Chapter 15
Creating the Digital Image

Objectives
- Describe how a digital image is created and processed.
- Sequence the steps of image production and evaluation of the digital image.
- Identify the components of a digital mammography system.
- Explain the postprocessing features available to the radiologist at the review station.
- Describe three methods of digital image production.
- Define the new terminology for digital image creation, storage, transmission, and retrieval.

Key Terms
- algorithms
- bit
- computed radiography (CR)
- detective quantum efficiency (DQE)
- digital array
- direct conversion
- dynamic range
- flat panel detector
- hospital information system (HIS)
- indirect conversion
- matrix
- modality worklist (MWL)
- modulation transfer function (MTF)
- noise
- nondirect imaging
- pixel
- postprocessing refinements
- radiology information system (RIS)
- signal
- signal-to-noise ratio (SNR)
- window center
- window width
HOW IS AN IMAGE CREATED IN FFDM?

What Does Digital Mean?

Digital is a different and more precise way to display information using electric signals, such as voltage, to represent arithmetic numbers. For example, how exact should the measurement of time be? You can be casual: it’s morning about 10 AM; or a bit more formal: it’s 10:17 AM; or if the occasion (such as a sports race) calls for exact precision, you may present time to include a fraction of a second as 10:17:21:36. Figure 15-1.

Digital precision is also useful in determining measurements such as weight, temperature, and distance. Digital methods exist to measure the flow of liquids in pipes, assess temperatures for processing a wide range of manufactured goods (from baby food, to steel, and plastics), and detect the speed of cars on a highway, along with many more practical purposes that contribute to our lives. Inherent in all these digital applications is the use of numbers and the decimal system.

With analog mammography, creation of an image depends on a system using x-rays as a light source, specialized film, and processing equipment to visualize structures within the breast. It is a meld of chemistry, physics, and mechanics that has progressed wonderfully over the years, enabling clinicians to visualize structures as small and faint as microcalcifications and as subtle as distortion of a very small mass. It got the job done well enough to become the “gold standard” for all future development. Yet, further development and improvement in imaging can only occur with the ability to see smaller changes that occur earlier in the development of breast disease. Analog mammography machines, like the analog watch with a second hand, are not capable of displaying more refined measurements.

Four Basic Functions

The four basic functions in x-ray image production are:

1. Acquisition
2. Processing
3. Display
4. Storage

With analog imaging, the film is common to all four functions; it follows a set production chain with few variables possible in each function. A latent image is captured on a film; that film is then taken into a darkroom where chemistry and the mechanics of rolling the film through a processor drop the processed film out of the dryer section. Next, the film is placed on a viewbox for physician review and interpretation. And finally the film is stored away in a medical film library. The design and use of film always involved making trade-offs because the film performs all four functions; optimization of one factor comes at the expense of another. Changes to any function will irretrievably impact the image in the subsequent stages.

Digital mammography is filmless. Yet all four functions occur and produce the desired results as surely as a digital watch with no hands tells time. See Figure 15-1. Digital imaging uncouples the four functions so each can be more exacting and expert and not be at the mercy of the other three functions. Digital imaging can push the limits of any function independently to get better results.

With digital imaging, a latent image is created in the digital array to visualize x-ray photons that passed through a breast. There is no film to handle, no specialized processing chamber to take this array to, and no extra equipment or chemicals that physically form, shape, or fashion an image we can see. Instead, we rely on fast-moving electrons invisible to the naked eye to acquire the shape and form of the structures within the breast as surely as those physical/anatomical structures are captured on x-ray film. So how does FFDM do this magic?

Fashioning an Invisible Cloak

After making the x-ray exposure, we do not remove the exposed digital array from the C-arm of the mammography machine and carry it to the darkroom. Instead, the latent image in the digital array is processed by a different piece of equipment—the computer. After the computer processes the latent image, we do not hang the computer on the viewbox to look at the image; we look on a computer monitor that displays the image. When we are finished viewing the image on the computer monitor, we do not place the monitor into a client’s x-ray jacket and send it to the film library for storage; we send the digital image electrons to a different piece of equipment in the digital mammography system—the PACS archive center. At the core of digital mammography is the computer, a digital marvel in its own right that keeps
everything in a common code so the digital images can be easily transferred from one part of the system to another; it maintains communications between the digital mammography unit, the computer, the viewing monitors, and then to PACS.

From the client’s viewpoint, the digital mammogram examination is virtually identical to the analog examination. The room is the same, the machines look alike, positioning is the same, compression is the same, and x-rays are still used to create the images. The only difference she notices is that the technologist never leaves the room to process the films because the images now appear on a monitor in the room about 15 seconds after the x-ray is taken.

The digital mammogram, from the technologist’s viewpoint, is easier and faster than the analog examination with one notable exception—fixing an electronic mistake. One quickly learns to avoid misspelling the client’s name and to make certain the view is labeled correctly. These digital mistakes cannot be as easily fixed as in analog imaging with a paper label and pen. When a technologist is finished positioning the client and dismisses her, in essence she has completed the digital examination. She does not walk to the reading room to hang films; the images are automatically routed to the monitor at the radiologist’s review station.

The digital mammogram, from the radiologist’s perspective, has changed with definite advantages and disadvantages. Digital images are available within seconds, detailed and exquisite, particularly images of the glandular breast; however, review and interpretation require more time, especially when postprocessing enhancements of the digital images are necessary.1–7 See Table 15-1.

### What Exactly Is a Digital Image?

What exactly is a digital image? The short answer: electronic signals processed into assigned shades of gray. We understand the art of analog imaging because we have a film we can touch. We see the results of our work when a film drops out of the film processor, and we make judgments about how to further handle an underexposed or overexposed film. However, we are not able to hold a digital image in our hands so the digital imaging process is somewhat of a mystery. Filmless imaging is a major departure from the past, with significant benefits for medical imaging.

The relationship of radiation to the breast and its ability to pass photons through living tissue is the same for analog and digital mammography systems. The difference between the approaches begins with how the x-ray photons are collected, processed, displayed, and stored. The digital camera you take with you on vacation can collect, process, and display light passing though its optics (lenses). Digital mammography systems collect, process, and display x-ray photons without use of an optic system; yet the two digital imaging concepts are much the same. The digital mammography machine’s computer converts signal strengths from x-rays that pass through the breast tissue into numbers; computers “like” numbers. The computer rapidly constructs an image based on the signal strength numbers, each with an assigned value for lightness or darkness.8

### We Have an Image

X-rays that pass through the breast are collected, measured, and stored in the digital imaging system as an electronic “signal” as surely as light is collected, measured, and processed by chemicals to display light and dark shadows on a photographic film. Signal equates to measurable or detectable information and, in our case, is represented as voltage or current. The amount of voltage or current is assigned a numeric value. Computers and their software instructions, called algorithms, process the numbers into meaningful data.

The amount of voltage is what determines the shade of gray at each specific location. In digital mammography, more x-ray photons collected in an area on the detector produce a “high signal” and areas with few x-ray photons recorded produce “low signal” See Figure 15-2. More x-rays pass through adipose tissue in the breast; this area of the digital detector is

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**Table 15-1** • An Overview of Analog and Digital Mammogram Exam

<table>
<thead>
<tr>
<th>ANALOG</th>
<th>FUNCTION</th>
<th>DIGITAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Usual method</td>
<td>Position client</td>
<td>Usual method</td>
</tr>
<tr>
<td>Usual method</td>
<td>X-ray exposure</td>
<td>Usual method</td>
</tr>
<tr>
<td>Film processor in darkroom</td>
<td>Process latent image</td>
<td>Computer in mammography room</td>
</tr>
<tr>
<td>Film on view box</td>
<td>RT review image</td>
<td>Computer monitor in mammography room</td>
</tr>
<tr>
<td>Carry films to reading room</td>
<td>Images to reading room</td>
<td>Electronic transfer to reading room</td>
</tr>
<tr>
<td>View box</td>
<td>MD reviews images</td>
<td>Computer monitor</td>
</tr>
<tr>
<td>Not possible</td>
<td>Postprocessing enhancements</td>
<td>Window/level; magnify; invert</td>
</tr>
<tr>
<td>Films in x-ray jacket</td>
<td>archive images</td>
<td>automatically saved to PACS</td>
</tr>
</tbody>
</table>

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struck by more x-ray photons (high signal). Glandular tissue attenuates many of the x-ray photons so fewer x-rays pass through the breast and strike the digital detector (low signal). Every place on the surface of the digital detector, as small as the period at the end of this sentence, can receive a signal. Further, these small dotlike spaces (called pixels) are arranged in ordered rows and columns; there are millions of pixels in the array. Electronic wires connected to the array send a readout of how much radiation reached each specific location.8,9

Each pixel records shades of gray, depending on how many photons struck the pixel. The range of grays is quantified as bits. The number of bits represents the maximum number of pixel values, or shades of gray. Mammography flat panel digital detectors typically use 14 bits; $2^{14} = 16,384$ shades of gray. The 16,384 shades of gray comprise the vast dynamic range of digital imaging. See Figure 15-3.

Digital mammography images usually are displayed on high-resolution monitors. These are no ordinary general diagnostic x-ray monitors; they present extra fine detailed images for radiologists to display and interpret mammograms. MQSA recommends mammography monitors be 5-megapixel (MP) monitors as compared with the 2- to 3-MP PACS monitors used to display general diagnostic x-ray images, although it is permissible to interpret mammograms from the less resolute monitors.

While reviewing the digital image on the monitor, the radiologist has various postprocessing refinements (additional computer algorithms) that allow better visualization of structures in the breast.8–10 These include window/leveling, magnification, and inverting an image. In the not-too-distant future, the radiologist will have truly remarkable medical imaging tools including: 3D reconstruction, tomosynthesis, US-Fusion, and more.

When the radiologist completes a review of images on the high-resolution monitor, the images are stored in the facility’s PACS system. A PACS network is a central server that acts as a database storing images from all digital modalities. A physician interpreting an examination can call up prior client examinations from PACS and display these images on a high-resolution...
How Do We Create a Digital Image?

Production of the digital image begins at the gantry of the mammography machine. Figure 15-4. The gantry is the C-arm structure that consists of the x-ray tube, collimator, compression device, grid, and digital array. The x-rays that exit out of the bottom of the breast strike the digital array.

The digital array is either a direct detector or an indirect detector. But for preliminary discussion both are treated as the same. A separate discussion of the two approaches and their differences appears later in this chapter.

The Digital Array

The x-ray photons that pass through the breast continue on to strike the digital array. The array is like a 2D sheet of graph paper with thousands of columns and rows. Each small square within this graph is known as a pixel. There are 10 to 25 million pixels in a typical digital array; the collection of pixels is also called a matrix. Figure 15-5.

Think of the digital array as a “wafflelike plate” with a series of tiny bins (pixels) in a grid pattern; each bin can store electrical charges. At the beginning of the x-ray exposure, all the bins are empty. When the x-ray exposure is terminated, each pixel stores a value that corresponds to the amount of radiation it received. The more radiation a pixel receives, the more electrical charge it stores.

The number of bits in an image determines the number of gray levels. As the number of gray levels increases, more detail can be portrayed. Illustrated here is this effect for an image with 1, 3, 5, and 7 bits (2, 8, 32, and 128 gray levels).
bin holds different amounts of x-ray photons (small electrical charges). Each pixel is assigned a numeric value based on the number of photons that struck it. This discrete value represents a brightness level.

There are several conflicting requirements for determining the optimal size of a pixel in digital mammography. Make the pixels too large and one cannot visualize the small structures necessary for diagnosis. Make them too small and they individually don’t receive enough x-rays and are noisy; in addition the file storage requirements become enormous.

Your family’s digital camera is based on the same principle and has greatly improved picture detail and sharpness from the early 3-MP cameras to today’s 10 MP–12 MP cameras. More pixels translate into sharper images because more information about the image is available. Table 15-2. However, more pixels also means memory storage fills up faster. Millions of bits of information require more time to readout and display an image. A sufficiently large memory to accept data and readout the large amounts of information (detail) is a crucial element in all digital imaging endeavors, whether using your family camera or a digital mammography machine.

As pixels become smaller, the resolution increases (Figure 15-7), however, it becomes more difficult to manufacture the array. These newer arrays require more sophisticated manufacturing techniques at greater expense to assure quality control. Continued improvements to digital imaging systems consider an optimal balance of: pixel size, resolution, manufacture cost, time to display an image created from millions of these smaller pixel size data bits, and the total amount of data these small pixels create that must now be stored in picture archive and communications systems (PACS) (11–13).

In digital mammography, the size of a lovely microcalcification determines the size of pixels in the array. Pixels must be

<table>
<thead>
<tr>
<th>Table 15-2</th>
<th>Comparison of Imaging Modalities and Matrix Size</th>
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<tbody>
<tr>
<td>DIGITAL IMAGING MODALITY</td>
<td>MATRIX SIZE</td>
</tr>
<tr>
<td>Nuclear medicine</td>
<td>128 × 128</td>
</tr>
<tr>
<td>MRI</td>
<td>256 × 256</td>
</tr>
<tr>
<td>CT</td>
<td>512 × 512</td>
</tr>
<tr>
<td>CR</td>
<td>2048 × 2048</td>
</tr>
<tr>
<td>DR</td>
<td>2048 × 2048</td>
</tr>
<tr>
<td>Digital mammography</td>
<td>4096 × 4096</td>
</tr>
</tbody>
</table>

Figure 15-5
The digital array replaces the film + cassette. Millions of individual pixels comprise the matrix of the digital detector.

Figure 15-6
(A) Before the x-ray exposure all the pixels are empty. (B) After the exposure, the pixels record the number of photons that interacted with each pixel. They display this as a shade of gray. (C) How the digital detector “sees” the number of photon interactions.
smaller than the calcium in order to display them. We visualize microcalcifications that are 0.1 to 0.2mm, which is the equivalent of 0.004 – 0.008 inches, the width of a human hair. Figure 15-8. It is humbling to consider that this basic requirement pushed digital imaging to its limits in order to perform digital mammography. As pixels are made smaller, fewer x-rays will strike each individual pixel; some pixels will not receive an adequate signal to include in the construction of the digital image. Without an adequate signal from these pixels, the image will appear “noisy”—a visual kind of electronic static.8,9,14

**A Mag View of a Pixel**

The pixels each contain a transistor connected to a series of wires; this combination is called a thin film transistor, or TFT.15 When the digital array is struck by x-rays, the
varying x-ray intensities are captured as very small electrical voltages that are stored in the transistors; each pixel registers a unique voltage (signal). Figure 15-9A. The readout electronics measure these voltages (signals). Reading each pixel empties the pixel of its charge.

The first step in this readout process is to identify which pixel is to be read. This is accomplished by electronically turning on and off a switch connected to that specific pixel. The voltage signal represents the number of x-ray photons absorbed by that pixel; the voltage signal per pixel is so small that it must be amplified so that it can be processed. The amplified signal passes into a circuit called “sample-and-hold.” This circuit stores the voltages and measures the strength of the signal. The sample-and-hold circuit creates an analog signal; this analog signal must be converted into a digital signal in order to be processed by and stored in a computer.

Analog-to-digital converters (ADC) convert the analog signal to a digital signal; they do this for each individual pixel. The greater the ADC signal, the more x-ray photons struck that individual pixel.

The ADC sends the digital raw image to the technologist’s workstation (acquisition workstation—AWS) where the computer applies image-correcting algorithms that visually enhance the appearance of the image on the monitor (Figure 15-10).

**Preview Image Processing**

Once the preview image arrives at the AWS, the computer automatically applies several image-correcting or image-enhancing software functions. These algorithms improve visualization of detail by correcting minor mechanical defects (such as dead pixels) and enhancing visual perception (e.g., window/level).

1. The digital array’s matrix is composed of millions of pixels. Odds are very good that some of these pixels will not work, that is they no longer readout the correct voltage signal in response to the number of x-ray photons that interacted with the pixel. These non-working pixels are known as “dead pixels.” The pixel is stuck in the “0” (open position) or in the “1” (closed position) so that it always reads the same voltage output regardless of the number of x-ray photons that struck it. Dead pixels either appear as a white or black...
The dead pixel is brought back to life by the service engineer. Service “maps” the location of this errant pixel from its exact location in the rows and columns of the matrix; this location is programmed into the AWS computer. On all subsequent exposures the AWS computer applies a correction factor to each dead pixel. This correction factor is an averaging of the signal values from the dead pixel’s neighboring pixels.

2. Another algorithm automatically applied to the preview image is a field of uniformity correction. The concept: if all the pixels were exposed to a uniform x-ray field, the voltage signal in all pixels would be equal. However, during the manufacturing process not all of the pixels are created equal; that is if neighboring pixels are exposed to the same number of x-ray photons, the voltage output will be similar but not identical. The field uniformity algorithm multiplies the signal from each pixel by a correction value to compensate for pixel-to-pixel variations and render the image more uniform.

3. The digital array can record thousands of distinct pixel values, or shades of gray, while the computer monitor can display only 256–1024 shades of gray at a time. Another automatic background image-processing algorithm contracts the 14-bit or 16,384 shades of gray into a more manageable range so that our eyes can distinguish structures in the breast. This algorithm reduces the data to 4096 (12 bit) shades of gray for storage in PACS. This is further reduced to 8–10 bits (256 to 1024 shades of gray), the number of gray tones suitable for computer monitor display. At first blush, it might seem that we are throwing away a lot of information, reducing each pixel’s number of shades of gray from 16,000 to 256, however, the human eye cannot see more shades of gray so nothing perceptible is lost.

4. We can adjust the contrast and brightness levels of the image on the monitor; this function is called windowing. The window postprocessing feature is one of the wonderful benefits of digital imaging; however, when the image is first displayed, the person viewing the image does not want to spend time manipulating the image so that it is not too light or too dark. The computer optimizes the display of the image on the monitor so the technologist and radiologist will typically not have to apply window/leveling to their initial review of the image.
5. When the x-ray exposure terminates, the preview image appears on the technologist’s monitor. Computer algorithms are applied to the image to optimize the display. In the digital world each radiologic examination, whether imaging a chest, a breast or a bone, has a typical histogram stored in the computer for comparison. The computer uses a look-up table (LUT) for image processing; it compares your image to what it “should be.” If your image is “off,” the computer uses the LUT to correct density and contrast for display.8,14

6. Another algorithm, known as peripheral equalization, allows us to visualize from the skin line to the pectoral muscle. The overexposed subcutaneous adipose tissue plus the burned-out skin line are made brighter by the computer to match the appearance of the tissue in the center of the breast. At the same time this algorithm darkens the area under the pectoral muscle so that it too matches the appearance of the tissue in the center of the breast.16,17 Figure 15-11.

7. Lesion conspicuity algorithms enhance the contours and shapes of structures in the breast. This is accomplished by contrast and edge enhancement, spatial and frequency filtering, and by suppressing electronic noise. Edge enhancement makes calcifications and spiculation more visible, however, there is a concomitant increase in noise. Smoothing makes large, low contrast structures such as cysts, lymph nodes, and masses easier to perceive.6,17

Window/Level

The AWS is linked with the facility’s information system, or network. The AWS has a hard drive that temporarily stores the image while long-term storage takes place in PACS. PACS stores and distributes the images to workstations, printers, etc. via the network. PACS also supplies the modality worklist (MWL) to the AWS.

When the technologist accepts the images she just acquired, the images are automatically routed to various destinations electronically: for example to PACS, CAD, and the radiologist’s review station. The primary duty of the radiologist is to review the images on a monitor. Part of this review process involves windowing: interactive processing of the image that adjusts the contrast and brightness levels. Windowing involves: window width and window center.8,14 Figure 15-12.

1. Window width computer manipulation is like making contrast adjustments on your television set. This determines the range of pixel values displayed within

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Figure 15-11
(A) This is the preview image that first appears after the x-ray exposure terminates. (B) Shortly thereafter the final image, with numerous algorithms applied to enhance the image, takes its place. (Images courtesy of GE Healthcare. Milwaukee, WI.)

Figure 15-12
An example of image processing applied to an image. In this instance a small region of the mammogram has been modified to enhance the contrast (conspicuity) of a cancer.
the gray scale on the monitor. Since the monitor is capable of displaying only 256 shades of gray at a time while the image stored in PACS typically has 4096 shades of gray, the radiologists could conceivably spend a great deal of time “windowing” if they wanted to visualize all 4096 shades of gray.

The computer displays only those pixels whose values fall inside the specified range of 256 shades of gray. If the value in the pixel is lower than this range, the pixel will display black; if the value in the pixel is above the specified range, the pixel will display white. Increasing the window width results in a broader range of pixel values; this is less contrast. Decreasing the window width results in a narrow range of pixel values; this is high contrast. Figure 15-13.

2. Window center computer manipulation adjusts brightness. This function sets the center pixel value around which the window width is positioned. Figure 15-14. A high window center setting makes the image darker because more tissue with high image pixel values are within the displayed grayscale. Increasing the window center results in a darker image; decreasing the window center results in a brighter image. The pixel value determines the shade of gray displayed on the monitor; if the pixel was struck by many x-ray photons, the pixel displays a black image; white if struck by few photons; and shades of gray if an intermediate number of interactions. Figure 15-15. A typical digital mammography image stored in PACS contains 4096 pixel values (2^12 bits). This mammographic dynamic range far exceeds what our eyes can perceive, but by windowing the radiologist can manipulate the image to better visualize structures in the breast.

Quality of the Image

Accurate detection of signal intensity, the strength of the voltage striking each pixel, is crucial to producing quality images. Sensitivity of digital detectors to signal intensity can change over time, thus digital systems require strict adherence to QC procedures. Generally requirements include weekly updating of field uniformity of the array. The digital detector is composed of millions of pixels. If they were all struck by the same number of x-rays, some pixels would produce a larger signal while others will produce a slightly lower signal. This calibration procedure uses a uniform phantom to bring the system back to optimal settings. The quality of the digital image depends on maintaining the millions of pixels in the array so that they all respond equally to uniform radiation exposure.

Figure 15-13

(A) A low-contrast image. (B) A high-contrast image. (C) Film-screen imaging produces high-contrast images; however, the narrow latitude captures only 100 shades of gray. The wider latitude offered by digital imaging provides us with high-contrast, low-contrast, and all levels in between.
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The procedure called flat-fielding consists of two parts: 1) calibration and 2) correction. 1) The calibration component of flat-fielding is one of the QC tests a technologist performs. The technologist x-rays a uniform phantom, making multiple exposures. The computer averages the multiple images to determine the average response to x-rays for each pixel. This data is now used to correct all subsequent images. 2) The correction component of flat-fielding is done automatically as an image is acquired; the computer applies algorithm processing to smooth the appearance of the image. Because this variation in signal intensity (mottle) always occurs at the same place in the digital detector and with the same intensity, the corrections determined during the calibration step are performed to bring the pixels back to optimal efficiency.

A well designed digital system balances contrast, spatial resolution, and dose efficiency; in digital terminology these are determined by the dynamic range, signal-to-noise ratio (SNR), contrast-to-noise ratio (CNR), small pixel size, modulation transfer function (MTF), and detective quantum efficiency (DQE). From a physics perspective, digital imaging is expected to improve clinical performance relative to film imaging due to:

1. A lower x-ray dose to the client because the digital array is more efficient in detecting incident x-ray photons.
2. Better visualization of microcalcifications due to the superior dose performance for the smallest objects.
3. An improved display of breast structures from the nipple all the way to the densest chest wall region, resulting from the linear response throughout the vast dynamic range; and the ability of digital image processing to equalize image quality throughout the range of densities in a breast.

Factors That Affect Image Quality

The physics principles involved with applying radiation to the breast demonstrates analog and digital imaging have much in common. The advantage for digital mammography comes from the fundamental differences in how the x-ray energy that passes through the breast is collected, processed, displayed, and stored.

With analog mammography, the film assumes three roles: image collection, image display, and image storage. Once a film is exposed, the quality and appearance of the image is determined. In contrast, digital mammography separates these three roles. Image collection is done by the digital image array. Image storage is handled by the facility’s PACS. Image display is handled by the radiologist’s computer review station. Additionally, digital imaging has a fourth step—image processing. The digital image can be manipulated at the computer to optimize the signal at each pixel and for each region of the breast under review. This is facilitated by the wide dynamic range of digital detectors.

Contrast is extremely important for both analog and digital imaging. Contrast is the ability to differentiate the x-ray attenuation co-efficiencies for all breast structures and types of tissue; for example: adipose tissue is dark, glandular issue...
is light, Cooper's ligaments are white, and so on. In general, tumors appear white similarly to glandular components, and this is why cancer detection is so difficult in mammography. Contrast is essential so small differences in x-ray attenuation, or observed white in the mammogram, are visible and allow the detection of cancer amongst the clutter of normal breast tissue.

In analog imaging, contrast is primarily controlled by the x-ray tube target material and the kVp used; digital imaging uses image processing, which is essentially windowing the image differently. Digital imaging relies on wide dynamic range detectors to effectively perform this windowing throughout the range of breast tissue, allowing optimal visualization from adipose tissue to glandular tissue.

Resolution is the ability to visualize very small structures. Analog imaging relies on the size of the focal spot and the line pairs of resolution offered by the screen–film recording media. Spatial resolution in digital is less than half as good as analog imaging, and yet comparison of phantom images between the two methods shows digital "sees" more clearly. The ACR phantom minimum requirements for analog imaging are four fibers, three spec groups, and three masses. Yet digital imaging using the same phantom "sees" more fibers, spec groups, and masses. Clearly there is something more to resolution than line pairs/mm.

Noise, in any form, is the #1 enemy of resolution; it obscures detail by making the image "grainy." Noise is signal that does not originate from the object; it is fluctuations in intensities. If you x-ray a homogenous phantom you will see slight variations of density throughout the image. All x-ray images exhibit this noise or mottle. Sources of noise for analog imaging come from the light of the intensifying screen (line spread function), the film emulsion, the film processing cycle, and x-ray quanta. Digital imaging also has sources of noise—the primary cause being the x-ray quanta, with others including electronic noise in the digital array and imperfect QC calibration procedures or system drifts. In general, for the same amount of x-ray radiation striking the client, the noise is lower in a digital image than in a film image. This is especially important for imaging the smallest objects and for the lowest contrast objects, and manifests itself in the generally superior ACR phantom scores, for example. Even though film mammography can image more line pairs/mm than digital, in a real breast imaged with clinical x-ray doses, the noise of film is sufficiently higher than digital images. This difference gives digital imaging superior performance.

Evaluating the Digital Image

Different technologies require different measuring tools to evaluate the quality of an image. Analog uses its appropriate tools; digital uses tools appropriate for evaluation of electronic signals. In analog imaging the elements that define image quality are: contrast, resolution, dose, and noise. In the digital milieu these terms have a different name: SNR, MTF, and DQE.

1. SNR: Signal-to-Noise Ratio. SNR measures the quality of information in the image and is determined by the number of x-ray photons absorbed by the digital detector. Signal is the difference in intensity of two areas in the breast, for example: cancer and the adjacent normal issue. The digital imaging chain optimizes the image according to the SNR. Digital imaging utilizes higher kVp settings and tungsten target tubes to enrich the number of photons that exit the breast to strike the array, thus ensuring a higher SNR. The use of higher kVp and harder metal targets/filters results in lower contrast. However, the dynamic range of more than 16,000 shades of gray and the ability to manipulate the image to improve the contrast between structures and the background clearly offsets the loss of contrast. Figure 15-16. Also refer to Figure 15-21.

2. MTF: Modulation Transfer Function. MTF evaluates the overall system resolution. It measures the signal...
Transfer over a range of spatial frequencies. This evaluates how well the imaging system transfers shapes or structures from the incident to the output x-ray pattern. The individual MTF of each subsystem in the imaging chain (e.g., pixel size, focal spot size, line spread function, magnification) is taken into account.

MTF is measured under perfect laboratory conditions using a bar pattern with 100% contrast under noiseless conditions—not clinically relevant conditions. You can have a very high-MTF value but yet not be able to visualize a lesion due to the pixilation of the image.

Figure 15-17

1. What is contrast?
2. What is noise?
3. In mammography why do we want high contrast and low noise?

DQE relates to detectability of objects and is a great single measure for image quality. You control DQE by:

1. Increasing the number of x-rays that reach the detector
2. The efficient detection of x-rays by use of an efficient scintillator and high-pixel fill factor
3. An efficient coupling of scintillator and photodetector
4. Low electronic noise

Maximize the SNR to achieve a high DQE; increased signal and decreased noise provides greater visibility of small structures.
DIGITAL MAMMOGRAPHY
DEPARTMENT

The digital mammography department has finally caught up with the other medical imaging services—using sophisticated systems to capture images, and send and store those images and related information electronically. Figure 15-19.

1. Gantry—This is the section of the mammography machine that houses the x-ray tube, digital array, the breast positioning and compression mechanism, and paddles. Clients are most familiar with the gantry because this is where they are positioned and compressed.

2. AWS—Acquisition workstation. This is the computer and monitor interface between the gantry and the technologist.

3. MDRS—Physician review station. After the technologist acquires the digital image, the AWS computer sends the images to the output devices, one of which is the MDRS. The physician interprets the softcopy images at this workstation.

Image Archive & Connectivity

Figure 15-19

Wilhelm Roentgen would be amazed if he visited a radiology department today. Everything familiar is gone; darkrooms replaced by a room full of computers, electronic image processors and monitors; glass plates, chemicals, and film replaced by digital arrays; and cables that connect everything for instant image display.
4. PACS—Picture archival communication system. A vast computer network for long-term storage of all digital images. An output destination.

5. CAD—Computer-aided detection. CAD is a “second reader” that assists the radiologist in detecting regions of interest in the image. This is a computer on the network containing software that analyzes digital mammograms and identifies areas of potential concern to avoid being overlooked by the radiologist. In facilities that use CAD, the computer is accessed as an output destination.

6. Printer—An output destination. MQSA regulations require digital units be connected to a printer. Typical is a laser printer similar to the kind used to print CT and MRI examinations, with a mammography software upgrade.

**Case Study 15-2**

Refer to Figure 15-19 and the text and respond to the following questions.

1. Which component contains the digital array?
2. Which component(s) does the technologist utilize?
3. Where is PACS physically located?
4. Why do all the components interact with “DICOM connectivity”?

**Digital Mammography Room**

The digital mammography room contains the gantry and AWS. The analog machine is replaced by a brand new digital machine or by a completely refurbished analog unit that has been rebuilt as a digital machine. This machine has a permanently mounted digital array. The array is one size and one size only; there is no exchange of Bucky sizes as in analog imaging. Even though the digital detector is only one size, systems utilize different size compression devices to match the breast size, the same as with analog systems.

While the initial capital cost to replace the analog machine with a new digital machine is high, digital examinations do not take as long for the technologist to perform so more examinations can be done on the unit each day. Additionally fewer repeat images are required, which again increases the productivity of the new machine. Also, insurance companies generally have higher reimbursement rates for digital examinations.

**AWS**

The gantry and C-arm components of the digital and analog machines are similar and familiar to a technologist so she quickly feels comfortable positioning the client. Learning computer commands at the technologist’s console is usually the difficult part when mammography services are in transition from analog to digital imaging. There is nothing in analog mammography that is comparable; technologists learn a new skill and vocabulary to operate a digital mammography machine. If the technologist takes x-rays of other parts of the body, she will probably be familiar with digital mammography and thus be familiar with the computerized process of digital image acquisition. However, if she exclusively images breasts, digital is a new world of imaging that awaits.

**Paperwork be Gone**

Well almost. An organized computer-based information system links the client information between the mammography facility, radiology services, billing, and the required reporting to government and insurance agencies; it also facilitates appointment scheduling, delivery of the physician’s report, delivery of radiographic images, and finally storage of all data in an information base. What took 59 steps to accomplish in the analog world requires just 9 steps with digital. Learning the alphabet soup of computer networking systems involved can be somewhat disorienting. But with experience and practice DICOM, hospital information system (HIS), radiology information system (RIS), HL7 and others involved in co-ordinating the paperwork and images to flow smoothly, you’ll appreciate the digital system.

The paperless process begins when the client phones the mammography center to schedule her appointment. The central scheduler enters the woman’s personal information into the computer; the language used by the computer is HL7 (health level seven). The computer operates using a RIS program or HIS: this is a database that stores, manipulates, and distributes client data.

When the client arrives at the mammography center, the receptionist selects the woman’s name from the modality worklist (MWL), a list of clients scheduled for that day generated by RIS/HIS. Use of the MWL ensures the client data is entered consistently and correctly from one year to the next. The technologist should always verify the spelling of the name, and that the appropriate procedure (screening, diagnostic, wire localization, etc.) was entered correctly by the receptionist at the time of registration before pressing the x-ray button to begin the examination. The “almost” from the section title refers to the avoidable hassle of having to fix incorrect data after the examination is started and incorrect information is accepted by the computer. This paperless system does not come with erasers or whiteout. So, with that cautionary note and a newly enforced discipline of reading carefully before acting, you will enjoy one of the benefits of digital mammography.

Before the examination begins, the technologist selects the woman’s name from the MWL at the AWS. The technologist then positions the client and compresses the breast the same way she did with the analog machine. The IRSD of the digital machine is one size, not two interchangeable sizes as with the
analog machine. Table 15-3. The complex electronics and expense to replace the digital platform, should it be “mishandled,” necessitated design of the digital machine with a permanently mounted one-size IRSD.

Outwardly the gantry of the digital unit looks and functions quite similarly to the analog machine, making the transition to the digital world quick for the technologist. Figure 15-20.

As with the analog machine, the x-ray tube on the digital machine can be either molybdenum (Mo) and/or rhodium (Rh) or the digital machine may use tungsten (W). Digital detectors offer their best performance with harder beams, unlike analog film, and that is responsible for the increasing popularity of Rh and especially W anodes. Figure 15-21. Just like analog systems, one can phototime the digital examination, having the system select the appropriate target, filter, kVp and mAs. The AEC electronics are capable of selecting the combination of exposure factors that yield the best dose versus the best quality image.

Table 15-3 • ISRD in Mammography Machines

<table>
<thead>
<tr>
<th>ANALOG &amp; CR IRSD</th>
<th>DIGITAL IRSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>18cm × 24cm</td>
<td>GE 2000D, DS 19cm × 23cm</td>
</tr>
<tr>
<td>24cm × 30cm</td>
<td>GE Essential 24cm × 31cm</td>
</tr>
<tr>
<td></td>
<td>Hologic 24cm × 29cm</td>
</tr>
<tr>
<td></td>
<td>Siemens 24cm × 30cm</td>
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</tbody>
</table>

AEC: Phototiming the Image

We phototime the image using both analog and digital imaging techniques. But how each system determines when to terminate the exposure is very different. We are familiar with the
analog method of placing the photocell(s) under the glandular tissue to achieve the proper amount of optical density darkening. With analog imaging, photosensors “count” the x-rays that pass through the breast; when a predetermined amount of x-rays are detected, the exposure is terminated. The photosensors are located in the IRSD, beneath the Bucky and the cassette. Figure 15-22.

Phototiming with digital is different. With digital imaging, we cannot have photosensors located “under the cassette” because there is no cassette. One cannot position the photosensors under the electronic-rich digital array because the electronics would be in the way of the photons as they exit the breast and no signal would strike the photosensors.

Nor can the digital machine have a phototimer device on the top surface of the digital array. The exquisite imaging performance of the digital array would show the phototimer as an artifact superimposed in the breast.

How then does the digital phototimer work when it cannot be placed on top or under the array? The answer—the array itself acts as the photosensor. At the initiation of the exposure a short (0.05 second or so) low dose x-ray pulse is sent through the breast. The digital array is quickly sampled by the computer, which searches for the densest areas, (Figure 15-23) and calculates the optimal final exposure techniques so as to generate a high-quality image. The main x-ray exposure then continues. This all happens automatically and efficiently behind the scenes with minimal technologist input.

In the digital world, we rarely have underexposed or overexposed images. This is partially because the automatic exposure control is very accurate, and also because postprocessing with the window/level feature uses all the information about the photons captured in the detector array. Its wide dynamic range with over 16,000 shades of gray allows for accurate “reconstruction” of structures the human eye could miss if using film.

So, how do we ascertain whether or not we have an acceptable digital image since we cannot use the too light/too dark criteria used with film? The answer is the exposure number. Computers and digital imaging are all about making numbers do wonderful things for us.

S#, EI, DEI, REX, ...

When the digital machine phototimer terminates the exposure a number displays on the AWS monitor along with the image. This number should fall within an acceptable range, as stated by the equipment manufacturer. The acceptable range is a numerical index that indicates the exposure range which ensures a diagnostic image is produced with an appropriate radiation dose.8,14

If the exposure number is too low, the image will look noisy because the signal to the matrix is not sufficient to overcome
the noise inherent in the imaging process. If the exposure number is higher than the ideal range, the digital image looks good, however, the client receives more radiation than required to produce the image. If the exposure number is significantly higher than the optimal range, the pixels will be saturated; it receives so much signal that it cannot distinguish between different tissue types. It is possible, due to the window/level function, to produce an image that is technically “bad” and yet on the monitor looks good.

With some digital machines the AWS computer is programmed to automatically window/level the image to predetermined (calculated) values so the technologist and radiologist do not have to perform this function. Other equipment manufacturers have the technologist establish the window/level display for each exposure to look good to them. Close monitoring of the QC tests that track the exposure number reliability/reproducibility are important to ensure the production of a good image with an acceptable dose.

Accept or Reject?

On termination of the x-ray exposure, the image displays on the AWS monitor in the mammography room. Figure 15-24. The preview image appears approximately 15 seconds after the technologist releases the x-ray exposure button. The preview image is a partial readout of the signal that accumulated in the 10–25 million pixels; no image-correcting algorithms have been applied. The technologist immediately begins assessment of the preview image: is the positioning adequate? Radiographic landmarks visible? Skin wrinkles? Correct electronic view marker (ex. RCC, LCC)?

Shortly after the preview image appears the finished image takes its place. Now the technologist examines the details: exposure number okay? Motion? Since the AWS monitor is not the same resolution quality as the radiologist’s monitors, the technologist may activate the magnification box or enlarge the entire image to check for motion. If the technologist is performing diagnostic imaging of a region of interest (ROI), she has many of the same postprocessing features on her AWS as are available to the radiologist.

If the technologist rejects the image, the computer prompts her to select a category for the reject reason. This feature makes the dreaded reject/repeat QC test at least tolerable. If she accepts the image, she continues on with the next view. Should the technologist change her mind and choose to un-reject a previously rejected image, a mechanism is in place to permit this. If, on the other hand, she changes her mind and wants to reject a previously accepted image, depending on the configuration set-up of the acceptance feature this can be done quite easily or it can be a very time consuming activity.

Outputs

After accepting the image(s), the digital image is automatically routed to the predetermined outputs: PACS, CAD, RT workstation, MD review station, printer. If for whatever reason the images do not reach some of the selected destinations, the technologist is able to resend the images.8,14,19

Physician Review Station

Softcopy review of the digital mammogram images takes place at the radiologist’s review station. Generally this consists of two 5-MP monitors on which to review the images, a 3-MP multimodality monitor on which to view breast ultrasound and/or MRI examinations, and a keypad for efficient postprocessing commands.19 Figure 15-25.
The special high-resolution monitors can be a component of the digital imaging system designed by a mammography machine company. These systems are more comprehensively designed with more advanced postprocessing features for faster review of mammography examinations. Currently, it is permissible to read from PACS monitors even if they are not 5 MP.

The digital reading room is darker than a film reading room. The suggested ambient room light for reading analog images is 50 lux or less, while digital is 20 lux or less. The digital monitors should be positioned at right angles to the film viewbox to minimize the spectral reflection.

Previous Digital Examinations

When a facility has previous digital examinations to compare with the current digital examination, the previous cases must be retrieved from PACS storage. This retrieval process occurs in one of three ways:

1. **Manual**—An employee of the facility retrieves prior examinations from PACS before the client’s mammogram appointment. Previous examinations are now on the radiologist’s review station for comparison with the current examination.
2. **Prefetch**—This retrieval method requires a broker connected to the facility’s HIS/RIS system. When the client’s mammogram appointment is entered into the computer, the study order triggers the retrieval of prior examinations; this usually occurs automatically in the middle of the night when PACS is not busy.
3. **Autofetch**—This automatic retrieval method is set into motion when the first image from the current examination arrives in PACS or at the radiologist’s review station. If multiple AWS and/or radiologist review stations are located at a facility, they need to “talk” to one another. A workflow manager (server) will direct the routing, auto or prefetching, and the archiving of images.

Electronic Wax Pencil

When radiologists read analog images, they mark a ROI on the film using a China marker or wax pencil. In the digital world the radiologist marks with an electronic wax pencil. Figure 15-26.

After placing a mark around the ROI a radiologist may/may not attach an electronic message (annotation). A radiologist may elect to save the markings and annotations in PACS, which can be useful when sending images to the referring physician. Saving markings and annotations depends on the capabilities of the PACS system; some may or may not support this function.

Some PACS systems can support GSPS (gray scale presentation state). With GSPS the markings are stored in PACS as an overlay. If the PACS system cannot support GSPS, then the markings may be saved as secondary capture (SC). With SC the markings are saved by creating a copy of the image with the marks attached. The result: if you took four images and the radiologist made a mark on one of them, there will now be five images stored in PACS. The SC image has poorer resolution than the GSPS because it is an electronic copy, but it serves the purpose to identify the location of a marking.

Hanging Protocols

Digital mammography is flexible and responsive to radiologists’ preferences when they review an examination. The various scenarios for constructing the hanging protocols in digital far exceed the options in analog. The following examples illustrate only a few hanging protocols from all the possible combinations available to radiologists. Figure 15-27.

A computer can be programmed to display images whichever way the radiologist wants to read them. The actual choices are dependent on the mammography software provided by the equipment vendor. Dedicated digital imaging systems offer more sophisticated programs. A PACS vendor will generally have only basic reading functions; their mammography software is considered a works in progress for many companies trying to become all things for all systems. While PACS vendors are responsible for all imaging modalities, mammography equipment manufacturers specialize because they cater to only one modality.
PostProcessing Image Enhancements

A radiologist has many “tools” available for viewing and enhancing mammogram images. While all the tools are designed to improve visualization, not every tool is used by every radiologist; they have their favorites and specific conditions for applying them. A radiologist may spend little time using these tools to read the basic four-image screening examination of an adipose replaced breast. Yet may spend more time and use more postprocessing tools when reading diagnostic examinations or when dealing with a predominately glandular breast. It does take longer for a radiologist to read digital examinations than to read analog examinations; studies cite up to 60% longer.7,19

Paradoxically it is the fantastic “tools” available to the radiologist for postprocessing an image that increases their workload.4 –6,8,11,14 Some of the tools include:

1. Window/level: the computer records, pixel by pixel, how much electronic signal was captured. Radiologists can manipulate this data very easily to view areas of the image as light or as dark as they wish and as high in contrast or low in contrast as they choose. Figure 15-28.

2. Magnifying glass: a radiologist can activate the mag-glass and move it throughout the image. Use of the mag-glass should not be confused with use of the mag-view. A magnified view (mag-view) is created on the mammography machine using a small focal spot and a magnification-imaging platform. Figure 15-29.

3. Zoom: the entire image displays in full resolution. The breast cannot be zoomed and displayed in its entirety since the image is too large to fit on the monitor; the radiologist pans the image (moves superior-inferior-anterior-posterior) until it has been viewed in its entirety. Figure 15-30.

4. Inversion: what is white on the image now shows up black, and what was black is now white. Figure 15-31.
Figure 15-28
In analog imaging two separate x-ray exposures would be required to obtain these differing contrast and optical density images. Contrast and brightness levels are dynamic with digital imaging. Only one x-ray exposure was required; computer manipulation supplies the rest. (Image courtesy of GE Healthcare. Milwaukee, WI.)

Figure 15-29
The portion of the breast inside the mag-box displays at full resolution. The mag-box can be positioned anywhere on the image.

Figure 15-30
(A) Decreased resolution is required to visualize the entire breast on a monitor. (B) One step in the radiologist's hanging protocol displays the image at full resolution, where the breast is now larger than the monitor. In order to inspect all of the breast, the radiologist must move the zoomed image on the monitor. (Images courtesy of GE Healthcare. Milwaukee, WI.)
The technique is especially useful when looking for calcifications.

5. Measurement: calipers opened on an area are dragged across the image and closed. The distance between the 2 points displays in millimeters (mm). Figure 15-32.

6. Rotation: useful for making back-to-back comparisons of images. Figure 15-33.

7. CAD: toggle a keypad button to display the CAD marks. Figure 15-34.

It is possible to activate multiple postprocessing features at the same time. For example, you can magnify, invert, and window/level all at the same time. The postprocessing features are conveniently located on a keypad for the radiologist. Figure 15-35. This keeps the functions confined to a space-saving location to minimize moving a mouse across a mouse pad. Use of the keypad facilitates the interpretation process for the radiologist.

The Weakest Link

The weakest link in analog imaging is human eyesight; in digital imaging it is the radiologist’s monitors. The monitors can only display a fraction of the information captured by the digital array; in fact the digital image resolution must be reduced to display on the monitor. The typical home PC computer monitor has approximately 1000 × 1000 pixels; the 5-MP mammography monitors are 2000 × 2500 pixels for a total of 5 million pixels; yet the digital array totals nearly 25 million pixels. Use of the magnification or the zoom postprocessing enhancement brings us closer to the individual pixel display resolution, however, with this expansion of the image, the breast is now too large to display on the monitor. The radiologist must move the image superior-inferior-anterior and posterior to inspect all of the breast tissue, one section at a time. Refer to Figure 15-30. This movement adds time to the evaluation process.

When digital mammography was first commercially available, the monitors were of the cathode ray tube (CRT) vintage, much like our home TV sets. Large glass vacuum tubes are coated with a phosphor that gives off light when electrons strike it. Its strong suit is that black is the darkest black. CRT tubes quickly gave way to the liquid crystal display (LCD) technology used in laptop computers and flat screen TVs. The strength of the LCD technology is that its light source is placed behind the liquid crystal display and displays the entire color range of white. Mammographers are interested in the “whites.” Figure 15-36.

Case Study 15-3

Refer to Figure 15-28 and the text and respond to the following questions.

1. If these are analog films, what is the difference between them, and how was this accomplished?

2. If these are digital images, what is the difference between them, and how was this accomplished?

3. What other digital postprocessing tools are available to the radiologist?
Figure 15-33
Radiologists often compare current (c) and prior (p) images oriented back-to-back to evaluate symmetry/asymmetry.

Figure 15-34
(A) CAD indicates a ROI to the radiologist by placing symbols on the image. (B) The monitor refines the display to depict the specific structures the computer deemed significant. (Images courtesy of Hologic/R2, Santa Clara, CA.)
There are several methods for producing digital images. They can be most clearly characterized in terms of how the electronic image is generated: direct-to-digital imaging and nondirect imaging. Direct-to-digital systems automatically generate signal and send the image to the controlling computer. In nondirect, the technologist must intervene. CR is an example of nondirect. The technologist must remove the exposed CR plate and transport it to an image plate reader in order to generate the image.

Indirect conversion methods are similar in behavior to screen–film imaging. X-rays produce light to form a light image, which is then detected by some sort of light-sensitive system. Film was the first method using indirect conversion, but of course this is not digital technology. The indirect digital conversion methods are CR mammography and a system that uses cesium iodide (CsI). There is only one type of direct conversion digital imaging. With this method, x-rays directly produce the image. Amorphous selenium detectors are used in direct conversion systems. Each has its advantages and disadvantages.
Computed radiography (CR) is nondirect, indirect conversion digital technology. The original CR product was introduced to the radiology department in 1981. General diagnostic x-ray slowly began their transition from film to CR; today most imaging centers and hospital radiology departments are filmless, with mammography often the sole holdout. Mammography CR has been used in Europe, Asia, and Australia for many years. With subsequent advances in CR imaging plate technology and image processing, Fuji’s CR mammography product was approved by the FDA in July 2006 (23). Several other companies are in the FDA review process for approval of their CR mammography systems.

Evaluation of CR Imaging

The ACRIN/DMIST study incorporated nondirect, direct-to-digital, indirect conversion as well as direct conversion digital imaging. ACRIN/DMIST established the quality of CR imaging as approximately equivalent to direct-to-digital imaging.¹ A 2003 study from the Mayo Clinic stated CR offers greater lesion conspicuity than analog imaging and that it is especially helpful when imaging glandular breast tissue. A 2003 study from the University of Vienna found CR very good at depicting image blackness but that flat panel (direct-to-digital) digital imaging outperformed CR in all other categories.²⁴

How Does CR Work?

CR has much in common with analog imaging: both use the same analog mammography machine. This is an economic advantage for the CR method since a facility can continue to use their existing analog mammography machine. Use of the existing mammography machine permits CR to use the two standard image receptor devices: 18cm x 24cm for use with smaller breasts and 24cm x 30cm for larger breasts. The CR system uses a CR cassette in place of the analog screen–film cassette; the CR cassette fits in the tunnel of the Bucky.²⁵ Figure 15-37.

However, unlike analog imaging, a CR cassette is not taken into the darkroom for processing. Instead, it is placed in a CR plate reader; it is similar to loading a screen–film cassette into a daylight autoload processor. Figure 15-38.
The imaging plate (IP) is extracted from the CR cassette; the IP reader scans the imaging plate to produce a digital image. Figure 15-39.

The IP is a flexible plastic sheet coated with a photostimulable x-ray absorbing phosphor material, also known as a storage phosphor. When the IP is struck by x-ray photons, some of the energy is lost as fluorescence while the rest causes photostimulable luminescence; the energy from the x-ray absorption causes the electrons in the phosphor crystal to be stored proportionally in traps in the phosphor material. The number of filled traps is proportional to the absorbed x-ray signal. The energy stored in the traps is the latent image. When the CR cassette is inserted into the plate reader, dual red laser lights scan the IP, one on each side of the plate. The red laser light discharges the traps causing them to release their stored energy as blue light. The blue light is collected, point-by-point, by efficient light detectors. By scanning the laser beam in a raster motion across the phosphor, and by recording the quantity of light emitted at each location, the scanner creates a digital image; line-by-line the digital image is formed. The collected blue light is transmitted through a filter to a photomultiplier tube. The photomultiplier tube logarithmically amplifies, digitizes, and processes the signal for film or soft copy display. The IP is then exposed to white light inside the image reader to erase any leftover signal. Thus, the IP is recharged and ready for use again.

The technologist critiques the image at the QC workstation and decides if the image is acceptable or if it needs to be repeated. Figure 15-40.
CR Advantages

1. **Economics.** CR is an economic alternative to direct-to-digital imaging. It is appealing to low mammography volume facilities. Approximately 70% of mammography facilities have one mammography machine; 30% have more than one unit. A facility can continue to use their analog mammography machine without having to purchase a new digital mammography machine. However, the facility must purchase CR cassettes, an imaging plate reader, an image and information processor, and the mammography technologist’s work console.

2. **Two sizes of IRSD (18 cm × 24 cm and 24 cm × 30 cm).** Retaining the analog mammography machine allows continued use of the two standard size image receptors mandated under the analog imaging requirements of MQSA.

3. **50 μm pixel size results in (theoretical) better spatial resolution than direct-to-digital detectors.** But due to light diffusion in the CR process, most of the high resolution of the 50 μm pixels are lost and final image resolution is equivalent in size to more than 100 μm, which is similar to the resolution of direct-to-digital imaging.

4. **CR imaging plate reader.** There are two advantages here. First, a facility has an option of purchasing a single cassette reader or a multiple cassette reader. With the multiple cassette reader the technologist can “load ‘n’ go.” Cassettes are read out in approximately 1 minute/cassette. The second advantage is the reader can accommodate multiple modalities: mammograms, chest x-rays, orthopedic examinations, etc. Each body part requires different software algorithms to correctly process the imaging plates.

5. **Dual side scanning.** Dual side scanning of the IP in the CR reader yields a 30%–40% improvement in DQE compared to single-side readers. However, with dual side scanners the computer has two separate images to meld into one image. The computer uses a spatial filtering process to fuse the two images. Dual side scanning readers were first introduced in 2006.

CR Overview

CR mammography is the same process used in CR imaging in general diagnostic radiology, however, special mammography CR cassettes are used. These cassettes are in the two standard sizes used in mammography: 18 cm × 24 cm and 24 cm × 30 cm. The cassettes are placed in the Bucky of the analog mammography machine. After positioning the client and making the phototimed x-ray exposure, the mammography technologist inserts the exposed CR cassette into the imaging plate reader. The reader processes the latent image by scanning a laser light, line by line, across the surface of the imaging plate; this process takes approximately 1 minute. The technologist views the image on the QC workstation located
in the mammography room or, if shared by multiple rooms, in a common technologist work area. The technologist accepts or rejects the image. The technologist’s console is not connected to PACS, it accepts images from the plate reader only. It cannot display prior examination images, only those images it just processed.

Fuji CR uses a sensitivity value (S#) as the exposure indicator. The technologist ensures the exposure to the imaging plate has an adequate electronic signal by confirming the S# falls within a specified range. For example, 100–200 is an acceptable range. Ideally, one would like the S# to be in the middle of that range; then the client receives the lowest dose for the best signal. The S# has an inverse relationship in that if the S# decreases then the exposure increases; conversely as the S# increases the exposure decreases. In our example, if the S# was 50, the image would be outside the sensitivity value range and the image would be overexposed.

CR is digital imaging. Unlike direct-to-digital imaging technology that immediately displays the image on a computer monitor, CR systems create a latent image on a phosphor screen contained within the CR cassette. The cassette is placed inside a “processor” and then the image displays on a computer monitor.

**DIRECT-TO-DIGITAL DETECTORS (FLAT PANEL DETECTORS)**

Flat panel detectors refer to detectors that are built as large assemblies that automatically generate images when exposed to x-rays. As we learned, these can use either direct or indirect conversion methods of absorbing the radiation.

Both direct and indirect flat panel detectors are used in full field digital mammography (FFDM). The indirect method, similar to capturing a screen–film image, is a two-step process: (1) convert the x-rays to light (2) record the light on the digital array. The direct method uses a single step process: x-rays are (directly) converted into an image. No intermediate step is involved.

**Indirect Flat Panel Conversion Detector**

The indirect flat panel detector produces an image in much the same manner as screen–film imaging. Figure 15-41.

The x-ray photons that pass through the breast strike the scintillator material, which is made of cesium iodide. The scintillator material converts x-rays into light. The light is detected by photodiodes and converted into electrons. The electrons form the digital image. As with screen–film imaging, it is the diffusion of light in the scintillator that results in a less resolute image (blur).

**Figure 15-41**

Indirect conversion detectors work by absorbing x-rays, which give off light scintillations that are detected by photodiodes. (Image courtesy of Dr. Andrew Smith, Hologic. Bedford, MA.)

**The Indirect Imaging Process**

The scintillator is composed of cesium iodide (CsI); it is a phosphor screen, similar in function to the intensifying screen in the screen–film cassette. The CsI screen emits light when struck by x-ray photons. The CsI material then channels the light to a layer of photodiodes which converts light into electrical signals. The photodiodes are mounted on a substrate of amorphous silicon (a-Si) which houses the array of electronic switches and signal lines that sit atop the pixels. Each light sensitive diode element is connected by TFTs to a control and a data line. This results in a collection of digital data that describes precisely the x-ray intensity that strikes each pixel. Figure 15-42.

A close bonding process intimately joins the CsI scintillator material and the a-Si photodetector to reduce the loss of light as it is transferred from one layer to the other. If you make the CsI layer thinner to reduce the light spread, the thinness now adversely affects the absorption quantum efficiency. The CsI crystals are grown as needle-like columnar structures to channel the light to the photodiode surface. This columnar structure is conducive to minimizing the loss of light during the transfer process; however, there is still some degree of light spread which degrades the resolution. Light diffusion is a source of less resolution as up to 3 pixels away from the source (about 50 pixels in all) receive signal from one incoming x-ray.

**Indirect Conversion Resolution**

The resolution of the indirect detector is 100 μm (0.1 mm). This is the distance between two transistors. If the pixels were made smaller, would this improve the spatial resolution? The inherent resolution of this digital system is determined by light spread, not by pixel size; therefore, making pixels smaller will not make the image sharper.
Another factor that causes reduced resolution is the location of the portion of the digital array that actually “captures” the image. In screen–film imaging the film is placed at the top surface of the intensifying screen. The film is in intimate contact with the intensifying screen and it responds to the light emitted by the screen. The TFT array, where the digital image is captured, is at the bottom of the digital array and is not in contact with the scintillator layer. The light from the scintillator is channeled down to the TFTs; light spread occurs during the “channeling,” thus a reduction in spatial resolution. Figure 15-43.

If the scintillator were made thinner to reduce the distance the light diffuses, thus creating a sharper image, the array would become less efficient in absorbing x-ray photons and the SNR would suffer.

Direct Flat Panel Conversion Detector

The direct flat panel detector produces an image in much the same manner as xeromammography did. The x-ray photons that pass through the breast strike the photoconductor, which is made of amorphous selenium (a-Se). Figure 15-44. This interaction produces an electrostatic image with high spatial resolution. The flat panel plate is uniformly charged. The x-ray exposure causes the plate to discharge, with the degree of discharge proportional to the amount of radiation striking the plate.

The Direct Imaging Process

X-rays strike the amorphous selenium photoconductor surface; electron-hole pairs (+ & − ions) are created by knocking electrons off the selenium atoms. A high-voltage electric field is applied across the selenium layer; positive and negative electrodes are placed on the upper and lower surfaces, and an electric field is applied. This voltage differential propels the electrons in one direction and electron holes in the other. Ions travel in a straight line to the TFTs because of the voltage differential; lateral light spread is minimal, on the order of 1 µm. Therefore the spatial resolution is not affected. Figure 15-45.
Figure 15-44
The direct detector is made of amorphous selenium. This converts x-rays directly into an electrical charge. (Image courtesy of Hologic. Bedford, MA.)

Figure 15-45
Opposite electric charges are applied at the top and bottom surfaces of the a-Se layer. When x-rays strike the a-Se layer, the ions travel in a straight line to the TFTs. Spatial resolution is sharp because there is virtually no lateral light diffusion. The transistor array absorbs the electrical charge and measures the charge from the ions. The measurement of the charge is converted into a digital image. (Image courtesy of Dr. Andrew Smith, Hologic. Bedford, MA.)

Direct Conversion Resolution
a-Se is ideal for use in mammography; it is a very good detector of x-rays in the mammographic energy range. Selenium was used in the 1970s–1980s with Xeromammography so the manufacturing process is well understood. It has high x-ray absorption efficiency with excellent intrinsic resolution. The x-ray absorption capability (quantum efficiency) of the direct process is 95%; analog imaging is 50%–70%; and CsI scintillators are 50%–80%. Figure 15-46.

The a-Se photoconductor layer can be made thicker to absorb more x-rays, thus making data collection more efficient. With a thickness of 250 µm, this detector stops 95 percent of the incident x-rays. If this layer is made thicker it does not create more light blur, as it would with the indirect method.

Direct detectors do not have light spread, so the spatial resolution is limited only by the pixel size. Depending on the equipment manufacturer, 70–85 µm pixel sizes are typical. As monitor technology advances, future efforts will be directed toward reducing the direct detector pixel size to provide better resolution. The indirect method cannot be improved because its limiting factor is light spread (blur), not pixel size.

Figure 15-46
Percent absorption of incident x-rays for materials used in screen–film: Gd₂O₂S 34 mg/cm², indirect conversion CsI(Tl): 73 mg/cm², and second generation selenium: 250 µm thick. (Image courtesy of Dr. Andrew Smith, Hologic. Bedford, MA.)
In all detectors there is an inherent lower limit in the size of the pixel. If pixels are made too small, while the resolution may improve, the overall system may not. Very small pixels receive too few x-rays to generate an image, and the image is noisy. In addition, smaller pixels make large data sets that are challenging to transmit, store, and display.

Direct Conversion Weaknesses
All technology has advantages and disadvantages. The resolution of the direct conversion array is limited only by the size of the pixels. As pixels are made smaller, the amount of data in an image rapidly increases. This results in a longer wait time for the image to be readout by the TFTs and displayed on the technologist’s monitor; additionally, with more information acquired with each image, more storage space is required in PACS.

Another disadvantage is drifting of the dark signal, aka “ghosting.” The direct digital array produces an electronic signal even in the absence of an actual radiation exposure. The array is constantly “cleaned” to empty the TFTs of this dark signal.

SUMMARY
Digital imaging is more than the sum of new technology, science, and mathematics; it is a shift in our thinking, concepts, and language. It is all about how we think, see, and express our questions and answers. Invisible electrons move with the speed of light, sometimes through wires, sometimes through the air; they are shaped by digital technology to capture life-saving images and our words about them for our medical decision-makers in ways not available to them a mere decade ago.

As our minds decide what we want to see, and how we want to see it, we turn to digital technology for solutions to these present needs and our future hopes.

Digital is a paradigm shift. Now that we have seen it we can never go back.

REVIEW QUESTIONS
1. What is the difference between the matrix, a pixel, and a TFT?
2. What function does flat-fielding provide?

References
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