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EQUIPMENT REQUIREMENTS AND QUALITY CONTROL FOR MAMMOGRAPHY

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REPORT OF
TASK GROUP NO. 7
DIAGNOSTIC X-RAY IMAGING

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1. INTRODUCTION

An increased awareness of the benefits of early detection of breast cancer has caused a resurgence of the use of mammography. This has resulted in a large increase in the number of installed units and also in the number of manufacturers marketing equipment.

Mammography is one of the most technically exacting radiographic procedures. A small change in technique or processing factors can have a significant effect on image quality and radiation dose delivered to the breast. In order to produce mammograms at the lowest doses consistent with high diagnostic sensitivity and specificity, it is necessary that careful consideration be given to the selection of equipment, patient positioning and imaging techniques and the establishment of an effective quality control program. This document is intended to assist the medical physicist in providing the required expertise to make such decisions.

It is assumed in this report that the reader is familiar with the basic principles of radiological imaging and we have concentrated here on their specific application to mammography. For those interested in reviewing these principles several excellent texts on radiological physics are available.

2. METHODS OF IMAGING

2.1 Film-Screen vs. Xeroradiography

Two types of image receptors are in widespread use: high resolution film-screen systems and xeroradiography. Typically, the former consists of a single, thin, highly-absorbing intensifying screen and a single-emulsion film. Recently, a dual-screen image receptor using double-emulsion anti-crossover film has been introduced. Antiscatter grids for mammography are now widely used for film-screen mammography. The xeroradiographic technique has been described in detail elsewhere[1,2,3] and is discussed in Section 4. The xeroradiographic system is used with a more penetrating x-ray beam than in film-screen mammography and images display significant edge enhancement, providing very high spatial resolution (where edge

structure exists) while imaging a wide dynamic range of tissue attenuation. This is especially useful near the chest wall. Images are produced through an electrostatic process in which charged toner particles are attracted to charged areas on a selenium plate and transferred to a background of white reflective paper. The edge enhancement effect is caused by toner particles following distorted trajectories due to fringe fields above the selenium image plate. This results in enhanced response at high spatial frequency. On the other hand, the modulation transfer function of xeroradiography systems at low spatial frequency (broad-area contrast) is inferior to that of film. By adjustment of polarity in the processing unit, either positive or negative images can be produced. Some facilities use the negative mode because images can be produced at a lower radiation dose than in positive mode.

The choice between the use of film-screen and xeroradiographic imaging systems may be dependent upon several factors which are discussed below.

2.1.1 Choice of X-ray Equipment

Xeroradiography may be performed with a conventional small focus tungsten target tube with aluminum filter and a conventional generator operating in the 42-52 kVp range. Film-screen systems require a special thin window x-ray tube, usually incorporating a molybdenum target and molybdenum filter, and a generator designed to operate at low kilovoltage (22-35 kVp). Both systems require dedicated angulation, compression and positioning apparatus.

2.1.2 Differences in Patient Positioning

Craniocaudal and medio-lateral oblique views are recommended for film-screen mammography. Craniocaudal and medio-lateral views are generally used for xeroradiography. A grid is frequently used to improve contrast when film-screen mammography is employed. Since xeroradiography is relatively insensitive to low spatial frequency (broad area) information and the scatter radiation field exiting the breast is of low spatial frequency, a grid is generally not used. Firm compression of the breast is essential in film-screen mammography

for reasons discussed in Section 3.1.4. Less firm compression can be tolerated with xeroradiography due to its wide recording latitude.

2.1.3 Differences in Diagnostic Image Quality

Film-screen imaging tends to provide better images of subtle, soft tissue density tumors, while the edge-enhanced contrast of xeroradiography is useful for visualization of miicrocalcifications and masses with well-defined borders and/or fine, radiating fibers. "Differences in diagnostic image quality between the two techniques are subtle . . . . rarely will one technique permit the detection of a breast cancer and the other show nothing suspicious" (NCRP 85, Page 37)[2].

2.1.4 Considerations of Convenience and Personal Preference

Viewing ease - xeroradiographs are viewed by reflected light under normal room illumination conditions. This is convenient for referring clinicians. Film images require low ambient light on a masked viewbox to display subtle contrasts. Localized "bright-lighting" is also often required to view information in the darkest regions of the film. Use of a magnifying lens to aid in visualizing fine structures is valuable with both techniques.

Reliability - Equipment reliability and downtime may vary for the two techniques. The xeroradiographic processor is more mechanically complex than the film development unit and proper routine maintenance is essential. Quality of service may vary locally and advice in this matter should be sought from colleagues.

Availability of backup processors - Many facilities are equipped with more than one automatic film processor, and although a dedicated processor is highly recommended for mammography, a second unit can be used in an emergency. An alternate xeroradiographic processor is much less likely to be available in a given facility, and this may affect system downtime when the xeroradiographic processor is out of service.

2.1.5 Differences in Radiation Dose

The average glandular dose for non-grid film-screen imaging* is normally two to three times lower than for the original xeroradiography system (Xerox 125), although the increasing use of grids for film-screen imaging may bring the dose from the two techniques closer together when each system is used optimally. Faster film-screen systems have been introduced recently which can compensate for the dose increase when grids are used. Imaging systems are constantly evolving and dose comparisons will change with time. Typical skin entrance exposures and mean glandular doses (at the time of writing) are given in Table 5-2.

In summary, studies to date have shown that the two mammography methods produce images of similar diagnostic utility with only subtle differences in diagnostic information content. When performed optimally, each excels in different aspects of breast imaging. Major differences are in the choice of x-ray source, image processing, and viewing equipment. There may also be a significant difference in radiation dose for various film-screen vs. xeroradiographic techniques. The reader is referred to NCRP Report No. 85 (Pages 34-39)[2] for a more complete comparison between the two techniques, keeping in mind that improvements and changes have occurred in both techniques since that report was published.

2.2. Magnification Mammography

Magnification radiography is often required if a mass or small calcifications are discovered on a mammogram. A coned-down magnified view with strong compression is often performed, using a special small compression paddle with the breast supported on an elevated table. While some units are equipped to provide 2x magnification geometry, most focal spots perform better at 1.5x magnification. Images at the lower magnification are usually sharper due to the reduced focal spot unsharpness (penumbra).

* e.g. Single Kodak Min-R screen with Kodak OM-1 or Dupont Microvision film or equivalent with standard 90-second processing.

For film, an optical density of 1.0-1.3 above base + fog for the main parenchymal area of the breast should be achieved. Grids are not recommended for use with magnification since both the air gap between the breast and image receptor and the small field size reduce scattered radiation. In addition, the use of a grid would increase the patient exposure, tube loading, and motion artifacts due to prolonged exposure time. When magnification is used, all structures in the breast are projected on to the image receptor at reduced spatial frequency. The signal-to-noise ratio of the receptor improves as spatial frequency is decreased (since the MTF is higher and film granularity noise is less important[18]) and less scattered radiation reaches the receptor. Under these conditions, it may be acceptable to use a higher kVp to allow decreased exposure time. Increase in kVp may also be necessitated to avoid excessive exposure times on some tubes with very low mA rating for the small focal spot. Typically, magnification views are obtained at 30 or 32 kVp with film-screen, depending on breast thickness.

3. FILM-SCREEN IMAGING

3.1 Selection of Equipment for Film-Screen Mammography

3.1.1 X-Ray Source Assembly

It has been found that excellent contrast for typical breast thicknesses (i.e.. 3-5 cm compressed) is obtained with a molybdenum target, beryllium window x-ray tube with » 0.03 mm of molybdenum filtration[4,5,6]. The half-value layer of such a source assembly is required to be no less than 0.3 mm of aluminum[29,33] (tested at 30 kVp). At 28 kVp, which is more typical for imaging the average breast, the HVL should not exceed 0.37 mm Al, although some commercial units cannot meet this recommendation. More penetrating beams result in an obvious loss of contrast and compromise imaging of microcalcifications. Excessive filtration can be caused by x-ray tubes with thick glass windows, which, under no circumstance, should be used for film-screen mammography. Such windows typically have a filtration equivalent to » 0.7 mm of aluminum and remove a significant Percentage of the quanta below 20 keV from the x-ray beam. Even when the tube is equipped with molybdenum filtration, HVLs of » 0.4-0.5 mm of aluminum at 28 kVp may result. Glass mirrors and permanently installed Al filters in non-dedicated units can also raise the HVL. Table 3-1 lists typical combinations of kVp, target, window, filter and half-value layer for film-screen and xeroradiographic imaging. Molybdenum target tubes do not provide an appropriate spectrum for xeroradiography without heavy filtration which compromises tube output and heat loading. They are, therefore, not recommended for this purpose.

TABLE 3-1 X-RAY TUBE/FILTER CONFIGURATIONS

Image Receptor	kVP Range	Tube Target	Tube window	Filter Material	Filter (mm)	HVL (mm Al)
Film/Screen	25-35	Mo	Be	Mo	0.03	0.3-0.37*
Xerox	42-52	W	Be/Glass	Al	1.0-2.5	1.0-1.6
	43-48	Mo	Be/Glass	Al	1.5	0.8-0.85

* Minimum HVL at 30 kVp must meet regulatory requirements.

In order to achieve the high resolution required for the perception of microcalcifications, the focal spot size is an important consideration in mammography. Mammographic film-screen systems have limiting (high contrast) resolution as high as 16 cycles/mm although their noise limitations usually restrict the visualization of biological structures[7] to frequencies below about 10 cycles/mm. It is important that the focal spot does not significantly reduce the resolution beyond this point. National Electrical Manufacturers Association (NEMA)[8] and International Electrotechnical Commission (IEC)[9] specifications allow the effective size of the focal spot to be substantially greater than the nominal size (see Table 3-2) and in practice, such is generally the case.

Table 3-2 NEHA/IEC Focal Spot Tolerance Limits

Nominal Focal Spot Size (f_{nom}) (mm)	Maximum Focal Spot Dimension (f_{eff})	
	Width (mm)	Length (mm)
0.10	0.15	0.15
0.15	0.23	0.23
0.2	0.30	0.30
0.25	0.40	0.40
0.3	0.45	0.45
0.4	0.60	0.85
0.5	0.75	1.1
0.6	0.90	1.3
0.8	1.2	1.6
1.0	1.4	2.0
1.2	1.7	2.4
1.4	1.9	2.8

For a desired limiting resolution, R (cycles/mm), due to a focal spot of uniform intensity, the maximum effective focal spot dimension in mm is:

$$f_{eff} = \frac{M}{R\,(M-1)} \qquad (1)$$

where M is the geometrical magnification factor of the object of interest [i.e. the focal spot-to-image receptor distance divided by the distance from the focal spot to the object]. Since structures in

the breast furthest from the image plane receive the greatest magnification, the tissue near the x-ray entrance surface of the breast will be imaged with the most unsharpness. Utilizing this equation and assuming a 5 cm object-to-film distance, the nominal spot size (f_{nom}) for grid and contact work to achieve a resolution of 12.5 cycles/mm should be $\leq$ 0.5 mm (f_{eff} = 1.0 mm) for a 60-65 cm SID.

For a 50 cm SID, magnification is increased and the nominal focal spot should be smaller, i.e., $\leq$ 0.4 mm. If magnification technique is used, the nominal focal spot size should be $\leq$ 0.15 mm for I.5 x magnification and $\leq$ 0.1 mm for 2x magnification. These results are summarized in Table 3-3 showing f_{eff} which is the largest effective dimension acceptable when viewed from any point in the image area. If significantly larger focal spots are employed, a loss of sharpness and a potential decrease in visibility of 'microcalcifications will result. Some systems employ a tilted tube mounting to increase output and field uniformity. Since the NEMA standard specifies that the nominal focal spot size is measured orthogonal to the tube port, correction for the tilt angle (see Section 6.8) must be done when verifying the nominal focal spot size[10] from measurements of the effective size.

Table 3-3 Actual (f_{eff}) and Nominal (f_{nom}) Focal Spot Sizes necessary to achieve an Object Plane Spatial Resolution of 12.5 cycles/m at the Chest Hall

SID (cm)	Magnification	f_{eff} (mm)	f_{nom} (mm)
80	1.07	1.2	0.6
65	1.08	1.1	0.5
50	1.11	0.85	0.4
--	1.5	0.23	0.15
--	2.0	0.15	0.10

Because of varying design characteristics of x-ray tubes, SID, window construction and ripple performance of different generators

(discussed later), specification of tube current can be misleading in predicting x-ray output. Measured output exposure rate data are much more useful. To ensure acceptable exposure times in film-screen mammography for the range of breast thicknesses, the exposure rate available at the entrance surface to the breast for non-magnification work should be at least 500 mR/s at 28 kVp. Significantly lower x-ray output results in longer exposure times and occasional problems with patient motion and reciprocity law failure of the film. An x-ray unit providing 500 mR/s should be capable of sustaining its maximum current for approximately three seconds.

Table 3-4 Source Assembly Specifications
(Film-screen mammography)

Target	Molybdenum
Window	Beryllium
Added Filtration	0.03 - 0.06 mm of Molybdenum
Half-Value Layer	0.30 - 0.37 mm of Al at 28 kVp (with compression plate)
Focal Spot Size (nominal)	≤ 0.5 mm contact or grid at 65 cm SID ≤ 0.4 mm contact or grid at 50 cm SID ≤ 0.15 mm for 1.5x magnification ≤ 0.1 mm for 2.0x magnification
Tube Current (for 22-35 kVp range)	
Large Focal Spot	≥ 100 mA for 3 s (or 500 mR/s at breast entrance)
0.1 mm Small Focal Spot	≥ 20 mA for 6 s
0.15 mm Small Focal Spot	≥ 30 mA for 3 s

The x-ray tube current achievable on the small (i.e., 0.1-0.2 mm) focal spot should be as high as possible. Currently some manufacturers have been able to produce tubes that achieve 25 mA on a 0.1 mm focal spot and 50 mA on a 0.2 mm focal spot. Desirable source assembly specifications are summarized in Table 3-4.

3.1.2 X-Ray Generator

Several types of x-ray generator, characterized by the shape of the voltage-wave form produced, are available. Typical wave forms associated with these types are shown in Figure 3-l. The single phase generator has 100 percent voltage ripple. Since the efficiency of x-ray production depends on approximately the second power of the kilovoltage, the radiation output varies considerably during an exposure. In order to obtain a given effective output, the instantaneous tube current (and input power) must be approximately twice that of a constant voltage source. This may shorten the life of the filament of the x-ray tube, and also result in problems associated with space charge in the tube. The large, intermittent instantaneous heating applied imposes an effective limit on single exposure target loadability.

Capacitive smoothing of single-phase generators can be used to yield a more uniform output voltage. Additional means must be employed to eliminate the capacitive decay at the end of an exposure and ensure prompt shutoff. A grid-controlled x-ray tube can be used for this purpose.

Three-phase and medium- or high-frequency inverter type generators yield nearly constant potential waveforms. The amount of voltage ripple can vary depending on the design. Some high frequency generators are available with less than 2 percent voltage ripple. For a particular mA and kVp setting, the effective radiation output rate from a constant-potential generator (i.e. 1 ϕ CAP, 3 ϕ or CP) is approximately twice that of an unsmoothed single-phase unit. Since the effective kilovoltage is higher, x-ray production is more efficient. With constant voltage, the tube-current waveform is also approximately constant, yielding more temporally uniform anode heating and greater single exposure target loadability. Also, x-ray beam

quality is more uniform over the exposure time.

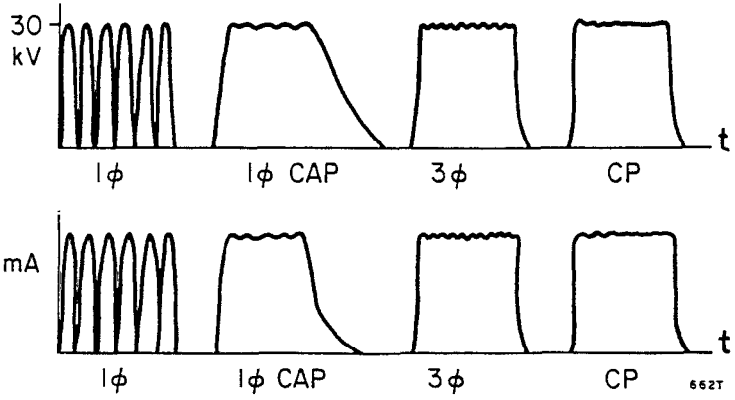


Figure 3-1 Typical Voltage and Tube Current Waveforms for Mammographic Generators

1 φ (single-phase), 1 φ CAP (single-phase, capacitor-smoothed), 3 φ (three-phase), CP ("constant potential" inverter type)

For these reasons, it is desirable to employ a generator that produces a quasi-constant potential waveform, i.e., three-phase, high frequency or single-phase with capacitive smoothing.

Inverter-type generators have the additional advantage of closed loop kV regulation. This eliminates problems caused by line voltage variations. In general, mammography units that utilize such high frequency technology are capable of excellent exposure reproducibility.

In practice, film-screen mammograms are obtained with applied tube kilovoltages within the range of 25 to 35 kVp. The peak x-ray tube voltage should be adjustable within this range in 1 kV increments. In general, automatic exposure control (AEC) should be used, however, it is necessary to have manual techniques available for imaging patients with implants, performing special views, performing specimen radiography and for checking tube output. For manual operation, either the mAs or the exposure time should be adjustable in 15-20% increments and the actual mAs or exposure time should be clearly indicated on the control console for both manual and AEC operation. This value should be displayed until the next exposure is initiated.

The x-ray generator power requirements for film-screen mammography are modest, typically less than 10 kW. The power that can be used is usually limited by the loadability of the x-ray tube focal spot. One other consideration is the type of power switching employed. Most systems use solid-state switching but some manufacturers still use mechanical contacting which provides poorer precision of exposure control.

It is important that the generator is either designed to correct automatically for variations in line voltage or else provide visual indication of line voltage changes and a manual adjustment that allows adequate correction.

Desirable x-ray generator specifications are summarized in Table 3-5.

Table 3-5 X-Ray Generator Specifications for Film-Screen Mammography

Power Rating	3 - 10 kW
Tube Output	500 mR/s minimum at 28 kVp
High Voltage Waveform	Three phase or high frequency inverter type
kV Selection	25-35 kVp in 1 kV increments Accuracy ± 1 kVp
Time/mAs Selection	0.02 - 6 sec, 15-20% increments or 2 - 600 mAs, 15-20% increments
Technique Indication	Manual - selected mAs shown AEC - post exposure mAs indication essential

3.1.3 Geometry

The source-to-image plane-distance (SID) must be adequate to allow good access and flexibility in patient positioning. Distances of 60-65 cm are typical. Shorter SIDs can be employed if a smaller focal spot size is used (see Equation 1) to control geometrical unsharpness due to the focal spot. Shorter SIDs also compromise the ease with which localization studies can be performed and result in a shorter air gap (and hence an increase in the scattered radiation) for a given magnification factor. It is extremely important that the unit be designed such that the central ray projects parallel to the chest wall. If the central ray from the tube (the ray that is perpendicular to the film-screen cassette) is toward the center of the image receptor as illustrated in Figure 3-2b, a few mm of tissue close to the chest wall will not be imaged unless the compression device is moved in or out. Geometry such as that shown in Figure 3-2a should be employed so that the plane of the compression device is orthogonal to the central ray and is capable of only up and down movement.

3.1.4 Compression Device

In film-screen mammography, the importance of effective compression cannot be overemphasized. Compression causes the breast tissue to be spread out over a larger area and reduced in thickness. This results in a significant reduction in the ratio of scattered to primary radiation[11] reaching the receptor and an improvement in contrast. Spreading the breast tissue out over a larger area also reduces the superposition of structures, thereby improving the conspicuity of pathology. Because the path length through the breast is reduced, less dose is required and exposure time can be decreased. At the same time there is less beam hardening so the radiation has a lower effective energy (better contrast). Finally, with a thinner breast, a lower kVp technique can be selected and, since the breast is more uniform in thickness, a higher contrast film can be employed. Finally, by clamping the breast in place, anatomical motion is reduced. Thus, for a multitude of reasons, firm compression is absolutely essential.

Curved and uniform compression devices are compared in Figures 3-3a and 3-3b. The curved compression device tends to push breast tissue back toward the chest wall while the uniform compression device is preferred because it tends to pull tissue away from the chest wall which results in more of the gland being imaged. Use of the flat plate results in more uniform compression and reduces the required dynamic range (latitude) of the receptor.

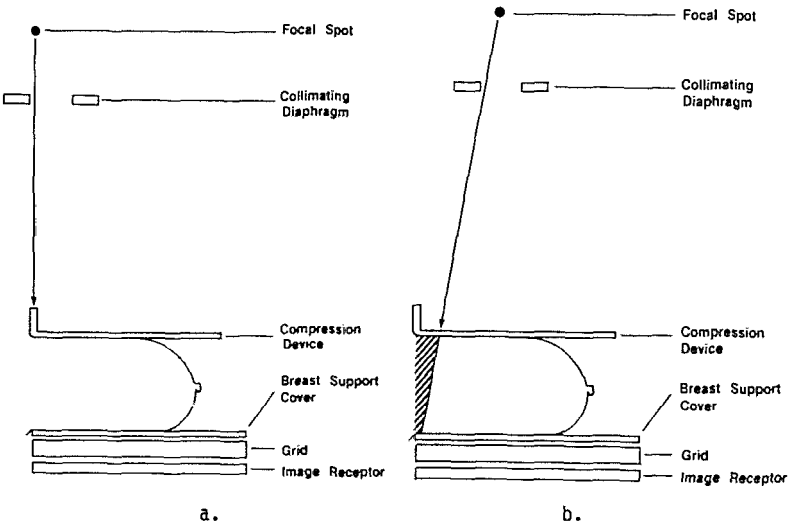


Figure 3-2 X-ray Beam Geometry for Mammography
a. Correct alignment
b. Incorrect alignment causes tissue to be excluded from mammogram.

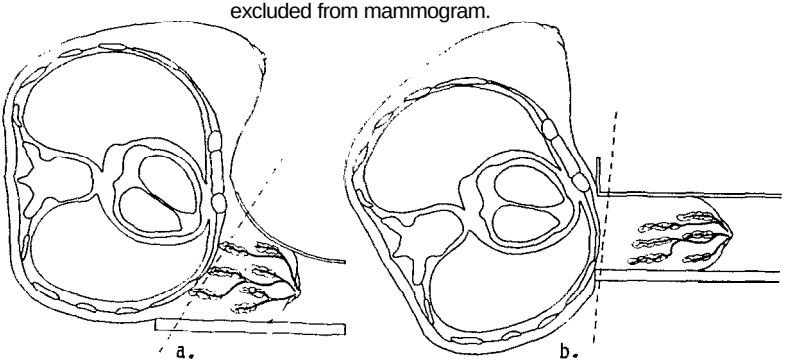


Figure 3-3 The effect of compression plate shape on positioning
a. Curved plate
b. flat plate provides more uniform compression

To minimize patient discomfort, it is desirable that compression can be released remotely from the control console after exposure.

3.1.5 Grid

In mammography of dense or large breasts, image contrast can be reduced markedly by scattered radiation from the breast being recorded by the imaging system. The scatter-to-primary ratio for a breast of average size and density can be 0.6 or greater[11]. The use of a grid significantly improves image contrast for large or dense breasts. To avoid excessive increase in patient dose, the grid should have a high transmittance of primary radiation. For this reason, carbon-fiber covers and fiber-interspace material are often used. Because of the low energies used in mammography it is important that the covers be of uniform construction so that structural artifacts are not introduced. Typically, a mammographic grid can reduce the scatter-to-primary ratio at the image receptor by a factor of 3 or more while requiring at least a two-fold increase in exposure if the kilovoltage is not raised (see Section 3.2.1). It has been suggested that a grid will significantly improve the diagnostic quality of mammograms in about 20% of cases[12]. Where women receive periodic mammography, previous examinations should be used to assess the need for a grid.

Reciprocating grids may produce grid lines in cases where the exposure only takes place over a few oscillations of the grid. It is important that the grid assembly be sufficiently rigid that grid motion is not impeded when the breast is under vigorous compression.

High strip density (approx. 80 lines/cm) aluminum interspace grids that are very thin are also available. These are designed to be placed in or directly above the film-screen cassette and are intended for stationary use. In mammograms produced with stationary grids, grid lines are evident upon close inspection and may interfere with the perception of small, subtle microcalcifications.

High strip density aluminum interspace grids with a grid ratio of 3.5:1 have slightly greater Bucky factors than reciprocating 5:1 fiber interspace grids of lower strip density. In addition, the aluminum interspace grids do not provide the same degree of contrast

improvement. Other practical problems encountered with stationary, high strip density grids are: 1) several grids are needed for efficient patient throughput if they are placed in the film-screen cassettes, 2) they can be easily damaged if they are not mechanically secured to the front of the cassette, and 3) non-uniform grid lines can result in local variations in image density.

3.1.6 Automatic Exposure Control (AEC)

In mammography, the automatic exposure-control (AEC) detector is normally located behind the image receptor. The AEC should be capable of maintaining optical density within ± 0.15 OD as the peak kilovoltage is varied from 25 to 35; and as the breast thickness is varied from 2.5 to 8 cm for each technique - nongrid, grid, and magnification. A range of density selections should be available with each increment increasing or decreasing the film-screen exposure by ≈ 15-20%. In addition, there should be adjustments to provide proper compensation for different film-screen combinations. A desirable capability, which would reduce repeats, is for the unit to select the correct AEC mode, focal spot size and mA automatically by sensing the presence of the Bucky assembly or the magnification platform. [Manual override must also then be provided.]

Many of the current mammographic units operated in AEC mode have difficulty in yielding images of constant optical density as breast thickness and tube potential are varied. This can be due to several effects: reciprocity law failure of the film for long exposures through large breasts, beam hardening effects on the sensitivity of the sensor, variation in scattered radiation, sensor offset currents, etc.

Shown in Figure 3-4 are AEC responses for four typical mammography units[15]. To compensate for AEC deficiencies on existing equipment, one can develop an AEC density setting/breast thickness/kVp technique chart[13]. This is accomplished by first measuring the film density versus phantom thickness (typically for PMMA* or BR12**

* poly-methyl-methacrylate, e.g., Lucite, Plexiglas, Perspex
** a tissue-equivalent plastic designed to mimic the attenuation of the breast[14]

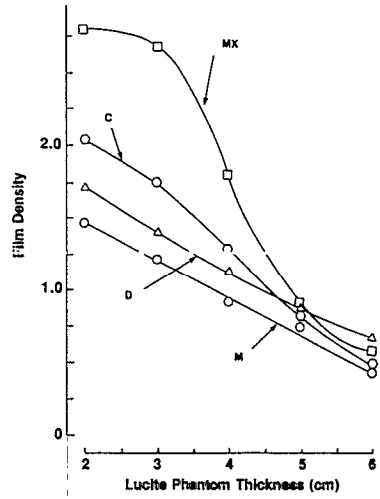


Figure 3-4 Breast thickness tracking with typical AEC devices on commercial mammography units (from LaFrance[15])

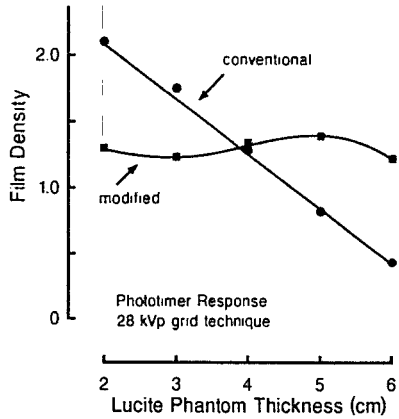


Figure 3-5 AEC thickness tracking with and without additional compensating circuitry (from LaFrance[15])

phantoms) for an AEC density setting of "0" and the x-ray tube voltage of interest. For thicknesses where the density is incorrect, the +/- AEC density setting should be adjusted to bring the film density within the desired range and this setting recorded. An AEC technique

chart can thus be developed by repeating this process in a systematic manner provided that a sufficient range of AEC density settings is available.

Compensation circuits have been developed[15] to maintain approximately constant density over the normal range of breast thicknesses and kilovoltage settings and for the different techniques - nongrid, grid, and magnification. Figure 3-5 compares the density tracking of a modern mammography unit at 28 kVp before and after the installation of such a device. The modification makes the short AEC exposures shorter, leaves the exposure times for average (4-5 cm thick) breasts unchanged, and lengthens the long exposure times.

Recently some manufacturers have introduced improvements in their AEC units intended to yield more consistent film densities across varying kVp and breast thickness and densities. These include short pre-exposure "test shots", multi-element sensors, and automatic sensing of compressed breast thickness by means of an encoder on the compression plate.

3.1.7 Choice of Film-Screen Combination

In the selection of screens, film, cassettes, film processors and chemicals for use in mammography, it is important to consider i) film gradient, ii) system speed, iii) film-screen blurring and iv) noise. Once the receptor combination is selected, proper processing is essential. Processing will be discussed in Section 3.3.

3.1.7.1 Film Gradient

Film gradient is defined as the slope of the curve of optical density versus log(exposure). Gradient determines how changes in the optical density (OD) in the mammogram will result from the variations in x-ray intensity across the breast. Film gradient is affected by 1) film type, 2) processing conditions (solutions, temperature, time, agitation, replenishment rate), 3) fog level (storage, safelight, light leaks) and 4) the optical density of the exposed film. The characteristic curves of six systems are shown in Figure 3-7a. The trend is to use mammographic films with high film gradient, i.e. with

the maximum slope of the characteristic curve being between 2.8 and 3.5. Maximum gradient occurs at different OD for different film types (Figure 3-7b), which may affect the optimum exposure for that film.

It is important to note that overall radiographic contrast is influenced by both subject contrast and film gradient. Therefore, a mammogram of acceptable contrast is best obtained by 1) use of appropriate beam quality, 2) firm compression, 3) use of a grid when necessary, and 4) properly processed high-contrast film.

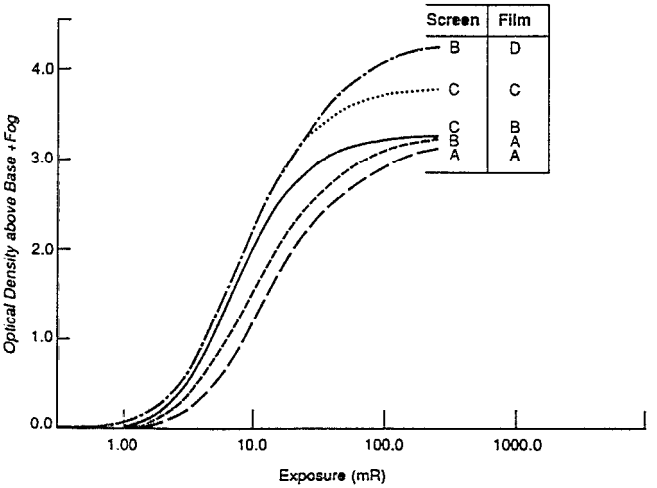


Figure 3-7a Typical characteristic curves of combinations of screens and films available for mammography (from Yaffe[16])

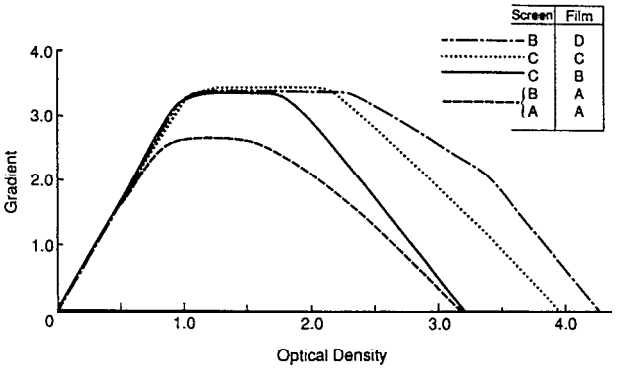


Figure 3-7b Gradient vs. Optical Density for the characteristic curves in figure 3-7a.

Note that the characteristic curves of some mammographic films still have a significant gradient above optical density 3.0. Useful image contrast (e.g. near the skin line of the breast) can be obtained if the dark parts of the image are viewed with a bright light, or on properly masked high intensity lightboxes with low ambient room light levels.

3.1.7.2 Film Speed

As indicated in Figure 3-7a, the speed of the image-receptor system and, therefore, radiation dose depends on the type of intensifying screen(s), and type of film. Both speed and gradient depend critically on film processing (see Section 3.3).

Another factor relating to film speed is reciprocity law failure. This phenomenon becomes important when long exposure times are required e.g., when grids or small focal spots for conventional or magnification techniques (low mA settings) are used. The definition given for exposure, (E = I x T) implies that the response of the film to radiation of a given quality will be unchanged if the product of intensity (I) and exposure time (T) remains the same i.e., there is reciprocity between I and T.

This relation holds well for direct x-ray exposures: however, for exposure of film to light, it fails when long exposure times (greater than 1 second) are used. When reciprocity law failure occurs, additional exposure may be required to provide the proper optical density on the mammogram. An example of technique adjustment due to reciprocity law failure is shown in Table 3-6. A properly designed automatic exposure control system should provide compensation for film reciprocity failure, (however, in underpowered mammography units this compensation may cause the unit to reach "backup time" on an exposure). Since increased exposures due to reciprocity law failure increase dose and also contribute to motion unsharpness, faster film/screen/processing combinations are recommended for underpowered units. Not all films have the same reciprocity-law failure characteristics, so that tests on large, dense breasts (or phantoms) should be made before a receptor combination is selected.

Table 3-6 Example of exposure time increase adjustment due to the use of a grid and film reciprocity law failure effect (from Haus[17])

Original technique (non-grid):	1.0 seconds
Exposure time increase due to grid	200 %
Exposure increase due to film reciprocity law failure in extending time from 1s-2s	15 %
New technique (grid)	2.3 seconds

3.1.7.3 Film-Screen Blurring

For film-screen mammography, light diffusion (spreading of the light emitted by the screen before it reaches the film) causes blurring. Factors influencing blurring include 1) screen phosphor thickness, 2) screen phosphor particle size, 3) light-absorbing dyes and pigments in the screen, and 4) film-screen contact. Film-screen combinations for mammography have traditionally utilized a single, high-definition screen in contact with a single emulsion film (Figure 3-8). The single screen is used as a back screen for

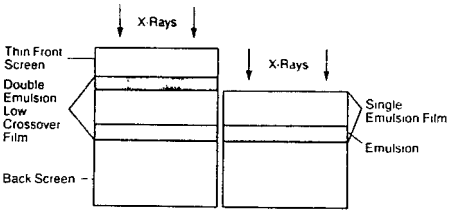
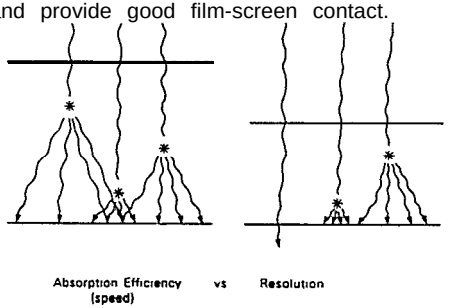


Figure 3-8 One- and two-screen image receptor configurations. The double-screen, double-emulsion film combination produces images with only slightly greater blur than the one-screen, single-emulsion film combination. This is due to the asymmetrical screen design (a significantly thinner front screen) and use of a reduced-crossover film in the combination illustrated on the left (from Haus[17]).

mammography so that the majority of x-ray absorption takes place at as short a distance as possible from the film emulsion. If the screen were used as a front screen, x-ray absorption would be highest in the plane of the screen which is furthest from the screen-emulsion contact surface. This causes greater light spread (blur) due to a greater diffusion distance. Factors in screen design which influence resolution and speed are illustrated in Figure 3-9a and b.

Mammographic film-screen combinations have very high resolution compared with combinations used for conventional radiography (Figure 3-10). Both parallax and crossover, which limit resolution in conventional systems, are eliminated in a single, back screen configuration. Single emulsion films, however, have the disadvantage that emulsion coating defects are more apparent than on those with double emulsion.

Cassettes designed for mammography should have front panels which provide both low x-ray absorption and intimate film-screen contact to minimize blur. Heat-sealed vacuum bags allow a slight reduction in dose and provide good film-screen contact.



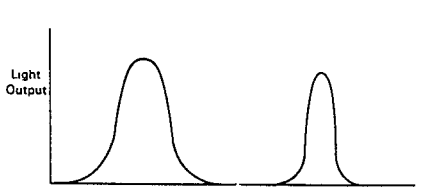
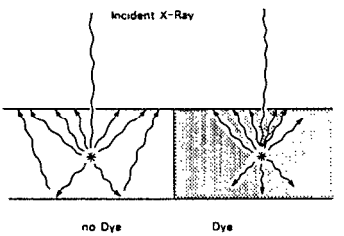
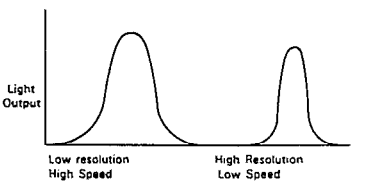


Figure 3-9a Effect of screen thickness on speed and resolution of film-screen systems. A front screen is shown, but the same effect occurs for rear screens. (see Fig. 3-11a)





3-9b Effect of dyes and reflective backings on speed and resolution in screens (from Yaffe[16])

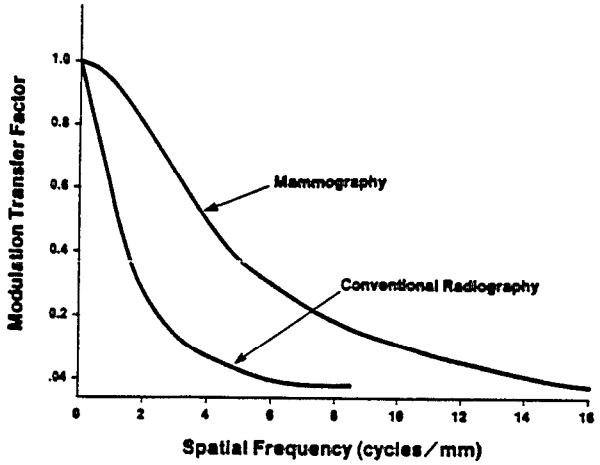


Figure 3-10 Modulation transfer function (MTF) curves of typical film-screen combinations used for mammography and conventional (general) radiography. Note the significantly higher resolution or the mammographic combination. (from Haus[17])

3.1.7.4 Noise

Radiographic noise or mottle is the unwanted random optical density variation in a radiograph that has been given a uniform x-ray exposure. It consists of three components: 1) film granularity, 2) quantum mottle, and 3) screen structure mottle. Screen mottle is usually of negligible magnitude. Film granularity is caused by the random distribution of the finite number of developed silver halide grains.

Quantum mottle is caused by the random spatial variation of the x-ray quanta absorbed in the image receptor. In general radiography, quantum mottle is usually the principal contributor to the optical density fluctuation seen in a uniformly-exposed radiograph. Factors affecting the perception of quantum mottle include: 1) film speed and contrast, 2) screen absorption and conversion efficiency, 3) light diffusion, and 4) radiation quality. When speed is increased due to higher x-ray absorption for a given film OD, quantum mottle is not increased. When speed is increased due to increased light output of

the screen per absorbed x-ray or increased film speed (faster film or increased developer temperature or time), fewer x-rays are used to form the image and, therefore, quantum mottle is increased.

In mammography, quantum mottle may not be the limiting factor governing noise because of the high quantum efficiency (approximately 70 percent) of the screen, low average energy of the photons and the relatively low light emission in the screen. in many cases film granularity is the primary noise source[18] and this is always the case at spatial frequencies higher than a few cycles per mm. This suggests that image quality might be improved by the use of finer grained film.

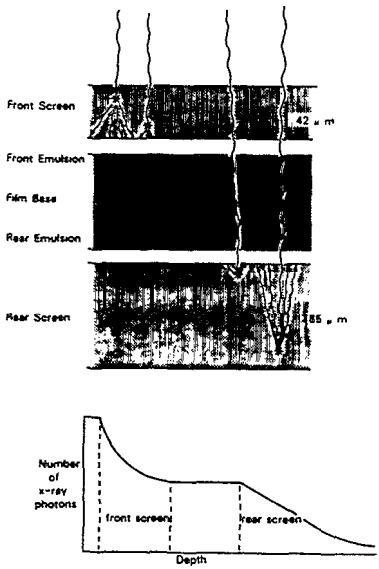
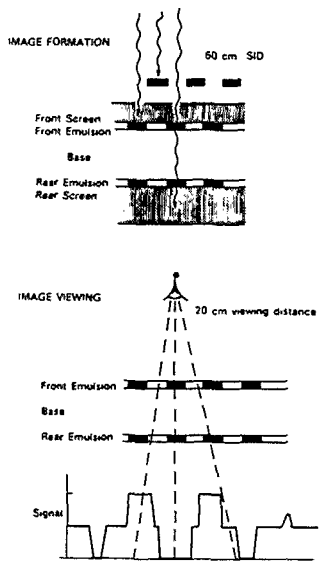


Figure 3-11a Double screen-double emulsion system showing different thickness screens and the proportion of x-ray quanta contributing to each "side' of the image



3-11b Magnified illustration of the effect of parallax with double emulsion systems (not to scale) (from Yaffe[16])

3.1.7.5 Higher Speed Film-Screen Combinations

Higher speed mammographic film-screen combinations resulting in reduced radiation dose can be obtained by employing a higher speed screen, higher speed film or with special double-screen,

double-emulsion low-crossover film systems (see Figures 3-8, 3-9, 3-11, Kimme-Smith[19], and Oestmann[20]). Assuming all other factors are optimized, systems are generally less sharp and present more noise (see previous section) than images produced using a conventional single-screen, single-emulsion combination.

In double-coated radiographic film, light photons may pass through one emulsion layer and through the film support to be absorbed by silver halide crystals in the other emulsion layer. The light which passes through the film to expose the opposite emulsion is called "crossover" or "printthrough". The resultant image blurring has historically prevented the use of such film-screen systems for mammography. Special anti-crossover mechanisms have been incorporated to minimize this effect in recently-introduced products. Viewing parallax (see Fig 3-11b) is the ultimate limit in the use of double emulsion films, since the image Is formed with a front-to-back divergent beam determined by the SID while the film will be viewed at close range for examination of fine details.

In some situations, the x-ray unit may be the major cause of image blur resulting from motion blur due to long exposure times or geometric blur due to focal spot size and magnification. For these situations, the higher-speed film-screen combination may produce mammograms with less overall image blur because shorter exposure times and/or a smaller focal spot size can be selected than possible when employing lower-speed, higher-resolution combinations.

3.2 Technique Selection

3.2.1 kVp

X-ray tubes designed for film-screen mammography usually have a molybdenum (Mo) target, a thin beryllium window, instead of the more absorbing pyrex glass used on normal tubes, and a molybdenum filter of about 0.03 mm thickness. Such tubes are operated in the 22 to 35 kVp range* and commonly have a rotating anode in order to achieve currents of 100-200 mA.

* The range 22-25 kVp is normally reserved for biopsy specimen radiography.

Some units designed for film-screen mammography may contain a beryllium window, tungsten (W) target tube with a total filtration equivalent to ≈ 0.5 mm aluminum (Al) or an added filtration of 0.03 mm molybdenum (Mo).* In order to provide high quality film-screen images, these tungsten target tubes must be operated at a voltage setting of 3 to 5 kVp lower than those used with molybdenum target tubes. The lower kVp requires increased exposure times and tube loading.

The choice of kilovoltage should be based on the expected breast characteristics of the patient and a technique chart should be constructed for each mammography unit. If the average breast is imaged at 25-28 kVp, an increase by 1-4 kVp flay be used for denser breasts and a reduction by 1-3 kVp for thin or flaccid breasts. Since "constant potential" waveforms give a higher effective energy spectrum, a drop in peak potential by 1-2 kVp may be necessary to obtain the same contrast as with single-phase systems or those with significant voltage ripple. Measuring and matching HVL is the best way to obtain equivalent contrast.

When grids are used in mammography, it is common practice to increase the kilovoltage by 2-3 kVp in order to offset part of the exposure increase necessitated by insertion of the grid[5].

3.2.2 Exposure Time

The maximum tube current used in dedicated mammography systems is normally limited by the instantaneous loadability of the focal spot to 100-200 mA for the larger spot (0.3 to 0.6 mm) on rotating anode tubes, and 15-50 mA on the smaller spot (0.1 to 0.2 mm) used for magnification studies. Exposures should be as short as possible to minimize unsharpness due to patient motion, and, therefore, maximum tube current should be selected whenever possible. When imaging large, dense breasts with the small focal spot, exposure times in excess of 3s may be unavoidable. The combination of generator and AEC should be capable of reliably controlling exposures as short as 30 ms.

* Note that the total filtration must be such that the minimum half value layer (HVL) requirement of 0.3 mm Al at 30 kVp[29,33] is met.

3.3 Film Processing

Following the manufacturer's recommendations for film processing in terms of development time, developer temperature, developer and fixer replenishment rates, and processor maintenance is of critical importance in order to achieve and maintain appropriate film speed, contrast, granularity and fog levels. Figure 3-12 illustrates the effect that changes of developer temperature has on these characteristics. Similar results could be expected if these variables were plotted versus development time. Note that when the developer temperature is lower than the manufacturer's recommendation, film speed is reduced. This loss in speed may dictate an unnecessary

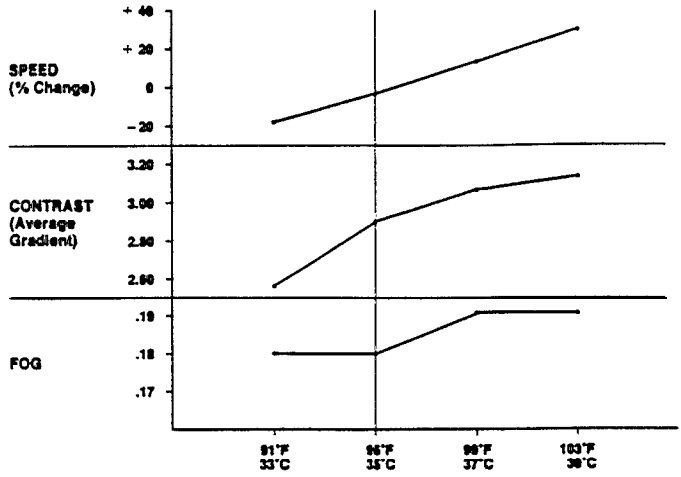


Figure 3-12 Percent change of film speed, and dependence of average gradient and fog with developer temperature. The vertical line indicates manufacturer's recommendations. (from Haus[17])

increase in radiation dose to the breast in order to produce mammograms of proper optical density. Generally, film contrast is also reduced when developer temperature is lowered.

3.3.1 Extended Process Cycle

As is apparent in Figure 3-12, increasing developer temperature can achieve higher film speed and contrast. Similar results can be achieved by increasing developer immersion times. This is commonly referred to as "push processing" or extended process cycle (EPC)[21,22]. EPC can be successfully used with most single emulsion coated films which contain conventional 3-dimensional silver halide grains because: 1) The relatively high amount of silver halide contained in some single emulsion film may not be fully developed in the normal process cycle. With EPC, silver halide grains that were previously exposed but not developed are activated, resulting in higher speed and contrast; and 2) previously unexposed grains in proximity to exposed silver halide grains are added to the previously developed grains.

It is also important to note that push processing does not provide comparable film speed and film contrast increases for all film emulsions (single or double emulsion). Tabular and mono-dispersed grain emulsions are designed to be processed using specified chemical solutions and are relatively insensitive to changes in development time and/or temperature.

Increased film contrast may enhance perception of details in the mammogram. The increased film speed will result in higher quantum noise in the image because fewer quanta are required to obtain a given optical density. Higher film contrast will make the noise (as well as the signal) more visible. Film fog may increase with increased developer temperature and/or time. Developer stability may also be affected when developer temperatures higher than recommended are used and, therefore, attention to quality control is especially important.

If EPC is used, the film processor should be dedicated to processing only the mammographic film selected for that process. The EPC can be achieved on many commercially-available film processors by modifying the film transport mechanism and/or adjusting developer bath temperature. It is also important that the replenishment rate be adjusted properly for EPC if the transport speed is reduced.

Replenishment rate adjustment to the requirements of the mammographic film is important for both standard and EPC because in a general x-ray environment, processors are set up to replenish developer and fixer chemicals at a specified volume per 14-inches (35 cm) of double emulsion film travel at a given film throughput per day. Replenishment rate adjustment must be performed by changing the setting on the replenishment pumps. Each film processor (regardless of manufacturer) must have these rates set and periodically verified to maintain processing control.

3.3.2 Storage of Film Processing Chemicals

Chemicals may be obtained in either pre-mixed or "user-to-mix" format. It is important, especially in the case of pre-mixed chemicals that large reserve stocks are not kept on hand but rather supplies are obtained on a frequent and regular basis in order to minimize chemical deterioration associated with aging.

Chemicals should be stored in an environment consistent with the manufacturer's specifications. Since chemical fumes can cause deterioration of radiographic film, chemicals must be kept in a location separate from where film reserves are stored.

Pre-mixed solutions are occasionally of variable quality and consequently it is important that the processor be checked with a sensitometric strip after solutions have been changed and the daily sensitometry should be closely monitored whenever a new batch of replenisher is introduced.

3.3.3 Preparation of Replenishment Chemical Solutions

In order to prevent chemical deterioration as a result of oxidation, contamination or precipitation during shelf storage in small facilities (or in satellite processors in large facilities where there is infrequent processing due to specialized workload), only adequate volumes of replenishment solutions to meet normal weekly requirements should be prepared at any one time.

Preparation of replenisher should be done in accordance with the manufacturer's specifications and sensitometric strips should be closely monitored after the new batch of replenisher is introduced.

In large facilities, a regular replenishment schedule should be established and maintained.

For dedicated processors which have a low workload (less than 30 films per day), "flood replenishment"[23] may be required in order to maintain the stability of the processing characteristics. Rather than replenishing using a fixed volume of solution per sheet of film processed, one provides a specific volume of solution per unit of time. The solution used in this case is standard replenisher mixed with starter.

3.3.4 Storage of Unprocessed X-ray Films

X-ray film must be handled and stored with great care if it is to remain in good condition. Even under the best conditions, film will gradually deteriorate. Generally, higher speed film has a shorter shelf life than slower film.

When ordering film stock, intake should be adjusted to the rate of use and only stock sufficient to meet demands without a large reserve supply should be kept.

When new film reaches a facility, boxes should be date-stamped so that older stocks may be identified and used first, always ensuring that the film is used before the expiry date. Film boxes should be stored vertically on shelves in an environment where the temperature is preferably in the region of 10°C (50°F) and does not rise above 20°C (68°F), with relative humidity in the region of 50%. Since dampness and high temperatures have the most damaging effects on photographic materials, rooms with damp floors and walls or subject to sudden temperature changes and condensation are to be avoided. Horizontal storage may lead to emulsion "pickoff", small clear spots on the film which may mimic microcalcifications. Film should be stored away from any possibility of exposure by ionizing radiation, and isolated from processing chemical fumes.

3.4 Viewing Conditions

The subtle contrasts which are recorded in the mammographic image may not be perceived if the film is viewed under less than optimum conditions. This requires that the amount of extraneous light reaching the eye be minimized. The viewing room should be dimly lit or illuminated only by light passing through the film. Viewboxes that are not being used should be turned off and wherever possible, portions of the viewbox that are not covered by the mammogram should be masked. It is desirable that the film on the outside of the image of the breast be exposed to x-rays so that this part of the film is blackened and intense transmitted light does not dazzle the eye. Since radiation falling outside the breast will primarily be absorbed by the mammographic screen which is of high atomic number, the amount of extra scattered radiation to the breast or to the main image will be minimal.

A variable-intensity "bright light" operated by a foot control should be available for scrutinizing regions of the image that are of high optical density, for example, the skin line and nipple. To make use of the maximum dynamic range of the film, exposures should be such that the area immediately outside the skin line approaches the saturation optical density of the film.

A high quality magnifying lens is necessary for investigation of fine detail, especially microcalcifications. A variety of specialized masking and viewing aids for mammography are commercially available, including a hood which both eliminates extraneous light and magnifies the image.

3.5 Quality Control

A structured quality control program must be employed to monitor the performance of mammography equipment and to provide a record in case of machine failure. The procedures must be performed regularly and require careful, consistent record keeping and regular comparison with baseline measurements obtained during acceptance testing. When problems are noted, appropriate remedial action must be taken with subsequent testing to verify correction of the problem.

In this section the elements of a quality control program are listed. Detailed methods for carrying out these tests are given in Section 6.

3.5.1 Processing: Sensitometric strips should be run at the same time every operational day to monitor speed, gradient and base-plus-fog. Films should be analyzed on a densitometer and results recorded daily. Processor chemicals should be changed and the processor thoroughly cleaned at the manufacturer's recommended intervals. Sensitometric strips should then be run and uniformly exposed films should be processed to detect roller wear.

3.5.2 Film Density: Uniformity and consistency of image density and the actual working OD should be checked and recorded weekly by imaging a uniform 4.2 cm PMMA phantom. This exposure should be made for the techniques commonly employed with the equipment - non grid, grid and magnification, using AEC or manual technique, whichever is used for patients. If the density changes by more than 0.15 OD from the established working density, the reason for the change should be determined and appropriate corrective action taken. The uniform phantom image should also be checked for processing and other artifacts.

3.5.3 Image Contrast: Measurements of the differences in OD, either behind two selected steps of a thin aluminum step wedge or behind a thin PMMA disc on top of the uniform phantom and a point in the center of the phantom should be performed and recorded weekly. This test can demonstrate changes in filtration, kVp, film emulsion and processor characteristics. While image contrast measurements help monitor overall changes in mammographic performance, they do not diagnose specific problems as do some of the other quality control procedures. A large change or long term drift in values of either density or contrast indicates that more specific tests of individual parameters affecting contrast - film processing, film gradient, x-ray tube kilovoltage (and waveform) and beam quality - should be carried out to localize the actual problem.

3.5.4 Entrance Skin Exposure (ESE) (free in air): The ESE associated with imaging a standard phantom should be measured at six month intervals for the techniques commonly used - non grid, grid and magnification. The ESE can be calculated from tube output measurements (Section 3.5.5), if the mAs used to obtain an image is known. Methods are described in Sections 6.4 and 6.5.

Mean glandular dose can be estimated from ESE and HVL for specified tissue compositions using Table 5-1 or References 24, 25. Note that exposure measurements without backscatter are required in order to use the tables in Section 5 for the calculation of dose.

If the ESE (and associated glandular dose) change markedly in a six month interval (i.e., >20%), the reason for the change should be determined and appropriate corrective action taken.

To check exposure consistency, an ionization chamber can be placed on a standard test object (approximately 4.2 cm of PMMA or tissue-equivalent epoxy) and an exposure made under the appropriate manual or AEC conditions and standard kVp.

3.5.5 Radiation Output: The mR/mAs for a standard kVp and distance should be measured (Section 6.4) and recorded at six month intervals. The mR/mAs measurement associated with the ESE determination is satisfactory for this purpose. Radiation output is a useful overall test of generator and tube performance and may allow prediction of impending tube failure.

3.5.6 Focal spot failure, particularly for microfocal spots, can be diagnosed with magnification images of high-contrast star patterns, or using a pinhole camera (Section 6.8). There is no recommended frequency, however a baseline star-pattern film should be taken on acceptance testing, and saved for comparison if there is a problem suspected with the focal spot size. Anode wobble or loss of bias may cause increased focal spot size.

3.5.7 Half value layer: Measurements should be done every six months in order to detect variations in beam quality due to changes in kilovoltage or filtration.

3.5.8 Screens: Uniform phantom images will enable detection of dirty or damaged screens, The frequency of screen cleaning is determined by usage and environment, but should be carried out at least weekly and each screen should be checked monthly by radiography of a uniform phantom. Visual inspection should also be carried out, using a strong light source, rather than standard darkroom illumination. An ultraviolet lamp provides an excellent way to find areas of damage, as well as embedded dirt. Scratches caused by fingernails and rings as well as creases in the screen can provide undesirable artifacts. Good contact between screens and film can be tested by imaging a flat copper screen of 30-40 mesh semi-annually. Dust artifacts are more easily discernable with single emulsion single-screen systems. Clinical images should be reviewed on a routine basis by the technologists and radiologists to identify artifacts.

Table 3-7 Quality Control Procedures For Film-Screen Mammography

Test or Procedure	Frequency	Performed by
Processing quality control (sensitometry, temperature)	Every operational day	Technologist
Uniform phantom image and contrast test	Weekly	"
Patient entrance exposure and tube output	Every six months and upon alteration or servicing of the machine	Physicist
AEC parameters including operation of back-up timer	"	"
Collimation	"	"
Half-value layer, kilovoltage	"	"
Screens: cleaning	Meekly	Technologist
unifom phantom	Monthly	
contact	Every six months	

4. XERORADIOGRAPHY

4.1 Selection of Equipment for Xeromammography

4.1.1 X-Ray Source Assembly

In xeromammography, x-ray tube voltages in the 42-52 kVp range are routinely employed. Total (inherent plus added) equivalent filtration should be 2.0-2.7 mm Al at 50 kVp for tungsten tubes and 1.6 mm Al for molybdenum tubes resulting in typical HVL's of 1.4-1.6 mm Al for W and 0.8-0.85 mm Al for Mo targets. Beams with HVLs significantly greater than 1.5 mm Al result in noticeable loss of edge contrast of microcalcifications with only modest reduction in mean glandular breast dose. Likewise, HVL's close to the regulatory minimum limit[29,33](i.e., 0.5 mm of Al for 49 kVp) result in only modest improvement in image quality at the expense of increased dose. In this range of beam quality, there is no advantage to employing a molybdenum x-ray tube target as almost all the Mo characteristic x-rays will be absorbed by the filter. Tungsten gives rise to 75% more bremsstrahlung x-ray production, can withstand higher heat loading and is preferred, although Mo tubes can produce equivalent quality images at only slightly elevated doses if filtration and kVp are carefully adjusted.

To ensure that focal spot unsharpness does not unduly degrade xeroradiographic image quality, nominal focal spot size should be sufficiently small for the SID and degree of geometric magnification employed (see Tables 3-1, 3-2, 3-3 and 4-1). In order to produce images with exposure times on the order of one second or shorter for typical breast thicknesses, the tube current for the large focal spot should be $\geq$ 200 mA. Likewise, the mA for the small focal spot should be as high as possible. With current state-of-the-art x-ray tube technology, this would be on the order of 50-75 mA for a 0.2 mm focal spot (and 50 mA for a 0.15 mm focal spot). Desirable xeromammography source assembly specifications are summarized in Table 4-I.

Table 4-1 Source Assembly Specifications

Target	Tungsten
Window	Glass or beryllium
Filtration (added + inherent)	W Target 2.0 - 2.7 mm aluminum equivalent Mo Target 1.6 mm aluminum equiv. minimum
Half Value Layer	W Target 1.0 - 1.6 mm of Al at 49 kVp Mo Target 0.8 - 1.0 mm of Al at 48 kVp
Nominal Focal Spot Size	≤ 0.6 mm contact 80 cm SID ≤ 0.5 mm contact 65 cm SID ≤ 0.35 mm 1.35 x magnification ≤ 0.20 mm 1.5 x magnification ≤ 0.15 mm 2.0 x magnification
Tube Current (for 40-50 kVp range)	
Large Focal Spot	≥ 200 mA for 2 sec.
0.15 mm Small Focal Spot	≥ 50 mA for 4 sec.
0.20 mm Small Focal Spot	≥ 75 mA for 3 sec.

4.1.2 X-Ray Generator

As in the case of film-screen mammography and for the same reasons, xeromammographic x-ray generators should be quasi-constant potential, i.e., three-phase, single-phase with capacitive smoothing, or high-frequency. As noted above, x-ray tube voltages in the 42 to 52 kVp range are generally employed and a slightly greater range is desirable. Because of the exposure latitude of xeroradiography, it is sufficient that the x-ray tube voltage be adjustable in 2 kVp increments. It is also sufficient that the exposure time be adjustable from 20 msec to 3 seconds or the mAs from 4 to 600 mAs in 25% increments. These specifications are summarized in Table 4-2.

Table 4-2 X-Ray Generator Specifications

Power Rating	10 - 15 kW
High Voltage Waveform	Three-phase, high frequency or single-phase with cap smoothing
kV Selection	40 - 55 kVp in 2 kV increments
Time/mAs Selection	0.05 - 3 s, 25% increments or 4 - 600 mAs, 25% increments
Technique Indication (essential)	Manual - selected mAs shown AEC - post exposure mAs indication

4.1.3 Geometry

The geometry requirements of xeromammography are similar to film-screen units and a large (65-80 cm) SID is desirable. The central ray should project along the chest wall to the edge of the image receptor as illustrated in Figure 3-2a.

4.1.4 Compression Device

Some facilities employ a curved compression device for (see Figure 3-3) for xeroradiography in order to image the ribs in the lateral or medial-lateral views. This allows greater coverage than with a uniform compression device, however, it may result in breast tissue being obscured by the ribs due to improper patient positioning. Wedge-shaped sponges are often used to facilitate positioning the lateral view for xeroradiography.

4.1.5 Grid

Although moving grids can improve image quality in xeromammography, the improvement isn't as marked as in film-screen mammography. Stationary grids are not appropriate for xeromammography, since the edge enhancement effect could cause grid lines to be disturbing to the viewer. Because of the large dose penalty and the small benefit, anti-scatter grids are seldom used for xeromammography.

4.1.6 Automatic Exposure Control

Because of the exposure latitude of xeroradiography, automatic exposure control is used less often and its requirements are less demanding than with film-screen systems. Because of this latitude, however, it is easy to utilize more radiation than is necessary for xeroradiography without the obvious indications of overexposure provided in film imaging. Care must be taken, therefore, in setting the operating point of the AEC. As in the case of film-screen mammography, the AEC detector is located behind the cassette and should have a sensitive area of 10-20 cm^2. Cassettes must be designed for AEC operation. The device should be capable of holding the

exposure to the xeroradiographic cassette to within ± 15% as the kVp is varied from 40 to 55 and breast thickness is varied from 2.5 to 8 cm. It is sufficient to have seven AEC density selections with each increment increasing or decreasing the exposure to the xerographic cassette by approximately 25%. In addition, there should be selections for the different techniques - contact and magnification. A post-exposure display of the exposure time or mAs used is essential to allow the operator to monitor machine function.

4.2 Technique Selection

4.2.1 kVp

Xeroradiography is performed at potential differences of 42 to 52 kVp. Tungsten targets are preferred because doses are lower and exposures are shorter, providing less motion blurring, although molybdenum target tubes can be used if appropriate filtration is used. Because the beam quality used for xeroradiography is greater than that used for film-screen imaging, tubes with either glass or beryllium windows are acceptable. Table 4-1 lists appropriate filtration ranges. Positive mode xeromammography is generally performed with 2.2 mm Al total filtration at 48 kVp. Acceptable images can be produced in the negative mode with 2.7 mm Al total filtration at 50 kVp with approximately 30% lower ESE. If a molybdenum target tube is used* it should have no less than 1.6 mm total Al filtration with 43 - 48 kvp being used for either positive or negative mode.

4.2.2 Filter

When a mammography unit with a molybdenum target tube is used for both film-screen and xeroradiography* examinations, a set of two filters is provided for the beryllium window tube and interlocked so that the 0.03 mm Mo filter is in place for settings below 40 kVp for film-screen imaging and the 1.0-1.5 mm Al filter is in place for settings above 40 kVp for xeroradiography.

*Use of a molybdenum target for xeroradiography is not recommended.

4.2.3 Beam Quality

A wide range in the half-value layer (HVL) of the x-ray beam is reported in the literature because total filtration varies so widely. For most mammographic applications, the HVL, filtration, and kVp will depend on the target material and xeroradiographic processor selected. Table 4.1 can be used to select the correct combination of kVp and filtration.

4.2.4 Exposure Time

The duration of the exposure is expected to be in the range of 0.5 - 1.0 s, depending on the equipment. Exposure times longer than 1.0 s increase the likelihood of motion unsharpness. Very short exposure times using high tube currents may result in focal spot blooming. Thus, it is advisable to use an exposure time as short as the x-ray tube and generator will allow without sacrificing spatial resolution.

4.3 Processing

Xeromammography involves three distinct steps: a) charging the selenium plate, b) formation of a latent image by x-ray exposure, and c) processing to produce a final image.

Because the selenium layer is a photosensitive surface, the plate must be charged, exposed, and developed in the dark. A light-tight cassette is used for the x-ray exposure and the plates are automatically loaded by the conditioner and unloaded by the processor without the need of a darkroom.

In the first step, the selenium plate is charged uniformly by an ion-generating device.

During the exposure, x-rays absorbed by the selenium layer discharge the plate to a degree which is proportional to the absorbed energy. This process leaves a residual charge distribution (latent image) on the selenium plate.

In the development process, a bias potential is applied between the plate and the development chamber. The polarity of the electric field is selectable. In positive mode development, the toner is attracted to the charged areas of the plate (i.e. unexposed regions); in the negative mode, the toner is attracted to the discharged areas. The electrostatic fringe fields near the surface of the plate control the deposition of the toner, resulting in an image with enhanced edges and with very wide latitude. The toner is then transferred to an opaque paper substrate which is used to view the xeromammogram. Negative mode xeromammograms require about two-thirds of the radiation exposure required by positive mode. Tests at Xerox Medical Systems on optimally adjusted processors indicate the following suggested voltages:

negative mode: back bias = 3500V, plate charge = 1600V
positive mode, back bias = 1450V, plate charge = 1600V

4.4 Viewing Conditions

Xeromammograms are viewed using reflected light whereas x-ray films require transillumination. Back illumination should be minimized when viewing xeromammograms, since it will reduce perceptibility of contrast. A magnifying lens is recommended for questionable areas, especially for confirming or ruling out the presence of very small features, such as microcalcifications.

4.5 Quality Control for Xeroradiography

In order to ensure that xeroradiographic images are produced at the minimum dose compatible with high diagnostic quality, it is necessary to monitor performance of all aspects of the imaging system at regular intervals. This is especially true in xeroradiography because of the wide exposure latitude which can allow problems to go unnoticed even though radiation doses may have increased significantly. In positive mode, a 1 mm halo around the skin is indicative of a proper exposure, while in negative mode no simple rule of thumb is available. In this section Table 4-3 outlines essential elements of a quality control program. Methods for carrying out the requisite tests are included in Section 6.

4.5.1 Exposure

For a well-filtered beam from a tungsten target (HVL around 1.5 mm Al), the optimal exposure at the receptor for selenium of thickness of 140 µm, is 2.5 x 10^{-5} C/kg (100 mR) for positive mode.

Table 4-3 Quality Control Procedures For Xeroradiography

Test or Procedure	Frequency	Performed by
Processing quality control	Every operational day	Technologist
Uniform phantom image	" " "	"
Dark dust all plates	Weekly	"
Clean all cassettes	"	"
Inspect and clean positioning sponges	Every month	"
Patient entrance exposure and tube output	Every six months and upon alteration or servicing of the machine	Physicist
Collimation	"	"
Half-value layer	"	"

5. DOSIMETRY

5.1 Estimation of Dose

Several major variables affect the dose to the breast in a mammographic examination including: the choice of imaging system, film processing, beam quality (HVL), breast compression, breast composition, use of a grid, and working optical density. These factors are discussed in NCRP 85[2]. The mean glandular dose is the preferred measure of the potential risk from mammography and can be estimated with reasonable accuracy. Mean glandular dose can be estimated using data from Table 5-I for a given target material when the breast thickness, HVL, and entrance exposure (free-in-air) are known. For women 40 years and older, the average breast composition can be reasonably represented by a composition of 50% adipose and 50% glandular tissue (50/50). For other compositions see the Handbook of Glandular Tissue Doses in Mammography[24].

It should be noted that the values in these tables have been calculated for "mathematical phantoms" and will not strictly reflect actual tissue distributions. For this reason, increased precision in determination of HVL, breast composition and compression thickness will not necessarily increase the accuracy of dose estimations.

Table 5-1[24,25]

Firm Compression - Uniform Breast Thickness
Craniocaudal View
50 percent (by weight) Fibroglandular Tissue Content
Mean Glandular Tissue Dose $\bar{D}_{gn}$ in mGy for 1 R
Entrance Exposure (free-in-air)

Breast Thickness (cm)	Molybdenum Target HVL (mm Al)		Tungsten Target HVL (mm Al)							
	0.3	0.4	0.3	0.4	0.6	0.8	1.0	1.2	1.4	1.6
3.0	2.20		2.20			4.70	5.35	5.95	6.45	7.10
4.0	1.75	2.20	1.85	2.35	3.25	3.95	4.55	5.15	5.70	6.30
5.0	1.40	1.75	1.50	1.90	2.75	3.35	3.95	4.50	5.10	5.65
6.0	1.15	1.45	1.25	1.60	2.35	2.95	3.50	4.00	4.60	5.15
7.0	0.95		1.00		2.05	2.60	3.10	3.60	4.15	4.70
8.0					1.80	2.30	2.75	3.25	3.75	4.25

1 mGy = 0.1 rad

The procedure for determining the mean glandular dose ($\overline{D}_g$) to either a breast of known composition or to a dosimetry phantom is as follows:

a. Note the target material of the x-ray tube and the compressed breast thickness

b. Measure the HVL at the kVp of interest with the compression plate in the beam (see Section 6.3.2).

c. Determine the entrance skin exposure, ESE, (free-in-air) in R, using methods described in Sections 6.4 and 6.5.1.

d. Determine the mean glandular dose (mGy) for 1 R entrance exposure (free-in-air) $\overline{D}_{gN}$ from Table 5-I or see Reference 24.

e. $\overline{D}_g = \overline{D}_{gN} \times ESE$

Table 5-2 gives data on ESE and mean glandular doses obtained by the Nationwide Evaluation of X-ray Trends (NEXT)[26] survey conducted in 1985 by the Conference of Radiation Control Program Directors and the Center for Devices and Radiological Health. Note that the values are for a phantom composed of PMMA and wax to yield an equivalent thickness of 4.3 cm PMMA which approximates a 4.7 cm thick compressed breast of 50/50 composition. This is considered to be representative of a breast of average attenuation. This information was collected before the introduction of a generation of more sensitive film-screen systems (ca. 1986).

Table 5-3 gives more recent unpublished NEXT[27] data from surveys in 1988 where a phantom composed of PMMA and wax to yield an equivalent thickness of 3.84 cm PMMA was used. Since the ACR (see Section 6.10.2) accreditation phantom has approximately this equivalent thickness, these data can be compared to measurements made with the ACR phantom. The 3.84 cm phantom is typical of a 4.2 cm thick compressed 50/50 breast, which is thinner than the average breast. The ACR phantom may be useful for intercomparison purposes, however, more realistic determination of average exposure and glandular dose can be obtained by use of a 4.2 cm PMMA-equivalent phantom. For users of the ACR phantom, this can be easily achieved by adding a slab of PMMA 0.36 cm (5/32") thick under the phantom for

dosimetry purposes. It is recommended that measurements are taken with both thicknesses in order to enable intercomparison of different facilities.

Table 5-2

Mean Glandular Dose Per Image (NEXT data[26])
4.3 cm PMMA-equivalent Phantom

	N*	Mean Dose (mGy)	Mean ESE (R)
Film-Screen Systems			
Grid	195	1.55	0.881
No Grid	52	0.78	0.437
All Systems	247	1.39	0.789
Xerox			
Positive Mode	95	4.14	0.898
Negative Mode	25	3.68	0.743
All Systems	120	4.05	0.865

Table 5-3

Mean Glandular Dose Per Image (NEXT data[27])
3.84 cm PMMA-equivalent Phantom

	N*	Mean Dose (mGy)	Mean ESE (R)
Film-Screen Systems			
Grid	157	1.40	0.725
No Grid	27	0.79	0.407
All Systems	184	1.31	0.679
Xerox			
Positive Mode	30	4.09	0.892
Negative Mode	9	3.81	0.678
All Systems	39	4.02	0.850

5.2 Maximum ESE and Dose

With modern mammographic technology, the examination can be carried out at doses much lower than required only a few years ago. It is recommended that for a 4.2 cm thick PMMA phantom the mean "glandular" dose for film-screen imaging with a grid be no greater than 1.8 mGy (ESE $\approx$ 1.0 R). For imaging without grid, the limits should be half of the above. If higher levels are encountered, the reasons should be investigated. See Section 6.5.2.

* number of facilities tested

6. TESTING OF MAMMOGRAPHY UNITS FOR ACCEPTANCE AND QUALITY CONTROL

In this chapter, methods for evaluating performance of mammographic systems are described. These tests should form the basis of an acceptance testing protocol for newly-installed equipment. Acceptance testing is necessary to verify that the equipment not only meets legal requirements, but also performs according to the specifications agreed upon by the purchaser and the supplier. It should be done before the equipment is used on patients and before final payment is authorized.

During acceptance testing, baseline measurements are obtained for use in the regular quality-control programs. Quality control (QC) testing should provide a practical method for monitoring changes in equipment performance. Since QC tests must be done on a routine basis, they should be straightforward to perform and not require difficult-to-obtain test equipment. Once a problem has been identified by the QC tests, it may be necessary to isolate its cause using more sophisticated tests and equipment. Where acceptance tests differ from quality control methods, this is indicated in the text.

The standards of construction and performance of mammography equipment discussed in this chapter may be useful in developing a specification document for the purchase of mammographic systems.

6.1 Mechanical System

Dedicated mammographic x-ray systems normally employ a "C-arm" geometry and must always incorporate a compression mechanism for patient positioning. Smooth operation of all moving parts and assemblies must be verified and electro-mechanical locks, interlocks, and other safety functions must be tested thoroughly.

6.1.1 General Installation

As dedicated mammography systems are often of free-standing design, one should verify that the entire system is installed properly

in the examination room and is stable. The control unit should be level and there should be convenient access for service and maintenance. There should be no obstruction which hinders the range of mechanical motions provided by the system.

It should be ensured that the mechanical stops and magnetic locks are properly set and adjusted to prevent accidental motion or collision against other mechanical parts or the patient. All mechanical motions provided with the system must be installed with proper cushions or bumpers at the extreme limits of the available motion ranges.

The up-and-down translation motion and the rotation of the C-arm must be smooth and easily locked (electromagnetically or mechanically) in the desired position. The image receptor compartment must secure the image receptor in its proper position, yet allow the radiographer to insert and withdraw it with ease. All surfaces in contact with the patient during positioning and exposure must be free of sharp edges and rough surfaces, and also be electrically safe.

6.1.2 Compression Device

The compression plate should be parallel to the image receptor support and aligned as in Figure 3-2a. The plate should be located such that a line projected from the focal spot, orthogonal to the image receptor, intersects both the bend in the compression plate and the edge of the receptor proximal to the chest wall of the patient.

Alignment of the compression plate can be tested by adjusting the compression plate to its normal position (» 5 cm above the breast support), placing a high contrast linear object (e.g. a paper clip or wire) on the plate against *the* bend *and producing a radiograph.*

If possible, the image receptor should be placed on the table in such a way that it extends over the edge (toward the patient) by a few centimeters. The normal position of the edge of the receptor and the edge of the light localizer field can be identified by placing other objects on the receptor. To avoid overexposure of the film during the

test, it may be necessary to place an attenuating phantom in *the beam (conveniently taped over the tube port after the localizer position has been marked).*

The processed image will then identify the projection of the bend in the compressor with respect to the normal position of the *edge of the image receptor. It will also demonstrate whether the radiation beam is congruent with the light localizer field and allow determination of the extent of the radiation field beyond the receptor (see Section 6.7).*

The compression device should be rigid and of a material that is crack-resistant to prevent pinching or cutting of the skin. A spare compression plate should be readily available to minimize down-time when a plate does break.

The pressure exerted by the compression device must be carefully evaluated. The compression device must be easily adjustable and it must also be stable when locked into its desired position so that the compression plate does not wobble. If compression is achieved by hydraulically or pneumatically-powered devices, their safety-limit controls must be checked carefully to avoid accidental overcompression. A recommended maximum compressor pressure is between 160 to 250 newtons (35-55 pounds) in both automatic and manual modes. This can be tested using a bathroom or spring scale.

It is also important to ensure that vigorous compression of the breast does not deflect the breast support sufficiently to interfere with proper motion of the grid during exposure. This problem would cause grid lines to appear on a radiograph of a uniform phantom.

6.1.3 X-Ray Shield

The x-ray protective shield which is normally attached to the control console cabinet should be mechanically stable, and preferably anchored to the floor. If the protective shield is designed to swing freely, then it should be provided with friction-stop hinges that permit it to be positioned to a location and remain there unless repositioned with some effort on the part of the radiographer. An

interlock to prevent exposure when the shield is not in proper position is recommended (and required in some jurisdictions). The attenuation factor or lead equivalence of the shield should be clearly identified. The operator should not be able to make an exposure from outside the shielded area.

6.2 Generator

Performance specifications and acceptance testing of generators have also been addressed in AAPM Report No. 14[28].

For the stated power rating, the generator should be operable at that power rating under any combination of tube potential and current for an exposure time of at least 1.0 second.

6.2.1 kV, mA, mAs - Invasive Testing

The performance of the generator should be evaluated with a high voltage divider (HVD), preferably capable of monitoring the tube potential, tube current and exposure time with a storage oscilloscope to observe the waveforms. For use with high frequency generators, the divider must have adequate bandwidth and frequency compensation.

This evaluation should be conducted with the assistance of the service engineer, since such verification is invasive and is circuit dependent. Note that most mammography systems have either a grounded anode or cathode unlike conventional x-ray systems which are center-tap grounded. When monitoring of the mA cannot be performed directly using an HVD, the mA can be determined by measuring the voltage drop across a precision resistor connected in series with the transformer ground.

In carrying out invasive testing, it is critical that the test equipment itself (i.e. HVD and oscilloscope) be accurately calibrated.

Generators utilized for dedicated mammography systems are, relatively speaking, of low power design, and often require exposures greater than 1.0 second. It is, therefore, important that performance is tested over the full range of time settings that might be used.

6.2.1.1 Kilovoltage and mA

The accuracy of tube potential is important. Two values should be assessed: the "average peak kV" during the exposure and the range of peak voltages over the exposure time (see Figure 6-l). The peak kV should be approximately constant during the entire duration of the exposure without spikes or sagging. The peak tube potential should, therefore. be sampled at 0.05 s, 0.50 s, 1.0 s, and 2.0 s to ensure that its average is within ±0.5 kV from the set kVp-value. It should be ensured that on polyphase equipment x-ray output is matched for all phases.

A one-point reading of tube potential using a peak-reading device is acceptable provided that it is accompanied by an oscilloscope display to ensure that the potential does not drift throughout any part of the entire exposure duration and that kV ripple is within the manufacturer's specification.

The tube current during the exposure should be sampled in the same manner as the tube potential with an allowable accuracy of ±10%.

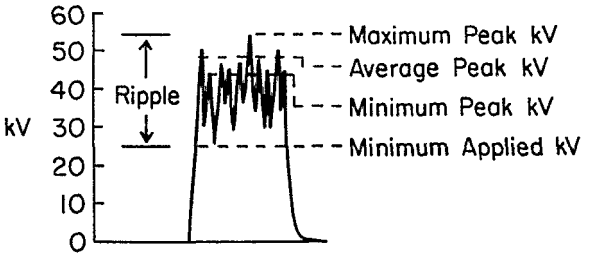


Figure 6-l Measurement of "Average Peak kV". Three-phase, 6 pulse generator.

6.2.1.2 Exposure Time

The accuracy of the exposure time can be measured from the tube potential waveform, taking the time duration from 75% of the peak voltage at the beginning and at the end of the waveform. The exposure time should be within ±10% of the timer setting for exposures greater than 100 ms and within ±10 ms for shorter exposure times.

The main concern is not so much the absolute accuracy of mA or exposure time, but the reproducibility and predictability of exposures. This requires that exposure output from the unit be linear with set values of mA and exposure time so that reliable results are possible with manual techniques. A graph of mR/mAs versus mA, mAs, or exposure time at any fixed kVp in the useful range of the machine should yield points which lie within ±10% of the best straight line fit for the range of mA and time or mAs values of interest. Measurement is described in Section 6.4.

It is essential that the generator be equipped with an mAs-meter that will display the mAs-value of the most recent exposure. The display should not be cleared until the next exposure is initiated. This mAs-meter will allow for monitoring of mammographic-patient exposure even if an AEC device is employed. The mAs-meter shall accurately display the selected or phototimed mAs-values within ±5% of the mAs delivered to the x-ray tube.

6.2.2 Roninvasive Acceptance Testing of Generator

Noninvasive kVp meters are available commercially for the mammographic tube potential range. Such devices are generally very precise; however, since they measure differential x-ray attenuation and not actual kilovoltage, their accuracy can be dependent on their positioning in the x-ray beam and other factors. A noninvasive kVp-meter can be cross-compared on each specific mammography unit with an invasive HVD measurement (when possible) at the time of acceptance testing. Subsequent measurements with the noninvasive meter can then be used for routine quality control to indicate variations in beam quality due to change of kVp calibration or filtration. If changes are noted, their cause should be investigated with the HVD.

Some generators provide internal HVD test points which can be used with an oscilloscope for kV calibration. The exposure time and waveform can be determined with noninvasive kVp-meters, if they provide a signal output port for oscilloscope display. It should be noted that the waveform observed with the noninvasive kVp meter is not a true kVp waveform but one which is a composite, dependent on both the tube current and the potential across the tube.

6.3 Beam Quality

Beam quality is dependent on kVp, voltage waveform and beam filtration. Variations in any of these may be detected by comparing the HVL of the x-ray beam under fixed operating conditions to previous measurements or to measurements taken on identical equipment.

6.3.1 Filters

While many dedicated mammography systems are manufactured for use with a film-screen receptor only, some systems are designed to accommodate both film-screen and xeroradiography.

As described in previous sections, it is strongly recommended that film-screen mammography be conducted with molybdenum filtration at 26-32 kVp tube potential range (≈ 0.3 mm Al HVL, see Table 3-4), and xeromammography be conducted with an aluminum filter at 45-55 kVp tube potential range (1.1-1.6 mm Al HVL, see Table 4-I). Many mammography systems are equipped with both molybdenum and aluminum filters. On some water-cooled tubes, oxidation of the filters may occur, causing a change in HVL and areas of non-uniformity in the field. Deterioration of the target track may also change the effective HVL.

When the molybdenum filter is in place in the filtration slot, the generator should be interlocked to function only at 39 kVp or lower: when the aluminum filter is in place, the generator should be operated only at 40 kVp and higher, to conform with the Federal requirements[29,33].

6.3.2 Half Value Layer

Using an ionization chamber calibrated for use with mammographic spectra, the half value layer should be measured as follows:

To ensure narrow beam geometry, restrict the beam to the smallest size which will still fully irradiate the ionization chamber. Place the compression device as high in the field as possible. The

compression device must be included in the HVL measurement since it is always in the beam.* This may be used as a stand for the HVL measuring filters. Place the ionization chamber centered (left-to-right) in the field but as near the chest wall side of the field [where the central beam of the focal spot falls) as possible. The chamber should be at least 6 cm from the compression device and 6 cm from the image receptor holder (or grid) to minimize backscatter.

A technique of 50 mAs (at 30 kVp for film-screen or 49 kVp for xeroradiography) or a value sufficient to give an exposure of at least 300 mR should be selected. The purpose of this technique selection is to operate the system under normal loading conditions and to obtain a dosimeter reading that is large enough to be precise. 30 kVp is used to confirm FDA[29,33] compliance, but HVL should also be measured at the normal working kVp. Record the exposure and compute half this exposure value. Next place 0.2 mm for film-screen or 1.0 mm for xeroradiography of type 1100 aluminum in the field as close to the collimator as possible (on the compression plate or taped to the end of the shortest cone available). Using the same mAs as before, repeat the exposure, and record the reading. Add 0.1 mm (0.25 mm for xeroradiography) of aluminum and repeat, continuing until the exposure is less than the half-exposure value computed initially. A semi-logarithmic plot or interpolation procedure should be used to determine the HVL. Before performing this test, reproducibility of output must be verified, as some variations in output may occur as the tube warms up. The aluminum attenuators must be checked for uniformity and interchangeability since some samples of 1100 aluminum have been found to have differences in allowed impurities which might affect low energy attenuation.

If on film-screen systems the HVL exceeds 0.4 mm, and the kVp is correctly calibrated, the service engineer should be asked to check the mirror installation and molybdenum filter to be sure that they are

* Some regulators (e.g. HHS) require that the compression plate be left out for HVL compliance tests if the unit can be operated without it. Units which comply with minimum HVL standards under these conditions may provide suboptimal beam quality when used with the plate. The plate should always be left in place for normal HVL tests and dosimetry.

correct. If the HVL cannot be lowered, the unit should be rejected in acceptance testing. For good contrast but low dose to the patient, the HVL for film-screen work should be between 0.30 and 0.37 mm aluminum. Higher values (but still below 0.4 mm) may provide adequate diagnostic images with low patient doses, but with degraded contrast.

6.4 Tube Output - mR/mAs (free in air)

This measurement (1) provides fundamental information on the performance of the x-ray generator, tube and filtration; (2) allows one to determine whether the unit can produce images with acceptably short exposure times, and (3) enables calculation of breast exposure and dose (see Section 6.5).

To perform the test, place the compression device in the normal position for imaging the average breast. Then tape the ionization chamber to the lower surface of the compression device, approximately 1.0 cm into the x-ray field from the chest wall. Using typical mA and time factors, make manual-mode exposures over the range of kVp settings used, and, for each, record the tube-output exposure and the nominal mAs. Plot mR/mAs vs. kVp on linear graph paper.*

Mammography units which are unable to produce both 8 mR/mAs and 50 mR/s behind the compression plate at the minimum kVp expected to be used for the average breast may require excessively long exposure times or high kilovoltage with loss of contrast for imaging thick or dense breasts and, therefore, may be unsatisfactory as the only unit available in a mammography center.

6.5 Entrance Skin Exposure

6.5.1 Measurement - Standard Dosimetry Phantom

Entrance skin exposure (ESE) to the breast can be measured using tube output (mR/mAs) data. For intercomparison of doses between different mammography units, or for monitoring changes in dose over

* Caution! The compression plates on some mammography units release pressure and retract automatically immediately following exposure. Care must be taken to protect the ionization chamber.

time, a standard phantom is recommended. A phantom composed of an equivalent thickness to 4.2 cm of poly-methyl-methacrylate (PMMA) over a uniform region is suggested (see Section 6.10.2). The other dimensions are not critical, but should be at least 9 x 9 cm in order to cover the AEC detector and provide adequate scatter.

In Section 6.4, measurement of tube output at the breast entrance surface (free in air) was discussed. In order to estimate actual exposure to a patient or phantom, the following steps are necessary.

(a) Determine mAs

The mAs must be determined for the imaging task for which the dose is to be calculated, e.g. a phantom, the "average breast" or a particular patient exam. The image receptor must be in place for any of these measurements. For manual techniques, the factors needed to obtain a properly-exposed image (i.e. gross OD of about 1.30) can *be* taken *from the technique chart. It should be verified that these factors are indeed appropriate. For ABC operation, a uniform breast phantom (either PMMA or BR12) should be used to obtain a film of optimum density. The mAs value is recorded from the post-exposure display. Alternatively, an independent invasive or non-invasive exposure time monitor that can operate without influencing the ABC sensor may be used. A small ionization chamber can* sometimes *be inserted* in *the primary beam without disturbing MC operation and used to determine exposure time by comparison with a manual technique of known mAs (measured in exactly the same geometry). Other devices sensitive to the scattered radiation from the phantom are also available.*

(b) Calculate Exposure

Exposure (free in air) is calculated by multiplying the mAs value determined in (a) by the mR/mAs as measured in Section 6.4. Note that some scattered radiation from the compression plate is included in the ESE as it would be in the actual mammogram. It is important to ensure that the

SID and distance from the compressor to the image receptor are consistent between the mR/mAs determination and this measurement. For breasts of thicknesses other than that measured in Section 6.4 inverse-square-law correction must be applied to tube output data.

6.5.2 Troubleshooting High Exposures

1) Processing Speed - Check developer temperature. Is it below the manufacturer's recommended temp?
   - Check immersion time in the developer.
   - Check replenishment: adequate volume per film?
   - Are enough films processed per day?
   - Have chemicals been mixed properly?
2) Check film density - for a uniform phantom image. Is the gross OD approximately 1.3 for the same technique as for average breast exposures measured?
3) Check AEC thickness tracking.
4) Check HVL. If it is below 0.30 mm at 28 kVp for film-screen mammography, or 1.0 mm at 49 kVp for xeromammography, there may be kVp, waveform or filtration problems.
5) Evaluate grid transmission and cassette front. Check for correct film emulsion placement and positioning of screens (double screen systems have thicker screens on back side).
6) Examine waveform to see if a phase is missing. This will also show up in mR/mAs differences from baseline readings.
7) Check film against a batch of known speed, since emulsion speeds may vary, especially on newly-introduced film types.
8) If exposures are long, reciprocity should be checked.

6.6 Automatic Exposure Control

Automatic exposure controls (AEC) for mammography should be able to yield images of reproducible density within ±0.15 OD over the expected range of kVp and breast thicknesses. Test images produced of uniform phantoms of varying thickness should not differ by more than

0.30 OD from each other. These tests should be carried out over the range of kVp customarily used by the mammography center. Uniform phantom material of PMMA or BR12 in slabs 2.0 cm thick to produce thicknesses of 2, 4, 6, and 8 cm should be used to test the thickness tracking. Both grid and non-grid exposures (at the appropriate kVp) should be included in this series. A calibrated densitometer will be needed to evaluate performance.

6.7 Collimation

It is extremely important to verify that the collimation mechanism provided with the mammography unit is equipped with proper radiation field definition devices such as cones, diaphragms, field blockers, etc. The radiation field must not extend beyond the image receptor except at the chest wall where it may extend by up to ±2% of the SID[30,34]. Markers placed at the chest wall should be imaged with no cutoff. The collimator alignment test can be combined with the basic geometrical test of the unit described in Section 6.1.2.

For a mammography system equipped with a collimator and a light localizer, the light field must be aligned with the radiation field within ±2% of the SID.

A simple test procedure is to expose a larger cassette with markers indicating the light field limits so that the processed film yields an optical density of 2.8 or higher. The areas beyond the light field should yield an optical density of less than 0.20 (base plus fog).

6.8 Focal Spot

The recommended method for measuring focal spot size is magnification imaging of the focal spot using a pinhole or slit camera. This is generally not practical as a field test because of the need for specialized tools, (pinhole of 30 µm diameter or slit of 10 µm width) precision alignment requirements, and motion problems".

If the focal spot size is to be measured following the NEMA[8] protocol (i.e. using a slit), measurements of focal spot size for

mammographic x-ray equipment can be made complicated because some x-ray tubes are installed at a tilted angle, i.e., such that the anode-cathode axis of the tube is not parallel to the plane of the image receptor. This is done to increase photon fluence and decrease the reported nominal focal spot size, although the effective focal spot size at the chest wall will be larger. The NEMA protocol specifies measurement on a line originating at the focal spot and orthogonal to the port of the x-ray tube.

For those x-ray systems with adjustable tube angulation, the x-ray tube should be set at zero degrees, or positioned perpendicular to the imaging plane. Since the effective focal spot will produce the clinical image, the tilt angle should not be taken into account when measuring the focal spot size for the purposes of determining resolution limit. It is recommended that the focal spot be measured at the chest wall, on the central (left-right) line of the film. For acceptance testing, a correction for the tilt angle using the NEMA correction factor[8,10] must be made.

The NEMA protocol for the measurement of mammographic focal spots calls for a tube potential of 30 kVp, with the tube current set to the maximum allowable current at the test voltage for 1.0 second, at the rotational speed for which the tube is rated, for the focal spot in question. For xeromammographic systems, the tube potential should be set at 50 kVp, and the maximum allowable tube current.

Since pinhole and slit measurements require special equipment, star patterns are routinely used for quick quality control checks on the focal spot size. Magnification imaging of star patterns will demonstrate the zero crossover point in the MTF of focal spots whose intensity distribution has sharp discontinuities. For spots whose intensity tapers off gradually, for example, gaussian spots from biased x-ray tubes, there is no definable crossover point in the MTF, but only a limiting contrast effect, and the measurement is quite subjective. The measurement may underestimate the true size by up to 50% and is, therefore, only of limited use for initial acceptance testing of biased focal spots. Results, however, are reproducible and can be compared if test images are kept throughout the life of the equipment. Microfocus spots require a 0.5° star since the blurred

area will be observed too close to the center of the 1° star for focal spots 0.25 mm and smaller.

6.8.1 Tolerance of Focal Spot Measurement

The NEMA protocol for the acceptability of the focal spot allows the size in the cathode-anode direction to be as large as twice the nominal size. Because of the high resolution requirements for imaging microcalcifications, it is recommended that the Purchase Specification require a tighter tolerance for mammography: i.e. the measured focal spot size should be no larger than 1.4 times the nominal size in either direction at the chest wall, on the center line of the film. In the event of disputes regarding measured focal spot size, one should refer to the NEMA protocol.

Probably the most practical approach is to specify in the Purchase Agreement that the manufacturer will provide a slit or pinhole radiograph of the source of the actual tube being purchased and measured under realistic operating kVp and tube-current conditions in the x-ray beam perpendicular to the film holder (at the chest wall) to verify the source size. Details of bias voltage settings required to achieve those results must also be included. These bias voltages must be verified as part of the acceptance procedure. Star-pattern magnification images should be produced at the time of acceptance testing to obtain a practical baseline performance standard on the new tube and should be retained and used for subsequent quality control measurements.

6.9 Leakage of Source Assembly and Tabletop Transmission

Because the patient's neck and eyes are close to the x-ray tube during a craniocaudal mammogram, it is necessary to ensure that leakage radiation exposure from the x-ray tube assembly is within acceptable limits.

The leakage measurement can be performed by fully blocking the exit port with at least 3 mm of lead taped to the collimator port of the tube housing. It is often more convenient to do this with the

tube rotated to *a horizontal position. To ascertain that the port is completely blocked, an exposure should be made with a pancake chamber or other sensitive detector in the field or using a 400 speed general-purpose film-screen cassette, Next, using an integrating survey meter whose probe is placed at the end of the tube (nearest the patient's face), make an exposure at the maximum kVp and mAs available. Measure the distance to this point from the focal spot and apply an inverse* square *law correction to this measurement* to *ensure that leakage exposure is less than 100 mR in one hour* at *1 m*[31,35]*. This implies that the product of exposure rate, x-ray time per image and maximum number of images that can be exposed in one hour is less than 100 mR.*

There is a standard for the maximum exposure transmitted through the image receptor supporting device[32,36]. This is to be averaged over 100 cm^2 (with no linear dimension greater than 20 cm) and measured at the minimum SID, maximum kVp and maximum mAs (at that kVp) for which the equipment is rated. The transmitted exposure, measured 5 cm from the closest accessible point beyond the support, must be less than 0.1 mR for each activation of the x-ray tube.

Such a low exposure is difficult to measure, but a test, for acceptance purposes, can be carried out using an integrating exposure meter with an ionization chamber of at least 100 cm^2 area. During this test, care should be taken to shield the periphery of the receptor support, especially along the chest wall (where the primary beam is allowed to extend past the supporting device).

6.10 Phantom and Test Objects

Test objects and phantoms are required to provide simple and quantitative assessment of resolution, contrast, dose, and overall system performance.

6.10.1 Resolution Tests

A high-contrast, bar or converging spoke test pattern capable of measuring up to 20 cycles/mm is useful for evaluating and tracking the resolution of the system. A 7-10x magnifier should be used to evaluate the image.

For evaluation of the image receptor alone, the pattern should be placed directly on the receptor, while for measuring overall system resolution it can be placed at the normal entrance level to the breast.

To test overall resolution performance, a test object containing high contrast specks simulating microcalcifications is useful. Test objects containing sets of SiC, Al_2O_3 or $CaCO_3$ specks ranging in size with their largest dimension being from 200 µm to 400 µm are found to be useful. No more than six specks in each size range should be present and each set should be isolated from the others for easy identification of the smallest resolvable set.

6.10.2 Uniform Phantom Images

Images of a uniform phantom composed of a material such as PMMA are useful for assessing uniformity of the x-ray field, screen and grid, as well as processing artifacts and consistency of AEC operation. It must be ensured that the material is completely free of air bubbles and nonuniformities. A set of uniform slabs, each 2 cm thick, of PMMA can be used to set up and test the tracking of the AEC versus thickness and kVp (Section 6.6). PMMA is a generic description of clear acrylic plastic which includes Lucite, Plexiglas, Perspex, Acrylite, Crystalex and Methacral. Its density is greater than that of water and may be as high as 1.21. Therefore, any PMMA breast phantom used for dosimetry or AEC calibration should be tested against manual exposures of clinical subjects to ensure that corresponding thicknesses of the acrylic give similar film OD to the comparable breast being imaged.

The ACR Accreditation Mammographic Detail phantom has been adopted by the American College of Radiology as a "standard" for the

evaluation of image quality of mammographic installations who seek accreditation by this organization. It can also be used to simulate the breast in order to verify that proper optical density is obtained for AEC exposures. This task group recommends the use of a phantom of equivalent thickness of 4.2 cm PMMA for the determination of patient exposures. The ACR phantom with an additional 0.36 cm (5/32") PMMA slab underneath is acceptable for this purpose. For intercomparison with ACR exposure data. it may also be useful to measure exposures using the ACR phantom without the added slab (See Section 6.4).

6.10.3 Film-Screen Contact and Uniformity of Speed

A copper mesh or fine screen with about 30-40 lines per inch can be used to check the uniformity of contact between the screen and the film. Areas of reduced pressure or dents in the screen will show up as fuzzy areas of altered optical density and indicate a need for the replacement of the screen.

The screens should be evaluated for uniformity of speed by exposing them to a fixed exposure with the uniform phantom and verifying that all films have densities matching to within ±0.15 OD. Before performing this test, reproducibility of output must be verified, as some variation may occur as the tube heats up.

6.10.4 Contrast Measurements

The contrast performance (both subject and photographic contrast) of the system can be evaluated using a step wedge. The wedge should provide the imaging system with the full range of exposures encountered in mammography, but also be reasonably thin to avoid problems due to oblique projection. A wedge built up of 15 sheets of type 1100 aluminum of 0.4 mm increments works well for mammographic imaging. Because of the dominance of photoelectric interactions in aluminum at these energies, the phantom can provide a sensitive indication of beam quality variations.

Since aluminum scatters to a lesser degree than breast tissue, such a phantom is not very useful for assessing anti-scatter techniques and for this purpose a more tissue-equivalent phantom is

required. A narrow strip or a disc of PMMA of thickness 2-5 mm or a PMMA stepwedge of 1.5 mm increments attached to the top of a uniform PMMA phantom 4-5 cm thick yields a low contrast image suitable for evaluating grid performance, and the effect of varying kVp on contrast.

The step wedge should be radiographed with the technique used for the average breast. Two steps in the phantom are identified from the processed image (Figure 6-2): one which yields a gross optical density about 1.3 and a second which gives an OD of approximately 1.6. These steps should be marked and the difference in OD used as an index of contrast on subsequent tests. The OD of the lower density step should be used as an index of imaging speed. The 15th step (6 mm Al) should essentially transmit no radiation and can, therefore, be used for measurement of the base-plus-fog density.

6.11 Photographic Quality Control (Film-Screen Mammography)

In addition to the material included in this section, excellent information on processor quality control techniques is available elsewhere[37,38].

Variations in both the amount of radiation required to produce a satisfactory image and also the image contrast frequently result from changes in the photographic processing. Since this is a chemical process, it is very sensitive to changes in the concentration of the chemicals, and the time and temperature of processing. For satisfactory results these factors must be regulated carefully and therefore, tests must be set up to monitor the quality and consistency of photographic processing. Because of the likelihood of drifts, the tests must be carried out and analyzed on every operational day of the processor. If drifts are discovered, further tests should be done in an attempt to determine the cause of the problem.

Increasing processor development temperature increases film speed (see Section 3.3.1), but replenishment rates must be adjusted to compensate for more rapid depletion and oxidation of chemicals. Furthermore, if processor thermostats are not absolutely reliable at

higher temperatures, 37°C should not be used, since fluctuations in temperature may cause a decrease in contrast and an increase in base plus fog density for some films. For processors which do not control the temperature of rinse water and have water pipes running adjacent to the developer tanks, or for those which have very small developer tanks and use cold replenisher solutions, developer temperature can oscillate significantly. It is, therefore, often more prudent to increase film speed by increasing immersion time rather than developer temperature. Speed drifts due to temperature fluctuations are found to be minimal when temperatures are in the range 34°C to 36°C.

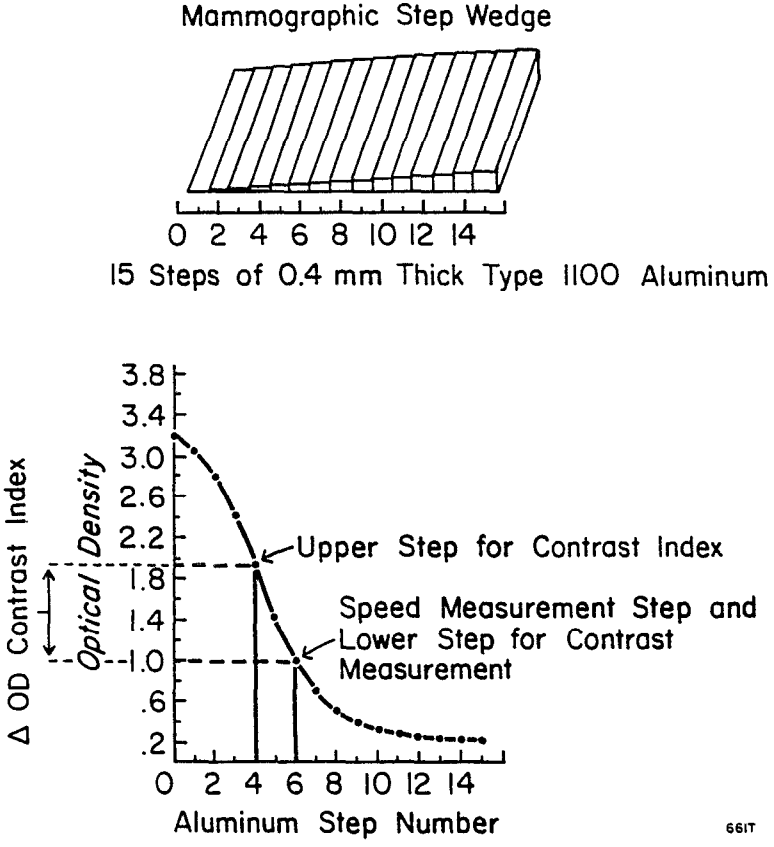


Figure 6-2 Use of a step wedge to monitor overall imaging speed and contrast. (from Yaffe[39])

6.11.1 Sensitometry and Densitometry

A sensitometer provides a set of reproducible levels of light which are used to expose the radiographic film in the darkroom. The film is then processed at the same time of the day, each operational day (preferably before patients are imaged, but after the processor temperature stabilizes). The optical densities (blackness) of the regions of different light exposure are measured using a densitometer. The results must be recorded each day in a log book. The same type of film used for mammography should be used for sensitometric testing. A box of film should be reserved for this purpose so that tests are conducted on the same emulsion batch. Occasionally this testing film should be cross-compared with the batch of film currently used for imaging patients.

If the sensitometer has a color adjustment, it should be matched to the color of screen light emission and should expose both emulsions If double emulsion film is used and only one side of the film if single emulsion film is used. Because of latent image failure, a consistent technique should be used for the production of test films and batches of films should not be exposed in advance to be used through the week[40].

The following information should be recorded (see Figure 6-2):

- speed point - This is the optical density under a particular step on the sensitometric image corresponding to a normal working density for the film, typically around gross OD of 1.3. The OD of the same step is recorded in the log book each day.

- contrast index - This is generally taken as the difference in OD of two steps in the sensitometric image whose densities lie in the straight-line portion of the characteristic curve of the film. Convenient points are the step used for the speed index and the step which yields a density 0.3-0.5 OD greater than the speed point. Once the steps to be used for the speed and contrast tests have been chosen they should remain the same for all future tests.

- base-plus-fog index - This is a measurement of the OD of the film where it has not been exposed to light or x-rays. This provides an assessment of the amount of film fogging. High values (>0.02 OD above baseline measurement) may indicate improper film storage, extremely high processing temperatures, excessively old film or quality control problems in the manufacture of the film.

A typical log form for recording the results of these measurements is provided as Figure 6-3. All three indices are important indicators of image quality and can be used to reveal not only the existence of problems but in many cases also the reasons for those problems[37]. The main advantages of the sensitometry technique are: (a) it is quantitative, (b) it tests the film processing only and isolates it from other possible factors involved in imaging, and (c) it provides results instantly which greatly simplifies the tracking-down of processing problems.

The facility should establish limits of acceptability for variations Of the speed point, contrast index and base-plus-fog (e.g. Figure 6-3) and take investigative action when values fall outside those limits.

6.12 Reproducibility and Uniformity

A very useful test of overall imaging performance and consistency which should be used by all facilities for weekly or more frequent verification of system performance involves producing a radiograph of a standard test object or phantom, always using the same technique factors and image receptor. To provide a contrast scale, the phantom should incorporate a step wedge or an added 5 mm thick PMMA disc. The average image density, speed and contrast of the resulting film can be compared with previous films. This method has been described in Section 6.10.4. Clearly this method is not able to distinguish between processing or generator performance faults. If changes are observed using this technique then it is necessary to use more refined tests to determine whether processing, the AEC or some other factor, e.g. the x-ray source or the image receptor, is causing the variation.

A uniform phantom film can be produced by imaging a 4.2 cm thickness of PMMA to obtain a gross OD around 1.3. Two such films

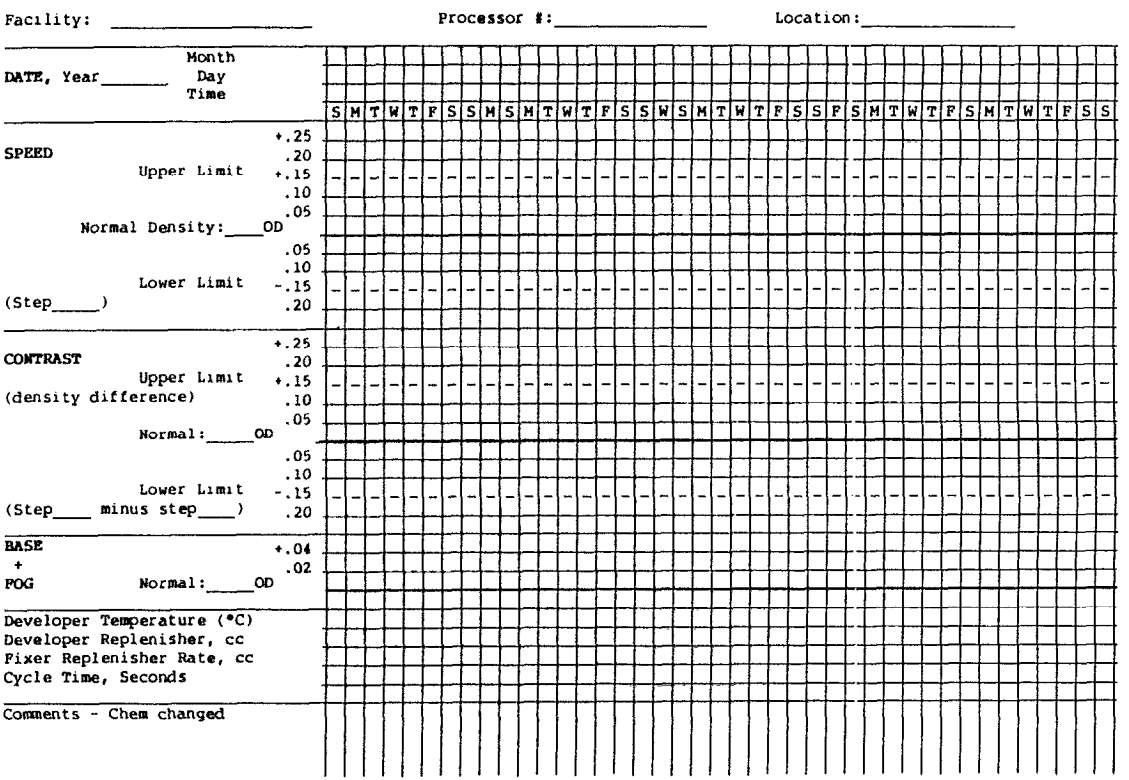


Figure 6-3: Photographic quality control

This chart may be freely reproduced.

should be put through the processor, one inserted lengthwise and the second widthwise. The two films should be identical, demonstrating an absence of roller marks. The OD of these films should be within 0.20 OD of the standard OD. This will show that mR/mAs, kVp, filtration and processing speed have not varied significantly. If a change greater than 0.20 OD is seen, the source of the problem must be detected and corrected.

6.13 Xeroradiographic Testing

Acceptance and quality control testing of the xeroradiographic mammography x-ray system is identical to the procedure for film-screen systems except where noted above and omitting Sections 6.10.3 and 6.11. In addition, the following information is applicable to xeroradiography.

6.13.1 Processor Adjustments

It is very important that the development voltage and toner supply rate of the processor are optimized for the beam quality used by the mammographic facility. If a lower HVL is used for average breasts, the development bias must be increased. If the development bias is not increased, the mAs and radiation dose will have to be significantly increased in order to obtain images of acceptable quality. With higher HVLs, it is important that the development bias be decreased in order to increase the edge contrast.

6.13.2 Resolution and Contrast

The evaluation of spatial resolution in xeromammography cannot be achieved by using conventional high-contrast test targets without adding absorbers to reduce subject contrast. Such targets will cause excessive toner migration leading to erroneous values which do not represent the true resolution of low contrast anatomical features.

The xeroradiographic development process provides an image whose contrast properties are very different from those of a film-screen image. The MTF at low spatial frequencies is low so that the system is relatively insensitive to broad area contrast and, therefore,

displays Considerable exposure and recording latitude. On the other hand, the system is sensitive to discontinuities (edges) in the radiation pattern which are enhanced in the processed image.

To assess the ability of the system to image fine detail over a wide range of breast attenuation, a "latitude phantom" should be used. Such a phantom is generally wedge-shaped and contains a collection of both low and high contrast objects in a range of sizes.

6.13.3 Processing

The following reference materials, available from Xerox Corporation are extremely useful for operation and quality assurance:

Operator's Manual: This manual contains basic information on the xeroradiographic process, operation of the system and routine maintenance.

Illustrated Guide to Image Analysis: This guide contains information on exposure conditions, common image artifacts and suggestions for their prevention. It can be very helpful for determining the cause of many problems relating to image quality.

System Plate Management Guide: This guide describes procedures for the initial installation of the plates, monitoring their quality and removal from use. A plate management log and a plate reference list is also included with this guide. The former is used to record the history of each plate referenced by its serial number and the latter is used to record any special problems such as artifacts.

Quality Assurance Procedures for the Xeroradiographic Process: This manual is a useful adjunct to the other reference materials and can be used as a check list for periodic quality assurance procedures.

Due to the highly specialized nature of the xerographic technology, special training is strongly recommended for the physicist or engineer who wishes to become involved in the repair and maintenance of these systems. The equipment supplier should be consulted for information on available training.

The appropriate charging and development bias voltages must be established by the service engineer. The physicist and quality assurance technologist should review the phantom images using both the aluminum Xerox phantom and a detail phantom, both described in Section 6.13.4. After consultation with the radiologist, an approximate technique should be established. After studies with patients, a technique chart should be established for varying breast size (small, medium, large) and composition (fatty, medium and dense).

During routine use, the proper function of the system should be monitored daily before any mammography is performed by recording an image of a phantom. The quality of the xeroradiographic plates and overall conditioner and processor performance should be monitored weekly by a process called "dark dusting". In this process, all the available plates are conditioned first and then processed without exposing them to x-rays. The resulting images should have a uniform appearance and they should be free from artifacts. Detailed descriptions of the appearance and origin of typical artifacts have been published by DeWerd[41] and by Xerox Corporation.

6.13.4 Phantoms

The use of some type of breast substitute phantom is highly recommended for all mammographic facilities. An aluminum wedge phantom is available from Xerox and it is specifically designed for xeromammography. This phantom incorporates resolution test targets, particles simulating microcalcifications, large low contrast "lesions" and fibers. This phantom is most useful for checking internal consistency, especially after the processor has been serviced. It is also useful for establishing an approximate exposure technique in a newly-installed system. Its intended use is only for xeromammography and it should not be used for the evaluation of film-screen imaging techniques.

Other phantoms which are made of PMMA and may incorporate test objects such as large low contrast masses, fibers and Al_2O_3 specks simulating microcalcifications are also available. The ACR Accreditation Mammographic Detail Phantom is used widely for evaluation of both Xerox and film-screen mammography.

7. REFERENCES

1. Stanton, L. Electrostatic Imaging Systems. In Taveras, J.M. and Ferruci, J.T. (eds.). Radiology: Diagnosis/Imaging/Intervention, Vol. 1, Chap. 8, J.B. Lippincott Co., Philadelphia, 1986.

2. NCRP. Mammography. NCRP Report #85.

3. Thourson, T.L. and Jeromin, L.S. Electroradiography. In Webster, J.G. Encyclopedia of Medical Devices and Instrumentation, Vol. 2, 1146-1168, Wiley, New York, 1988. ISBN 0-471-62969-3.

4. Jennings, R.S., et al. Optimal X-ray Spectra for Screen-Film Mammography. Med. Phys. 8: 5, 1981.

5. Feig, Stephen A. Mammographic Equipment: Principles, features and selection. Radiologic Clinics of North America 25: 897-911, 1987.

6. Beaman, S.A. and Lillicrap, S.C. Optimum X-ray Spectra for Mammography. Phys. Wed. Biol. 127: 1209, 1982.

7. Kratzat, M. Evaluating the Importance of Focal Spot Sizes in Mammography. Medicamundi Vol. 33, no. 2, 1988.

8. NEMA Standards Publication No. XR-5-1990. Measurements of Dimensions of Focal Spots of Diagnostic X-ray Tubes. New York, National Electrical Manufacturers Association.

9. IEC Standard 336-1982. International Electrotechnical Commission.

10. Kimme-Smith, C., Bassett, L.W. and Gold, R.H. Focal Spot Size Measurements with Pinhole and Slit for Microfocus Mammography Units. Med. Phys. 15: 298-303, 1988.

11. Barnes, G.T. and Brezovich, I.A. The Intensity of Scattered Radiation in Mammography. Radiology 126: 243-247, 1978.

12. Sickles, E.A. and Weber, W.N. High Contrast Mammography with a Moving Grid: Assessment of Clinical Utility. AJR 146: 1137-1139, 1986.

13. Niklason, L.T., Barnes, G.T. and Rubin, E. Mammography Phototimer Technique Chart. Radiology 157: 539-540, 1985.

14. White, D.R., Martin, R.J. and Darlison, R. Epoxy Resin Based Tissue Substitutes. BJR 50: 814-821, 1977.

15. LaFrance, R., Gelskey, D.E. and Barnes, G.T. A M-graphic Phototimer Circuit Modification that Improves Linearity. Radiology 166: 773-776, 1988.

16. Yaffe, M.J. Physics of Mammography: Image Recording Process. Radiographics 10: 341-363, 1990.

17. Haus, A.G. Recent Advances in Screen-Film Mammography. In Radiologic Clinics of North America 25: 913-928, 1987.

18. Nishikawa, R.M. and Yaffe, M.J. Signal-to-Noise Properties of Mammographic Film-Screen Systems. Med. Phys. 12: 32-39, 1985.

19. Kimme-Smith, C., Bassett, L.W., Gold, R.H., Roe, D. and Orr, J. Mammographic Dual-Screen-Dual Emulsion Film Combination: Visibility of Simulated Microcalcifications and Effect on Image Contrast. Radiology 165: 313-318, 1987.

20. Oestman, J.W., Kopans, D.B., Linetsky, L., et al. Comparison of Two Screen-Film Combinations in Contact and Magnification Mammography: Detectibility of Microcalcifications. Radiology 168: 657-659, 1988.

21. Tabar, L. and Haus, A.G. Processing of Mammographic Films: Technical and Clinical Considerations. Radiology 173: 65-69, 1989.

22. Kimme-Smith, C., Rothschild, P.A., Bassett, L.W., Gold, R.H. and Moler, C. Mammographic film-processor temperature, development time and chemistry: effect on dose, contrast and noise. AJR 152: 35-40, 1989.

23. Frank, E.D., Gray, J.E. and Wilkin, D.A. Flood Replenishment: A New Method of Processor Control. Radiologic Technology 52: 271-275, 1980.

24. Handbook of Glandular Tissue Doses in Mammography. HHS Publicatio FDA 85-8239.

25. Stanton, L., Villafana, T., Day, J.L. and Lightfoot, D.A. Dosage Evaluation in Mammography. Radiology 150: 577-584, 1984.

26. Conway, B.J. Nationwide Evaluation of X-ray Trends (NEXT), Tabulation and Graphical Summary of Surveys 1984 through 1987. Conference of Radiation Control Programme Directors Inc, Frankfort, Kentucky, 1987.

26a. Conway, B.J. Tabulation and Graphical Summary of 1988 Mammography Survey. Conference of Radiation Control Programme Directors Inc, Frankfort, Kentucky, 1990.

27. Conway, B.J. McCrohan, J.L., Rueter, F.G. and Sulieman, O.H., Mammography in the Eighties. Accepted for publication in Radiology, 1990.

28. AAPM Task Force Report 14. Performance Specifications and Acceptance Testing for X-ray Generators and Automatic Exposure Control Devices.

29. U.S.A. Food and Drug Administration, HHS. Title 21, Code of Federal Regulations, Chapter 1, Subchapter J. Part 1020.30 (m) (1) (i).

30. Ibid. Part 1020.31 (f) (3)

31. Ibid. Part 1020.30 (k)

32. Ibid. Part 1020.31 (1)

33. Canada. Radiation Emitting Devices Act, Revised Statutes of Canada, Chapter 34 (1st Supp.) Radiation Emitting Devices Regulations, Chapter 1370 Part XII Section 5 (2) (f) (ii).

34. Ibid. Part XII Section 11 (1) (a) (i + ii)

35. Ibid. Part XII Section 19 (h)

36. Ibid. Part XII Section 11 (1) (b)

37. Goldman, L.W. Radiographic film processing quality assurance: A self-teaching workbook. US Department of Health and Human Services. HHS Publication, FDA 81-8146. Rockville, Maryland, 1981.

38. Gray, J.E., et al. Quality control in diagnostic imaging. Aspen Publishers Inc., Rockville, Maryland, 1982.

39. Yaffe, M.J.. Mawdsley, G.E., and Mishikawa, R.H. Quality Assurance in a National Breast Screening Study. Proc SPIE 419: 23-30, 1983.

40. Poznansky, A.K. and Smith, L.A. Practical Problems in Processing Control. Radiology 90: 135-138, 1968.

41. DeWerd, L.A. Electroradiography (Xeroradiography): Equipment and Physical Principles. In Waggener, R.G., Kereiakes, J.G., and Shalek, R.J. (eds.) Handbook of Medical Physics Vol. 2, p. 123 CRC Press Inc. Boca Raton, Florida. 1984.