.
- b. Following AAPM Task Group 18 recommendations, the MTF at the Nyquist frequency of the display should be greater than 35%. Visual evaluation can be performed with the use of Task Group 18-QC or Task Group 18-CX test patterns [38] so that each image pixel is mapped to one display pixel. Using a magnifying glass, the horizontal and vertical line patterns should be discernible at all locations on the displayed image for all directions [42].
- c. Pixel size and displayed spatial resolution of the corresponding image can result in a smaller pixel (averaging, down sampling), a larger pixel (zooming, pixel replication), or a 1:1 mapping of each del to a display pixel.
 - 1) Adjacent del averaging enables the entire mammogram to be displayed, but with degraded resolution.
 - 2) With less averaging, displayed resolution will be improved by zooming the image up to the point at which one display pixel represents one del.
 - 3) Further zooming increases the image size on the screen and may be helpful by overcoming limitations of the vision of the viewer, but does not improve the spatial resolution of the image itself.
- d. MTF limitations of the display can be compensated to some extent by image pre and post processing [44-48]. Maladjustment or aging of the monitor can cause loss of spatial resolution. Frequent performance evaluation of the display device is

recommended as part of a routine quality control program.

7. Display noise

- a. Display noise refers to statistical fluctuations in the temporal or spatial characteristics of the display. Temporal noise is usually dominant in the dark regions of the displayed image, and difficult to characterize. Spatial noise is dominant in the brighter areas of the displayed images. Contributions to spatial noise include phosphor granularity for cathode ray tubes (CRTs) and pixelated background for LCDs. Periodic visual evaluation of display noise is recommended, using the Task Group 18-AFC (alternative forced choice) test pattern [38] and verification that all targets are rendered except the smallest one for primary (interpretation) displays, and the two largest sizes visible for the “technologist” and “clinician” review displays [42]. Failure of a display device might be an indication of improper luminance response, so verification of proper luminance is first necessary.
- b. Luminance fluctuations (either spatial or temporal), phosphor variations, and structured defects of CRT or LCD monitors are typical sources of noise. This adds to the level of quantum noise already present in a mammogram and impacts the detectability of low-contrast lesions that appear similar to quantum noise.
- c. Veiling glare, a low frequency light spread within the display, reduces contrast in the dark regions of the image bordered by a bright surround. For a mammographic display, the veiling glare described in terms of glare ratio should be greater than 200 [49].

8. Other display characteristics

- a. Reflection
 - 1) Specular and diffuse reflections off the display surface due to ambient luminance can reduce image contrast and affect image quality of a displayed mammogram.
 - 2) Luminance and grayscale calibration of the device should take into account ambient light reflection and reflection coefficient.
 - 3) To minimize image contrast losses, the intrinsic minimum luminance (L_{\min}) of the device should not be smaller than the ambient luminance (L_{amb}). As a practical guideline, L_{amb} should always be less than $L_{\min}/1.5$ [42].

b. Color tint

- 1) Displays are manufactured with subtle color tints. Preference of blue, yellow, or other tint is viewer specific.
- 2) The display device should have a uniform color tint across its display area, and the color tint should be similar across multiple display monitors associated with a workstation.
- 3) The color tint differences should be $<0.01 \Delta(u',v')$, such that variations in color tint are not noticeable on displays used for diagnosis [42].

c. Monochrome vs. color

- 1) No clinical specifications require color rather than monochrome displays for mammography. In general, color CRT devices have not been able to deliver the required performance in terms of luminance and veiling glare and thus have not been found to be suitable for mammography applications.
- 2) Addition of color has enhanced possibilities for mammographic displays, where annotation can be in color, or anatomic features, such as microcalcifications, can be displayed in color. With technological advances, newer color LCD monitors may deliver the required performance, and thus might be considered in the future for such applications.
- 3) A color monitor may facilitate the display of computer-assisted detection (CAD) probability maps in which scaled colors might indicate lesions with higher or lower degrees of suspicion.

9. Technology-specific LCD and CRT considerations

a. LCDs vs. CRTs

- 1) On-axis viewing is about the same with CRTs and LCDs.
- 2) Off-axis viewing for LCDs (for example, when a radiologist and resident are reviewing cases together) produces significant degradation in performance [50].
- 3) Evidence suggests that a flat-surface CRT is better than a curved surface CRT [51].
- 4) A protective shield designed to keep the screen clean on LCD panels adds distracting reflections and should not be used if possible.
- 5) The LCD has longer life, less drift, and requires less power compared to a CRT.

- b. LCDs
 - 1) Performance variations as a function of viewing angle should be controlled to minimize their impact on peripheral vision and multiple viewer conditions.
 - 2) Angular performance of a display 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 (typically ≤ 30 degrees) [52-54].
 - 3) For a workstation with more than one LCD, the LCDs should be oriented toward the viewer to minimize the impact of angular response variation and reflection.
 - 4) Warmup time can be up to 30 minutes from a cold start.
- h. Image displays should be able to display a ruler on the screen as a visual clue to indicate physical size.

C. Digital Image Presentation Issues

The IHE initiative has specified a consistent presentation of image integration profile that specifies a number of transactions to maintain the consistency of grayscale images and their presentation state information (including user annotations, shutters, flip/rotate, display area, and zoom). It also defines a standard contrast curve (the GSDF) against which different types of display and hardcopy output devices can be calibrated. Thus it supports display in hardcopy, softcopy, and mixed environments [4]. Currently the IHE has a digital mammography working group analyzing the unique workflow and presentation needs of digital mammography.

- c. CRTs
 - 1) Most CRTs are prone to special video artifacts, such as ghosting and overshoot. Those artifacts should be minimal and nondiscernible in normal mammographic viewing.
10. Other softcopy display guidelines
- a. Image displays must be able to display mammography CAD marks (when CAD is implemented) and to apply marks on the displayed image corresponding to all findings encoded in the DICOM mammography CAD structured reporting (SR) objects.
 - b. Image displays are not necessarily required to support “for processing” image presentations.
 - c. Image displays must be able to display images in “true” size [4]. This is critical since sizes of features in the image are generally judged visually, and not having this feature could distort the appearance of features and hence the judgment of interpreting mammographers.
 - d. Image displays must be able to display images in “same” display size even though they might be from different acquisition stations with different pixel sizes.
 - e. Image displays must support both mechanisms for background air suppression based on a single pixel value or a range of pixel padding values [4].
 - f. Image displays must be capable of annotating image information, image identification, and technical factor information [35].
 - g. Image displays must be capable of displaying simultaneously a set of current and prior conventional four-view screening mammogram images (left and right CC and MLO views).
 - 1. Time to bring up an image on a workstation should be 3 seconds or less from on-line local storage media. Times for retrieval of images from hierarchical storage management archives and from remote sites will vary significantly depending on prefetching rules, management of image routing, and network speeds, among other issues.
 - 2. Mammographic displays should be able to accommodate fast and easy navigation between old and new studies.
 - 3. Hanging protocols should be flexible and tailored to user preferences, specifically for mammography with proper labeling and orientation of the images.
 - 4. Workstation software tools must include window/level and zoom/pan at a minimum. Tool use generally increases reading time, so there is a balance between increased tool use, performance, and workflow.
 - 5. Specific recommendations regarding the types of tools that should be used with softcopy mammography display and how to use them most effectively do not exist. Further research on the ergonomics of tool use is encouraged.
 - 6. Multimodality datasets and interoperability.
 - a. Mammography workstations should accommodate and display images from several modalities.
 - b. Vendor-specific workstations form part of the “vertical industrial stack,” making image sharing among different workstations difficult. For those who seek best-of-breed solutions tailored to imaging needs, current capabilities are essentially nonexistent.

- c. To ensure that a workstation is capable of displaying digital mammograms correctly, it must conform to the IHE MAMMO profile. If it does not, then likely the workstation will fail to show all digital mammograms as they are intended to be displayed by the acquisition system manufacturer, and great caution is necessary.
7. An interpreting physician's or "primary interpretation" workstation is one that is used to render an "official" or "final" interpretation of a study.
 8. A "technologist workstation" is one used by the technologist during the acquisition and quality control process of an examination. It should also comply with and be calibrated to the DICOM GSDF standard [30]. Since the technologists will QA his or her images in a manner similar to what a radiologist requires to find subtle features these displays must be similar.
 - a. When checking for positioning, contrast, and patient motion, the technologist should use a monitor with the same maximum luminance (e.g., 450 cd/m²) as those used by the interpreting physician.
 - b. A high-resolution monitor similar to that of the primary interpretation workstation is desirable.
 9. A "clinician workstation" is one used to review images as an adjunct to the official interpretation by a radiologist and may not need the high-resolution displays necessary for final interpretation.
 10. Monitors used to display images acquired in the process of needle localization must provide sufficient spatial resolution compared to final image interpretation monitors, as long as means to provide zoom and pan features do not limit the intrinsic resolution capabilities of the detector.

D. Computer-Aided Detection

1. Studies of mammography CAD alone (without a human observer) suggest that mammography CAD detects some types of lesions (especially calcifications, although possibly less well with amorphous forms) very well. Mammography CAD is not designed to be used without human observers, and a human reader would not recall for further workup all mammography CAD marked lesions. In most cases, that is appropriate since the marked lesions are not cancers. More research is needed to ascertain how to allow human observers to better distinguish between false positives and true positives with mammography CAD.

2. Specialized breast imagers seem to benefit less from mammography CAD (at least in its current form in which lesions are simply pointed out and the likelihood of malignancy is not provided) than do nonexpert mammographers or general radiologists.
3. All mammography CAD algorithms should use "for processing" rather than "for presentation" image data, as many mammography CAD algorithms already apply various levels of processing. Processed image data may alter the effectiveness of the mammography CAD algorithms if not taken into account.
4. The mammography CAD prompt may influence performance [55-57].
 - a. A prompt that completely encircles the potential lesion may be more effective than one that simply points to the general area.
 - b. Using color or altering the brightness or size of the prompted region may be more effective than traditional prompts.
 - c. Visual search behaviors can change with mammography CAD, potentially affecting workflow as well as the detection of other unprompted lesions.
 - d. The number of false-positive prompts on the displayed image can affect performance, with larger numbers reducing true-positive detection rates.
 - e. Viewing mammography CAD marks after an initial interpretation has been made or as soon as the images are available does not seem to matter significantly.

E. Image Processing Considerations

Image processing has great potential to improve image quality and secondarily diagnostic accuracy and even to reduce the radiation dose necessary to achieve an image of acceptable quality [58-60]. Digital mammograms typically have a wide dynamic range, and the ability to process the recorded image data provides an opportunity to display data more effectively. Storage of "for processing" image data provides greater flexibility for subsequent postprocessing using different algorithms. Systematic variations in intensity can be equalized, local contrast can be enhanced, and the sharpness of calcifications can be restored. Enhanced visualization of subtle structures is suggested as a possible factor for the improved performance of digital mammography in patients with dense breast tissue [46].

1. Segmentation of the breast from the region of the direct beam is the first step for defining the areas to be processed, using edge detection algorithms and grayscale adjustment to equalize apparent tissue thickness. Artifactual appearance near the skin line can occur in the equalized image, and improper segmentation requires the ability to turn off the algorithm.

2. Spatial frequency restoration and deblurring are applied to render microcalcifications with more detail. With a linear system response to exposure, the image values may be converted to an array of frequency-dependent Fourier coefficients and the restoration may be done by modification of the frequency coefficients by using a filter derived from the MTF(f). This is performed by increasing spatial frequencies in proportion to $1/\text{MTF}(f)$.
3. Selective (adaptive) noise reduction attempts to reduce noise only in regions where tissue contrast does not have noticeable fine detail. Difficulty arises in reducing noise and preserving resolution with the same process. In some cases, noise reduction might not improve detection performance if the reduced noise texture is similar to that of target objects.
4. Unsharp masking and global latitude reduction increase the relative signal in underpenetrated areas and reduce the signal in highly transmissive regions. Fourier filters or spatial convolution kernels of large spatial extent create a low frequency blurred image which is then subtracted from the nonblurred image.
5. Adaptive local contrast enhancement and multiscale processing are other methods that have been used. When applying global latitude equalization or adaptive contrast enhancement, there is always some risk that subtle tissue characteristics of potential diagnostic significance may be diminished in relation to the detail that is enhanced.
6. Differently processed versions of the same digital mammogram are preferred depending on the task and lesion type, suggesting that workstations might implement several processing options for use during interpretation [46].
7. Desired processing parameters may vary with radiographic factors such as tube target, kVp, and tube filter type and thickness. One must be careful to ensure that the processing being used is appropriately matched to the techniques with which the mammogram was obtained.
8. Comparison of images from prior mammography examinations is essential in the interpretation of a new study. However, variations in the processing of prior and current images may make such comparison difficult. See the discussion below under "Archive" for further information on this subject.
9. Storage of image data in the DICOM format intended "for processing" and application of image processing at the reading station (or by a separate processing box located separately from the primary interpretation workstation) require image processing software that is applicable to the images from any digital mammography system. They also require an understanding of the characteristics of the image data from the digital mammography system or other input device (e.g., film digitizers).
10. Improved disclosure of the processing methods being applied by manufacturers, improved control of processing parameters, and the ability to process prior images are needed. The nature of these preprocessing steps must be made clear to the user, and the definition of what is considered "for processing" data should be specified.

F. Reading Environment

Factors as diverse as ambient light, temperature, noise, posture fatigue, and poor ergonomics may have significant effects not only on radiologist comfort but also on the quality, accuracy, and consistency of image interpretation [61 62].

1. Impact of ambient light: Low light luminance of a typical CRT high-resolution 5 megapixel ($2,000 \times 2,500$ pixel) Picture Archive and Communication System (PACS) monitor is in the range of $200\text{-}400 \text{ cd/m}^2$. This figure is approximately 10% of the output associated with conventional lightboxes, which can range between $1,700$ and $3,400 \text{ cd/m}^2$, and mammography lightboxes can exceed $6,000 \text{ cd/m}^2$. Despite the wide variation of maximum luminance values for softcopy and hardcopy display devices, because of the presence of the masked film on the lightbox with a minimum optical density of 1 or greater, there is much less variation in the average luminance transmitted by the mammography image presented to the viewer. Therefore, ambient light should be low and consistent, particularly in a hybrid viewing environment where stray light from bright lightboxes can be detrimental when displaying softcopy images.
 - a. Distracting glare and reflections occur from the display surface, even when antiglare coatings are applied.
 - b. Dark adaptation variations of the human eye affect the contrast sensitivity and hence the ability to detect low-contrast targets.
 - c. Fatigue levels and eyestrain increase, and interpretation accuracy decreases, with higher levels of ambient light [62].

2. A balance between ambient room lighting and monitor brightness is necessary. Use of newer generation, higher brightness active matrix LCDs is likely to permit an increase in background lighting levels.
3. Color of ambient light is an important consideration.
 - a. Incandescent lights are recommended, with “natural” light simulation color filters, if possible.
 - b. Fluorescent lights are not recommended.
 - c. A dimmer switch should be used, particularly in environments where many kinds of images are being read and/or hardcopy and softcopy images are being interpreted in the same environment.
 - d. Color of clothing may also affect lighting levels, with light colored lab coats creating additional monitor glare.
4. Amount of ambient light should be approximately equal to the level of the average luminance of a clinical image being displayed [62]; total darkness is not recommended.
 - a. Arrangement of the ambient lighting sources is a combination of indirect overhead lighting and local task lighting using dimmable sources.
 - b. Backlighting (e.g., light from a small lamp directed at the wall behind the display) is recommended to provide diffuse reflected light whenever possible.
 - c. Deskside lighting with focused or shielded light is recommended for taking notes, etc.
 - d. Partitions or other solid screens are recommended to minimize light reflecting from a conventional viewbox onto computer monitors.
 - e. Adjusting the ambient light levels to the average luminance emanating from the display of clinical images can be estimated with an illuminance meter positioned at the usual reading distance from the display, measuring average illuminance from a random selection of displayed digital images in total room darkness, and adjusting the ambient light illuminance to the same value as referenced from the same position with the monitor(s) turned off.
5. Other environment factors [62]
 - a. Flexibility allows for evolving technologies and for changing preferences by users.
 - 1) The cubicle approach with (preferably movable) partitions creates individual or collaborative interpretation pods.
 - 2) The “center-out” approach has clusters of workstations in the center of the space, with monitors pointed toward the edges of the room.
 - 3) Avoid placing monitors in the same area as light boxes or alternators. Place them at 90 degrees rather than 180 degrees to avoid reflections.
 - 4) Separate display workstations with opaque or electronically controlled partitions that can be moved or reconfigured depending on consultation needs and on evolving technologies.
 - b. Heat and noise
 - 1) Improved air handling is especially important to maintain optimal temperature and humidity levels.
 - 2) Radiologists are vulnerable to increased heat and poor ventilation. Consider direct and individually adjustable air conditioning vents for each workstation area and computers, using technology that can reduce ambient noise.
 - c. Ergonomic and connectivity requirements
 - 1) Prevention of debilitating injury and permanent impediments is essential.
 - 2) Chairs with lumbar support and adjustable height (including armrests), workstation table (with height adjustment), keyboard, mouse, and monitors should all be designed to maximize comfort and efficiency.
 - 3) Workstations should be designed to be scalable (to accommodate one or more radiologists) and flexible enough to evolve with changing technologies and institutional requirements.
 - 4) Dictation tools, Internet access, and other facilitators of the radiologic interpretation task should be readily accessible and easy to use while viewing images.
 - 5) Keyboards that allow the user to adjust their height and angle, and ergonomically designed input device alternatives to the more traditional mouse and trackball interfaces, should be considered.
 - 6) Monitor bases should allow adjustment of the monitor angle, and the user should be provided with information about the optimal distance between the eye and the monitor and the optimal viewing angle (the eye level should be slightly above the center of the monitor screen).
6. Additional information can improve performance and prevent deleterious effects from prolonged periods of image viewing, such as the 20/20/20 rule (every 20 minutes look 20 feet away for 20 seconds).

I. Strategies for Transitioning from Analog to Digital Mammography

A hybrid viewing environment negatively impacts radiologist efficiency and productivity, partly due to the incompatible optimal luminance and illuminance levels for each. Two possible scenarios for the transition include digitizing film or printing film from the digital system.

1. Digitizing previous mammograms for comparison on softcopy display:
 - a. Practical limitations of film digitizers include (1) less accurate digitization of high-optical-density areas on the film, usually greater than 3.5 OD due to low transmitted signals; (2) a small sampling pitch less than 50 microns that produces too large of a data set and may introduce too much film/grain noise, (3) a larger sampling pitch greater than 100 microns that attenuates details in the film by spatial averaging. Film digitizers specifically engineered for mammography film digitization are recommended; they should be used in a manner that provides adequate spatial and contrast resolution for comparison (not primary interpretation) purposes.
 - b. Digitized film mammograms should have a DICOM Information Object descriptor compatible with dedicated digital mammography workstations.
 - c. Image appearance should be similar to that of inherently acquired digital mammograms, requiring conversion and contrast enhancement algorithms achieved by knowledge of the characteristic response of the film, the acquisition device, and the image processing algorithms.
2. Initially printing film for all digital mammograms and using a lightbox for evaluation and comparison of analog and digital mammograms:
 - a. Printer should have resolution equal to or better than the corresponding resolution of digital mammograms.
 - b. Process should continue for at least one year to have a minimum of two digital comparisons.
 - c. Negative impact on workflow and efficiency should be considered.

V. TRANSMISSION, STORAGE, AND RETRIEVAL

The development of tools for image storage and retrieval has emphasized the isolated silo concept, with each manufacturer optimizing its own system, at the expense of the PACS interoperability common for other imaging technologies, such as computed tomography (CT) and

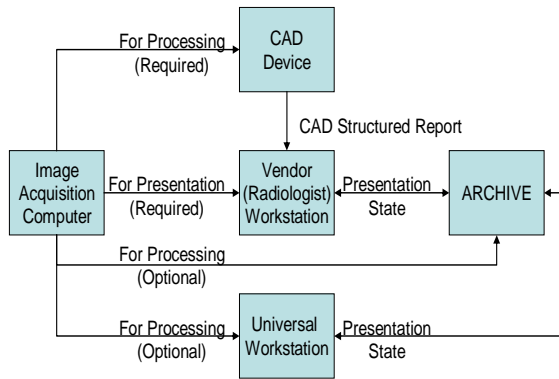
magnetic resonance imaging (MRI). The goal of DICOM transmission and storage standards is to provide a standard for storage and transmission, while the IHE mammography profile [4] provides a recommendation for best practice implementation and work flow. Relevant standards are the DICOM DX Image Information Object, the DICOM Digital Mammography X-Ray Image Information Object (MG), and the DICOM Mammography CAD Structured Report. Any of these information objects can be stored for later retrieval.

A. Digital Mammography Image and Data Types

1. The MG information object descriptor includes a specification for two types of image information. “For processing” represents image data that is corrected for detector acquisition but not processed for interpretation. “For presentation” image information has been processed by vendor-specific algorithms and is ready to be displayed on a workstation.
 - a. “For processing” image data requires mammography specific algorithms to produce an image for interpretation. Mammography CAD devices most commonly use “for processing” image data.
 - b. “For presentation” image data is processed for display on any DICOM-compliant and calibrated monitor acceptable for mammography viewing. DICOM presentation state information enables the reproduction of the appearance of the image on different devices or media.
2. Mammography CAD devices produce a DICOM mammography structured report and presentation state that should be used by enabled workstations to display the results of the mammography CAD process.
3. Digital mammography acquisition devices may transmit one or all three types of image data to other storage devices, display devices, or postprocessing devices such as mammography CAD systems (see Figure 1).
4. Vendors must support DICOM transmission of MG images, both “for processing” and “for presentation.” Many mammography CAD systems require “for processing” images to function optimally.
5. Telemammography use demands high speed networks and/or compression (see below). Reasonable transmission speeds may make the difference between an efficient, successful service and failure.

6. Other image datasets for consideration
 - a. File sizes of stereotactic biopsy unit images are typically 0.5 to 2 MB per image.
 - b. Breast MRI, breast ultrasound, breast CT, and breast tomosynthesis (the latter two currently in research feasibility studies) represent other large increases in the number of images that can be produced.

Figure 1. Flowchart of image data distribution.



B. Workstation Retrieval Requirements

1. The mammography display workstation must support receipt of DICOM-compatible MG images and mammography CAD structured reports “for presentation.”
2. Display of new data “for processing” should be optional and configurable for digital mammography workstations.
3. The display system should support DICOM query and retrieve of digital mammograms from a DICOM archive.
4. DICOM presentation states for displaying images with the ability to save and retrieve various presentation states as specified by the user are required.
5. Mammography workstations should support IHE Consistent Presentation of Images Integration Profile and IHE Mammography Image Profile, (see the IHE Radiology Technical Framework, Supplement 2006-2007 [4]).
6. Universal workstation
 - a. Should allow acceptance of “for processing” MG data, with mammography-specific hanging protocols and IHE Mammography Image Profile.
 - b. Should provide user-defined processing algorithms for digital mammograms.
 - c. Should allow multimodality image viewing of associated breast imaging studies (e.g.,

ultrasound, MRI, biopsy specimens, surgical specimens, other pertinent studies).

C. Archive

1. The archive device for digital mammography must support DICOM receipt of MG images.
2. Storage of “for presentation” images is required, to insure the ability of radiologists to reproduce the original images used for interpretation. The “for presentation” image set must be archived to PACS and be viewable with comparable quality on different but suitable workstations.
3. Storage of images “for processing” is encouraged, but is not required. The “for processing” image data storage is optional, with the possible exception of mammography CAD, which might require storage of the “for processing” data. Each facility should carefully consider the ramifications of archive space necessary for additional storage of the “for processing” images as well as the potential downstream benefit and legal implications of reprocessing of these data to create new “for presentation” image sets for future comparisons. Storage of these dataset should not be required for technical reasons, but may be required for local medical-legal ones.
 - a. Storage allows future reprocessing of digital image data for easier comparison of longitudinal studies.
 - b. It also allows newly available processing of previously acquired images for comparison purposes.
 - c. Future processing algorithms may also make an abnormality apparent that was not visible in the original interpretation with the processing then available.
4. Storage of mammography CAD structured reports is ideal but should be optional. However, those who choose to discard the mammography CAD information on which they based their interpretation should understand that the only way to reproduce the original mammography CAD data is to retain the original report. Reprocessing may yield different results.
5. The archive device should be able to query and retrieve digital mammograms.

D. Archiving Issues

1. Files sizes of uncompressed image sizes range from 8 MB for 18 cm × 23 cm FOV at 100 μm up to 50 MB for 24 × 30 cm FOV at 50 μm.

2. A standard screening exam of 4 views requires 32-200 MB.
 - a. 60 patients per day (screening and diagnostic) produce ~ 2-12 GB per day.
 - b. If possible, comparison of current studies to prior examinations is strongly recommended. See the [ACR Practice Guideline for the Performance of Screening Mammography](#). Assuming the average number of comparison examinations is 2, the daily available storage needs increases to approximately 6-36 GB for day.
 - c. Prior examinations may be imported from portable media. Prior examinations may have been obtained using a screen-film system, and these can be digitized for softcopy display. Currently, a digital practice of about 150,000 examinations per year would produce 25 GB of data per day, assuming nonstorage of the original. If the “for processing” images are stored, the data storage requirements for a practice performing 60 screening mammograms per day may be as high as 72 GB per day.
 - d. Although the FDA does allow the digitization of prior film examinations for comparison purposes, its current guidelines [35] do not allow film images to be digitized for archival purposes. The original film images must be maintained.
3. Analog to digital conversion strategies
 - a. Option 1: Prior film examination digitization requires an acceptable film digitizer and DICOM modality work list conversion for proper display on PACS for softcopy comparisons. Difficulties include variation in image presentation as well as image size.
 - b. Option 2: Facility prints all digitally acquired examinations for at least one year and perhaps longer. This will impact efficiency, productivity, and cost during the conversion time.
 - c. The facility will be committed to maintaining both film and electronic archives with the associated costs for an unspecified time in either scenario.
4. Location of archive
 - a. Option 1: Archive with all other digital images on the enterprise PACS.
 - b. Option 2: Dedicated mammography local storage (such as a mini-PACS).
 - c. Strategy may require a reanalysis of the human and electronic workflows to assure timely distribution. The workflow and retrievability requirements of mammography are generally different from those of the general radiology reading room. Option 2 will require an analysis of the potential

limitations in retrievability of images across a facility both inside and outside of the mammography department.

5. Infrastructure needs

Actual media and storage technologies are the least serious challenge for infrastructure, with large rotating Redundant Array of Independent Disks (RAID) storage a commodity. Issues of data volume and media compatibility require attention. Digital mammography presents unique challenges for complete electronic imaging in radiology.

E. Image and Data Compression

Digital mammogram compression can provide more efficient transmission and storage. The digital image is an exact representation of an inexact noisy signal, with finite limits to the amount of compression that can be applied. Mammography images are very suitable for compression (lossless or not) because of large black areas outside the breast.

1. Lossless or bit conserving compression takes advantage of redundancy in image data.
 - a. The amount of compression (2:1 to 3:1) depends on the complexity of the image information (area of the image containing breast anatomy) and noise characteristics of the image.
 - b. Compressing and decompressing the image data maintains original matrix size and perfect recreation of the digital pixel values.
 - c. Algorithms include run-length encoding (RLE), Joint Photographic Experts Group (JPEG), and JPEG 2000 methods.
2. Lossy compression achieves close recreation of the pixel values, but with some measure of finite error [63-67].
 - a. Recommended algorithms follow DICOM standards for the wavelet or JPEG 2000 type.
 - b. For error that is negligible compared to the uncertainty introduced by the detector and display components, a degree of lossy compression may be deemed acceptable at some point.
 - c. Compression ratios of 10:1 have been shown not to affect the detectability of large area masses.
 - d. Lossy compression can deleteriously affect the detection and appearance of microcalcifications, and therefore presumably mammography CAD of microcalcifications.
3. Advantages of compression include faster transmission time and smaller storage

requirements. Economics of storage technology are moving so positively that no long-term significant benefit accrues from high ratio (greater than 10:1) lossy compression. All compression ratios greater than 3:1 are likely to result in lossy compression, even though differences in the appearance of the images may be difficult to appreciate. Lossy compression violates the first principle of “store what you read,” since it is not likely that any digital mammography vendor would currently allow lossy compression of image data prior to display.

- a. Ethernet 100-base-T network transmission time for a MG study (“for processing” and “for presentation”) with 2:1 lossless compression is about 1 minute.
 - b. Cable type broadband network transmission time for a MG study (“for processing” only) with 20:1 lossy compression is about 3 minutes.
 - c. With storage costs lowering rapidly per terabyte, a MG study (“for processing” and “for presentation”) with lossless compression has very low isolated storage cost. With moderate lossy compression, this cost drops to a few pennies per study.
4. Lossy compression is not justified solely by the small cost savings to be realized. Even for image transmission, compression of images must be lossless primarily due to the potential loss of visibility of calcifications.
 5. For telemammography, access to sufficient bandwidth alleviates the need for lossy compression. If sufficient bandwidth is not available, facilities should not accept lossy compressed images for final interpretation. In these instances, remote on-line interpretation will be constrained by transmission speeds.
 6. Detection and characterization of calcifications by mammography CAD could potentially lead to segmentation of image areas that are not subjected to lossy compression and to the remainder being subjected to mild lossy compression, with reassembly of the image dataset at the receiving site.
 7. Future alternatives may be performed at an “acceptable” level of lossy compression before the radiologist optimizes and interprets the image for the “for presentation” data. This approach, however, is unlikely to be feasible unless it is proven to have essentially no impact on diagnostic accuracy.

F. Legal Challenges

The legal requirements for digital mammography are established by the FDA rule [6 1997 #35] and by the state that has appropriate jurisdiction.

1. For acquisition and interpretation, the legal requirements are the same as those for film mammography.
2. FDA regulations require that facilities maintain mammography films and reports in a permanent medical record of the patient for a period of not less than 5 years or not less than 10 years if no additional mammograms of the patient are performed at the facility, or a longer period if mandated by state or local law. The record retention requirements may be quite different from state to state.
3. Ramifications of the above requirement are complex, and could be interpreted to mean that the “for processing” image as well as the DICOM “presentation state” image must be retained. This may also require the storage of mammography CAD results at the discretion of individual facilities. Data will have to be transferred to accessible media as technology evolves.
4. Digitization of the current film library or the maintenance of both electronic archive and film libraries may be required. Each has profound financial consequences.
5. Security requirements for disaster recovery of digital imaging are far greater than those for film-based imaging. A physically separated redundant archive may be necessary in some jurisdictions.
6. Circumstances become more complex for the patient who is seen in more than one state as well as for the practice that receives images from more than one state. Clearly, the requirements of each jurisdiction must be analyzed carefully.
7. Use of lossy compression for data storage, transmission, and retrieval is not advisable and is not allowed by the FDA.

VI. QUALITY CONTROL RECOMMENDATIONS

A. Acquisition

1. Manufacturer-specific QC procedures are required under the current FDA rules for digital mammography and must be followed. Documents provided by the manufacturer of the digital mammography system define the

procedures and limits for corrective action for periodic tests (daily, weekly, monthly, quarterly, semiannually) performed by a designated technologist, and for annual tests by a qualified medical physicist.

2. ACR is designing a “harmonized” full-field digital mammography quality control manual and procedures for possible future implementation and adoption for all digital mammography systems.
3. Other requirements regarding the overall quality assurance program mandated by the FDA must be carefully followed. QC for hardcopy devices used for printing of digital mammography images should include implementation of the DICOM GSDF standards for printers [30]. Specific manufacturer QC test procedures, frequencies, and corrective action limits must be followed for digital mammography displays, workstations, hardcopy devices, and verification of proper grayscale rendition of printed images compared to displayed images is necessary. NEMA standards and document templates are available to assist in the recording of these processes [33, 34].

B. Image Display and Processing

1. QC guidelines for display monitors include implementation of the DICOM GSDF standard [30] and the mammography-specific recommendations of AAPM Task Group 18 [42]. These recommendations are outlined in the ACR harmonized full-field digital mammography documents (not yet available at the time of publication).
2. QC for image processing of digital mammography images should include interaction with radiologists and verification of reproducible image processing characteristics and proper rendition of images and correct functioning of task-dependent processing.

C. Storage and Archiving

1. Verification of DICOM metadata in header and accuracy of information.
2. Security and privacy protection.
3. Backup and disaster recovery testing.

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2. AAPM - American Association of Physicists in Medicine.
3. Bit - acronym for binary digit possessing two integer values, 0 and 1. In computer or electrical terms, a bit provides a logical or physical "switch" as an off (0) or on (1) value.
4. Bit depth - bit depth refers to a sequence of binary numbers that can encode a sequence of integer values, as 2^n bits. A bit depth of 1 encodes 2^1 or 2 values (0 and 1), while a bit depth of 8 encodes 2^8 or 256 values (0 to 255).
5. Byte - a sequence of 8 bits, a modular entity useful for computer addressing and manipulation. For digital mammography, a pixel in the digital image is most always represented by 2 bytes (16 bits), as usual relevant bit depths are 10 to 14 bits, the number determined by the characteristics of the detector.
6. CAD - computer-aided detection.
7. CAD SR - computer-aided detection structured report containing information regarding the evaluation of the mammogram by a computer and the locations of potential lesions identified by the algorithms.
8. CC/MLO - cranial caudal/medio-lateral oblique are common projections used for positioning the breast in a screening examination.
9. CCD - charge coupled device, an electronic sensor that produces charge in proportion to light incident on the photosensitive array.
10. cd/m^2 - candela per meter squared, the unit of luminance referring to the light intensity emission of a display monitor in the context of this guideline.
11. CR - computed radiography, a method of acquiring digital mammograms using a photostimulable storage phosphor and subsequent processing in a CR reader; most implementations use a passive detector housed in a cassette that replaces screen-film cassettes.
12. CRT (Cathode Ray Tube) - display device creating an image with the use of an evacuated tube, image phosphor coating, and electron gun (cathode ray) that is modulated by a video voltage and directed to a specific location on the phosphor. Brightness is determined by the number of electrons hitting the phosphor at any instant in time.
13. DICOM (Digital Imaging and Communications in Medicine) - a standard in widespread use for the collection, display, archiving, and retrieval of digital image information and associated patient information and reports.
14. DICOM "for processing" and "for presentation" images - "for processing" is the image that has detector blemishes and gain variations reduced by a "flat-fielding" process, but no other linear or non-linear image processing applied; this is often known as a "raw" image. "For presentation" is the contrast and spatial resolution enhanced image, most often using non-linear post-processing methods applied to the "for processing" image, so that a "generic" workstation can present the image data ready for presentation with minimal user adjustments.
15. DICOM IOD (Information object descriptor) - represents how entities such as mammography

APPENDIX A

Glossary

1. "Air" suppression - refers to the ability of the detector system to recognize pixels in the mammography image that are unattenuated by the breast, and setting those pixel values to a minimum display value that is not affected by image contrast adjustments, including inversion of image contrast (from IHE information).

- images are described by the DICOM standard with generic and specific information tags (metadata) contained in the DICOM header of the image. The DICOM IOD for mammography is “MG”.
16. DQE (Detective Quantum Efficiency) - a measure of the information transfer efficiency of a detector system as a function of spatial frequency with values ranging from 1 (100% efficient) to 0 (0% efficient). The DQE metric has a combination of object (MTF) to system noise (NPS) measurements of a real detector compared to an ideal detector.
 17. DR - the acronym given to a class of detectors that acquire images directly without the need for user intervention. Also known as digital radiography (a generic term). For digital mammography, this currently includes devices based on TFT arrays (see definition below) using CsI (cesium iodide) scintillators layered on photodiodes (x-rays to light to charge) connected to the TFT, or semiconductor *a*-Se (amorphous selenium) layered on charge collection electrodes (X-rays to charge). The slot-scan CCD is the third FDA-approved digital mammography system considered a type of DR device.
 18. FDA (Food and Drug Administration) - in the United States, the organization that regulates screen-film and digital mammography through the Mammography Quality Standards Act of 1992.
 19. FDA ODE - The Food and Drug Administration Office of Device Evaluation.
 20. FFDM - Full Field Digital Mammography.
 21. FOV (Field of view) - the area dimensions of image acquisition (the collimated field and imaged anatomy within the field) and image display (the method to map the acquisition image into the viewport). When the image matrix size is larger than the display matrix size, in order to view the total acquired image requires down sampling of the image and loss of resolution. One to one pixel mapping from acquisition to display achieves full resolution viewing of the mammogram, however only a subset of the image can be viewed at one time, requiring a “zoom and pan” operation at the workstation.
 22. GB - Gigabyte = 2^{30} bytes = 1,073,741,824 bytes.
 23. GSDF (Grayscale Standard Display Function) - a DICOM supplement (part 14) describing how devices can be calibrated to a response that provides a consistent grayscale appearance, independent of the display medium (CRT, LCD monitors, printed film).
 24. IHE (Integrating the Healthcare Enterprise) - an initiative by care providers and vendors to improve how information systems communicate to support patient care. A digital mammography-specific IHE profile deals with issues pertinent to the clinical needs for efficient operation and interconnectivity among acquisition, display, and archiving devices among others.
 25. JPEG (Joint Photography Experts Group) - image format that can provide image size reduction by compression either with bit preserving (lossless) or bit destroying (lossy) algorithms.
 26. JPEG 2000 - an image format that can provide image size reduction by compression using specialized “wavelet” algorithms with bit preserving or bit destroying methods.
 27. kB - kilobyte = 2^{10} bytes = 1,024 bytes.
 28. kVp (Kilovolt peak) - the peak applied voltage placed across the anode-cathode in an X-ray tube, which determines the peak X-ray energy in the output X-ray spectrum.
 29. L - the symbol for luminance with units of cd/m^2 , the light intensity of a video display monitor or a viewbox in the context of this guideline.
 30. LCD (Liquid Crystal Display) - a monitor that uses an electronic two dimensional pixel array to produce variations in grayscale corresponding to digital image values at the corresponding position in the digital image matrix. Liquid crystal light transmission characteristics are varied by electronic means, and the grayscale image is produced using a high intensity back-light source that is modulated by the transmission characteristics of each pixel making up the display.
 31. LUT (Look Up Table) - a digital mapping of input values to output values. An example is the window width and window level adjustments on a display workstation to change the contrast and brightness of the image.
 32. MB - Megabyte = 2^{20} bytes = 1,048,576 bytes.
 33. Megapixel (MP) - one million pixels, this term is often used to describe LCD monitors and CRT monitors based upon the number of pixels that can be individually mapped to the display surface. Common display matrices are 2 MP (1200 x 1600), 3 MP (1500 x 2000), and 5 MP (2000 x 2500).
 34. MG - the DICOM digital mammography information object descriptor, which has information about the image acquisition techniques, positioning details specific to mammography in addition to all conventional DICOM image metadata.
 35. MQSA (Mammography Quality Standards Act) of 1992 - a law governing the practice of mammography in the United States.
 36. MTF (Modulation Transfer Function) - is a method to quantify the spatial resolution transfer characteristics of an image detector as a function of spatial frequency.
 37. NEMA (National Electrical Manufacturers Association) - a standards body that represents manufacturers of diagnostic X-ray and mammography imaging equipment (among others).
 38. NEQ (Noise Equivalent Quanta) - a measure of the noise properties of a detector as a function of spatial frequency that includes quantum mottle, electronic noise, detector structure noise and other noise sources that represents the “equivalent” number of quanta as if the detector were recording only X-ray quanta. This number is lower than the actual number of quanta incident on the detector.

39. NPS (Noise Power Spectrum) - a frequency-based method to define the noise characteristics of the image receptor.
40. Nyquist frequency: - the maximum “useful” frequency contained in an image, defined as $1/(2p)$, where p is the sampling pitch, the distance between samples. In most digital detectors, the sampling pitch is equal to the sampling aperture, and therefore as an example, a 0.1 mm (100 micron) sampling pitch (aperture dimension of 0.1 mm) has a Nyquist frequency of $1 / (2 \times 0.1 \text{ mm}) = 5 \text{ mm}^{-1} = 5 \text{ line pairs/mm}$.
41. PACS (Picture Archiving and Communication System) - the acronym given to the components of an electronic imaging system responsible for collecting, displaying, archiving images from an acquisition device synchronized with information regarding the patient obtained from an information database, usually the Radiology Information System (RIS).
42. PSP (Photostimulable Storage Phosphor) - the imaging receptor used for Computed Radiography, usually made of a barium fluorobromide compound (BaFBr) whereby absorbed X-rays create an electronic latent image in the compound, subsequently “stimulated” with a laser beam with the release of “photostimulated luminescence” that is collected and converted to a corresponding digital value (grayscale) at each position in the image matrix.
43. QA (Quality Assurance) - the overarching program that verifies the process of not only the technical components but also the administrative, personnel and patient care aspects of mammography, largely specified by MQSA.
44. QC (Quality Control) - a program encompassing the technical aspects of an imaging system and its components to test, measure and verify adequate performance metrics, and to take corrective action and re-verification to ensure proper system function and appropriate image quality and patient safety.
45. ROI (Region of Interest) - a user-selectable area in an image to assess specific quantitative characteristics (e.g., average digital signal and standard deviation (noise) of the signal) or defined area in which a specific image processing algorithm is applied (e.g. magnification window).
46. RSNA - Radiological Society of North America.
47. SDNR (Signal Difference to Noise Ratio) - a method to quantitatively determine the differential contrast of objects in an image, by determining the average values and standard deviations of the values in user selectable ROI's, subtracting the object ROI from the background ROI (the contrast signal) and dividing by the noise signals added in quadrature. This is a useful metric for determining consistency of a digital receptor response with a consistent technique and known phantom configuration.
48. SIIM (Society for Imaging Informatics in Medicine) - (formerly known as the Society for Computer Applications in Radiology--SCAR).
49. SNR (Signal to Noise Ratio) - the average signal in a uniform field (usually defined by a selected ROI) divided by the standard deviation of the signal. This measurement does not typically consider variations in background induced by anatomy but does include noise sources such as quantum mottle, electronic signal variations, static detector imperfections, nonuniform gain.
50. SSCCD (Scanned-Slot Charge Coupled Device) - one of the FDA-approved digital mammography systems that uses a slot-collimated beam that moves across the breast in synchrony with a CCD detector array to produce the digital mammogram. Pre- and post-collimation significantly reduces scatter so that a grid is not required.
51. TFT (Thin-Film-Transistor) - an array of electronic switches (transistors) interconnected by gates (method of turning the transistor on and off) and drains (method of collecting the charge accumulated in each detector element and delivering to a charge amplifier for subsequent digitization) on a flat-panel detector.
52. “True” size - the display of an image such that an object in the image when measured with a hand-held ruler on the surface of the display measures as closely as possible to the true physical size of the object if located on the front face of the detector housing (from IHE information).
53. X-ray tube filters - Mo (molybdenum); Rh (rhodium) possess “absorption edges” X-ray energies used for mammography, and their use optimizes the X-ray beam spectrum by selectively removing the very low X-rays that otherwise mostly result in breast dose and high X-ray energies that result in lower subject contrast of the breast anatomy.
54. X-ray Tube Targets - Mo (molybdenum) and Rh (rhodium) are useful for mammography because of the characteristic X-ray energies generated at 17.5 and 19 keV (Mo); 20 and 23 keV (Rh), nearly ideal energies for imaging the breast and achieving good contrast with low dose. W (tungsten) does not provide useful characteristic X-rays but is becoming popular due to high power loading (shorter exposure times) and ability of digital image processing to adjust contrast to appropriate levels. All X-ray beams for digital mammography must be filtered (see X-ray tube filters).