Introduction

Mammography is the screening technique with the highest sensitivity for detecting early breast cancer, yielding a significant improvement in breast cancer survival. Since the first mammography units (xeromammography and screen-film mammography in the 1970s) became available, both the equipment and the examination procedure have changed and progressed. Technology advancements have affected almost all parts of the mammography units, with the highest impact on films and intensifying screens.

Screen-film systems are currently dominating the market and offer excellent detection capabilities of early or occult breast tumors with minimum radiation exposure to the patient and at a relatively low cost compared with other diagnostic imaging modalities such as computed tomography (CT) or magnetic resonance imaging (MRI).

Given the high performance of screen-film systems, it is reasonable to ask: do we need an entirely different system, such as a direct digital one, if the current system works well and perhaps can be further improved? The immediate response may be negative. Many radiologists are somewhat skeptical toward the technological developments that will yield a full-field, direct digital mammography system since a digital system will bring major changes to the image display and, more importantly, to the way in which an image is interpreted. Furthermore, the advantages of the direct digital system over the traditional screen-film are not straightforward, whereas screen-film has already proven its merits. Hence, one cannot easily make a good case for full-field, direct digital mammography systems and promote them as something more than an academic exercise. At the same time, one can see that screen-film mammography will naturally evolve into its digital counterpart because radiology departments are becoming more computerized, teleradiology is no longer a novelty and, more important, film is expensive and easy to lose.

This article introduces the developments in the area of full-field, direct digital mammography (subsequently referred to as digital mammography) and provides a view on possible advantages of digital over screen-film mammography (referred to hereafter as analog mammography). Several reviews and opinion papers on digital mammography have been published in the last two years. This paper summarizes these and other findings in a way that should provide a physician with the knowledge for approaching digital mammography systems. This paper also focuses on solid-state detector technology, which seems to hold greater promise for digital mammography than other technologies such as storage phosphor, scanning equalization, and dual energy projection radiography.

Analog vs Digital Mammography: Technical Differences

Technical differences between analog and digital mammography are important because these differences determine the advantages and disadvantages of the two systems. The Table summarizes the differences for the most important system parameters. It is not comprehensive but focuses on the components that represent the five basic steps followed in the generation of a mammogram: (1) x-ray production, (2) x-ray absorption, (3) recording of transmitted x-rays, (4) image development, and (5) image display.

Spatial resolution is the ability of the system to display two objects close to each other as separate images. It is usually measured with patterns of closely spaced lines. Hence, spatial resolution is defined in terms of line pairs per millimeter (lp/mm). The size of the smallest detectable object can be estimated from the number of lp/mm as corresponding to the width of a line, usually in µm (n lp/mm corresponds to 500/n µm).

Image contrast resolution is the ability of the system to display two areas that have slightly different optical densities (or gray levels for digital applications) as distinct images. The value of 0.04 listed in the Table for analog mammography is an average threshold difference value estimated from data on 10-mm-diameter carcinomas and 0.1-mm calcifications imaged at 30 kVp in a 50/50, 4.5-cm-thick breast including the effect of fog and scatter. Phantom studies with digital mammography systems have shown that, despite the lower spatial resolution, at least 20% improvement in contrast may be achieved.

<table>
<thead>
<tr>
<th>Components</th>
<th>Analog</th>
<th>Digital</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray tube (target)</td>
<td>Molybdenum or rhodium</td>
<td>Molybdenum or rhodium or tungsten</td>
</tr>
<tr>
<td>Grid</td>
<td>stationary or moving</td>
<td>optional</td>
</tr>
<tr>
<td>Exposure time</td>
<td>2 - 3 sec</td>
<td>1 - 6 sec</td>
</tr>
<tr>
<td>Average dose per view</td>
<td>less than 3.0 mGy</td>
<td>comparable to analog or less</td>
</tr>
<tr>
<td>Detector type</td>
<td>screen-film cassette</td>
<td>solid-state device (linear or 2D)</td>
</tr>
<tr>
<td>Detector size</td>
<td>18 x 24 cm or 24 x 30 cm</td>
<td>18 x 23 cm or 19 x 25 cm</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>15 - 20 lp/mm (33 - 25 µm)</td>
<td>5 - 13 lp/mm (100 - 40 µm)</td>
</tr>
<tr>
<td>Image contrast resolution</td>
<td>approximately 0.04</td>
<td>comparable to analog or better</td>
</tr>
<tr>
<td>Dynamic range (latitude)</td>
<td>25 - 100</td>
<td>5,000 - 10,000</td>
</tr>
<tr>
<td>Noise</td>
<td>quantum and film granularity</td>
<td>quantum and electronic</td>
</tr>
<tr>
<td>Image development</td>
<td>wet processing</td>
<td>wet or dry laser printers or digital</td>
</tr>
<tr>
<td>Image display</td>
<td>light box</td>
<td>CRT and/or light box</td>
</tr>
<tr>
<td>Image processing</td>
<td>film processing</td>
<td>CAD/post-processing</td>
</tr>
</tbody>
</table>

Components and Characteristics of Analog and Digital Mammography Systems From Yaffe MJ, Cheung L, and Williams MB.
**Dynamic range** is the ratio of the maximum and minimum signals that can be detected or measured accurately. The dynamic range of film is called *latitude* and corresponds to the range of x-ray exposures over which the film’s gradient is significant without saturation.\(^3,8,10\) As shown in the Table, the analog and digital systems differ significantly in dynamic range. In evaluating this difference, consider the dynamic range of the human eye, which is approximately 10\(^{10}\) (but a range of only 100 is available at a time) and the dynamic range of cathode ray tubes (CRTs), which currently ranges from 40 to 1000.

Noise is defined as random fluctuations included in the image data when the detector is exposed to a uniform x-ray. It is expressed in different ways (eg, variance, standard deviation, noise power spectrum, signal-to-noise ratio, noise equivalent quanta, detective quantum efficiency), with each quantity providing complementary information on noise.\(^13\) The definition of these quantities is beyond the scope of this article, but a detailed review and further references have been published elsewhere.\(^13\)

It is perhaps useful to summarize other basic terms used in discussions of digital systems. Digital images consist of small, usually square elements called **pixels**. Film optical density range is in this case replaced by **dynamic or gray scale** range, which is usually from 6 bits (\(2^6 = 64\) gray values) to 16 bits (\(2^{16} = 65,536\) gray values). Each pixel has a different **shade of gray** (depth), eg, 00001111 for an 8-bit image. Image resolution is defined as the size of the image pixel and is usually given in \(\mu\text{m}\) (\(10^{-6}\) m). Image matrix size is given either as the number of pixels in the x and y direction, such as 512 x 512, or as the total number of pixels, such as 262,144 or more accurately in bytes, such as 393,216 bytes for a 12-bit, 512 x 512 image (8 bits per byte). Computer space and memory are discussed in terms of **bytes**. Image transmission is usually discussed in terms of **bits per sec** (bps, kbps, or Mbps). CRT displays use similar terminology with the additional metric for **luminance**, the SI unit of which is the **nits**, but the more popular **ft-L** unit is commonly used.\(^4\)

From the differences listed in the Table, three are the most outstanding: the large-field solid-state detectors, the CRT display, and the communication networks for data transmission. All have provided arduous technical challenges, several of which remain unresolved.

The greatest challenge in detector development was the size and spatial resolution. Several solid-state detectors were available, but the problem was to design one that could produce a full image of the breast with resolution matching that of the film. All detection systems under development yield a spatial resolution lower than that of the screen film (Table). However, all claim improved contrast resolution, a property that is expected to compensate for the reduced spatial resolution. Different approaches are taken in detector design employing either area or linear solid-state devices. One system is using a mosaic of charge-coupled devices (CCDs), bonded together to create an imaging area of 19 x 25 cm.\(^9,10\) Another is using linear CCDs and a scanning mechanism (time delay and integration scheme) to generate the full breast image.\(^4,8\) Others are using amorphous silicon (a-Si)\(^14\) or amorphous selenium (a-Se)\(^15\) diodes attached together to form a two-dimensional array and an imaging area of approximately 18 x 23 cm. Schematic diagrams of the methodologies developed for digital mammography are shown in Fig 1. With the exception of the a-Se-based system, all use a phosphor screen or coating to convert the x-ray photons to light photons. The detector is either in direct contact with the phosphor, as in the case of a-Si, or coupled to it with glass or plastic fiber-optic tapers or a lens, as in the case of CCDs. Important parameters to consider when reviewing the systems are artifact generation, spatial and contrast resolution, dynamic range, acquisition time, and operating environment (eg, cooling of the detector).

![CRT Diagram](https://via.placeholder.com/150)

**Fig 1.** Schematic diagram of solid-state x-ray detector technologies employed in the development of digital mammography systems. The small-dashed lines in systems I and II represent the losses due to the phosphor glow emitted in all directions.

CRT technology is still lacking in terms of resolution (pixel size) and luminance requirements for mammogram interpretation. Consider that a light-box offers on the average approximately 880 ft-L\(^6\) and a CRT, depending on the type, offers 20 to 180 ft-L.\(^17\) Furthermore, the smallest pixel size available on CRTs is in the order of 100 \(\mu\text{m}\) (a 200-\(\mu\text{m}\) pixel is more common), yielding a resolution at least three times lower than that of the film. Luminance and resolution, however, are only part of the CRT story. Additional considerations are refresh rates, flickering, transmissivity, noise, distortions, and other parameters that affect the way an image is displayed and perceived.\(^8\) It is for this multiparameter issue that limited resolution and luminance may not be the hindering factors in the use of CRTs for digital mammogram display. Recent advancements in CRT technology and properly designed workstation-user interfaces may make primary reading of digital mammograms from CRTs equivalent to film reading.

The workstation-user interface has been recently recognized as an area of major importance in the display. This development aspect has been neglected until now because the technical support was not available. As interest shifts toward this direction, the scientific and medical community will be faced with new questions: How should a digital mammogram be displayed? What is a standard for digital image display? Which is the optimum display, and how is it defined? What are the new artifacts, and how are they manifested on the image? These questions were previously raised and answered for analog mammography. A long period of testing will elapse and numerous studies will be required before a standard is established and accepted for digital mammography. The large number of post-processing options offered with the digital display (eg, window level and width adjustments, gamma correction, contrast enhancement) will add to the difficulty of the job.\(^19\)

There is a wide array of picture archiving and communication systems (PACS) for transmission and storage of images, as well as dedicated interfaces for communicating medical information and data transfer that offer a variety of solutions to match specific needs and applications.\(^20\) It is beyond the scope of this paper to discuss PACS in detail. Digital mammography, however, provides a direct link to PACS in contrast to analog mammography where films would have to be digitized...
Two other issues are important -- the radiation exposure levels and the requirements of the Mammography Quality Standards Act (MQSA). In terms of radiation exposure, digital systems could theoretically reduce the current exposure levels while yielding images with better contrast (Table). In practice, this may turn out to be true only if images of quality similar to the screen film are to be obtained. If better contrast is desired, then the exposure levels will probably have to remain the same. As for the MQSA, current analog systems should comply with the accreditation requirements of the American College of Radiology. Guidelines for the digital systems are discussed below.

**Analog vs Digital Mammography: Quality Control**

The quality control requirements for digital mammography are not yet fully defined. They are expected to be significant operational factors, particularly in the early phases of operation, that will evolve as experience is gained from the first generation of digital systems. The requirements of 21 CFR 900.12 of the MQSA regulations establishing the minimum quality standards that must be met by analog mammography will likely be transferable to the digital systems. This is currently the recommendation of the Food and Drug Administration (FDA) to the manufacturers of digital mammography systems (see the FDA’s Web site at http://www.fda.gov/cdrh/ode/digmammo.html). Modifications and additional tests, however, will be necessary. The extent of these modifications and tests, as well as changes in the assignments of the technologists and the medical physicists, are unclear. New quality control tests may include signal uniformity of the acquisition system, CRT display evaluation, and evaluation of digital image processing tools, of archiving systems, and of detectors’ electronics. Tests such as image quality evaluation, kVp accuracy and reproducibility, automatic exposure control, artifact evaluation, and tests related to film processing, if a laser printer is used, will require modifications. Finally, tests such as phantom imaging, visual checklist, repeat analysis, compression, focal spot size evaluation, beam quality assessment, entrance exposure, and average glandular dose seem to be directly applicable.

**Cost of Analog vs Digital Mammography**

The cost of digital mammography has not yet been fully addressed either in an absolute scale or relative to the analog systems. Barnes and Fajardo indicate that the cost would depend on the volume of the facility. The authors showed that digital mammography can decrease labor cost and space requirements and that cost differences between analog and digital mammography are small for large-volume facilities. However, limited-volume facilities (fewer than 3,450 examinations per year) will experience higher costs for digital than for analog imaging. The potential benefits of improved image quality, improved sensitivity and specificity, more successful computer-aided diagnosis (CAD) applications, and more efficient telemammography applications that could result from digital mammography were not discussed. Whether these benefits will affect the cost remains to be determined. It seems, however, that digital mammography’s place in radiology will be determined by issues other than cost. Better image quality, ease of image manipulation and archiving, image availability, and compatibility with other digital diagnostic systems and teleradiology are strong reasons to foster the clinical use of the digital systems.

**Applications of Analog vs Digital Mammography**

The technical differences between digital and analog systems as well as the first comparative tests (Figs 2A–B) have led to speculations on the potential advantages of the digital systems in the diagnosis of breast cancer. The advantages of digital over analog mammography as described by investigators in the last two years are listed below:

- Improved detection efficiency of transmitted x-rays due to the response characteristics of solid-state devices.
- A linear dynamic range (latitude), wider than that of the screen film (Table) due to the digital integration process, limited only by the read-out speed.
- Increased signal-to-noise ratio (SNR) by merely separating the image acquisition and display processes.
- Reduced image noise due primarily to the elimination of the film.
- Enhanced contrast sensitivity and resolution in all areas of the breast due to the linearity of response of the detector. This implies improved display of poorly contrasted details, either in dense or dark areas of the breast.
- Reduced scatter without increasing radiation dose (probably only for some of the detectors, such as scanned-slot systems).
- Near real-time operation with increased image acquisition speed and instant image access due primarily to the elimination of the wet film processing.
- Enhanced flexibility of image presentation due to post-processing options independent of exposure conditions. Techniques available for post-processing include contrast enhancement, linear and nonlinear gray scale adjustment (window level and/or width), and zoom.
- Separation of detection, display, and storage processes allowing independent optimization of each step.
- Electronic archival and retrieval of images avoiding the frequent problems of low-quality copies or lost films.
- Automated incorporation of images into electronic patient records.
- Compatibility with PACS for transmission and storage of images.
- Compatibility with telemammography requirements (ie, improved access to quality mammography by underserved communities).
- Optimum application of CAD methods.

CAD is an area of significant research in mammography. To date, all CAD applications are based on digitized, analog mammography data. Currently developed CAD techniques aim at the detection and classification (differentiation between benign and malignant) of microcalcification clusters and masses. Several techniques have been implemented with the primary goal of high sensitivity in the detection and/or the classification of an abnormality. The success rate (sensitivity) of state-of-the-art CAD methodologies is now in the range of 85% to 95%. However, the specificity is relatively low, usually less than 40%, which raises concerns...
on the clinical viability of the techniques. Effort is now focused on increasing the specificity of the CAD methods without compromises in sensitivity. It is thought that overall CAD performance will improve with digital mammography because of the uncompromised signal quality and the wider range of acquired information. Regardless, an expanding role seems to await CAD in digital mammography. Considering the display and interpretation questions listed previously, CAD can play a role in addressing these questions and assisting radiologists in the correct interpretation of the new artifacts and signals that will accompany the digital technique. Therefore, CAD may actually resume a more basic assisting role than it currently has.

### Clinical Advantages

What do the potential technical advantages of digital mammography mean for radiologists, patients, and institutions?

For radiologists, the advantages mean consistently better images. Clinically, image quality is judged in terms of the adequacy of the portrayed normal anatomy and the ability to characterize detected lesions. Consistent improvement, even if minimal, in one or both of these areas means a decrease in the number of errors due to poor imaging technique and poor human judgment, as well as an increase in the efficacy and accuracy of mammography. Major improvement, however, is expected in cases where analog mammography is currently less successful. These cases include women with radiodense breasts who can comprise up to 40% of the general population, cases where lesions are located in thinner, less absorbing regions of the breast, and cases with inhomogeneous parenchymal density distributions.\(^{28,29}\)

Figs 2A-B show views of a patient in which an analog (Fig 2A) and a digital (Fig 2B) mammography system are used.

The figures present mediolateral oblique views of a moderately dense breast with calcifications shown around the nipple area and an ill-defined mass at the central posterior region. (Images were provided courtesy of Dr. Tim Cheung of Tex Medical Corporation, Bennett Division, Boyle, NY.)

The improvements in contrast and detail are apparent. The difference in detector response can also be seen in the darker areas of the breast, eg, near the chest wall and close to the skin, which show more detail in the digital image than the analog. Usually a post-processing technique, such as window level and/or width, is needed to take advantage of the full range of the recorded digital intensities. It is speculated that these post-processing methodologies and CAD will be the tools that will make the difference in the interpretation of digital mammograms. Another example of the advantage of post-processing for digital mammography can be found in the Web site of Dr Martin Yaffe at the Sunnybrook Health Science Centre in Toronto, Canada (http://www.sunnybrook.utoronto.ca:8080/~yaffe/DIGMAM.html).

Other clinical advantages include the availability of the original images at any time, more efficient use of the radiologist's time, and improved communication between radiologists or between radiologists and oncologists.

For the patient, the advantages mean possibly less radiation exposure (lower dose per image and/or fewer retakes), fewer tests, shorter procedure times, improved coordination and communication, and shorter waiting times. All these translate into greater patient comfort and increased patient satisfaction. Finally, the medical institution benefits by more efficient use of the physician's time, improved health care delivery, and cost effectiveness.

### Conclusions

We are at the beginning of the digital mammography era. The first generation of digital systems is currently being tested in several academic institutions and seeking FDA approval. They soon will be available in the market. Results from the first clinical trials, due in the near future, should provide valuable information on the new systems and should confirm or deny many of the speculations. It is certain that additional research and several improvements will be made before digital mammography becomes widespread. Moreover, the first applications will not be fully digital due to the unresolved technical problems in the area of digital display. Laser film hard copies will be used in the beginning, but even with this conventional display medium, there will be differences in image quality that will dictate changes in the interpretation. A long period of training lies ahead for the radiologists, the physicists, and the technologists.

Nevertheless, the radiologists will be asked to evaluate the new technology and to compare it to the current standard of practice. A positive or negative attitude toward digital mammography should be based on possible short- and long-term improvements in patient care and health care delivery rather than convenience and status quo. To do so, the radiologists need to have an indepth understanding of the technical differences between analog and digital systems as well as their impact on their clinical practice.

### References


