# CHAPTER 3: DIGITAL IMAGING IN DIAGNOSTIC RADIOLOGY

## 3.1 Basic Concepts of Digital Imaging

Unlike conventional radiography that generates images on film through chemical processing, digital radiography generates images through electronic processing. The creation of the electronic image involves several steps (Figure 3-1). First, the patient is positioned in front of detectors that record the x-ray intensity transmitted through the patient. All electronic detectors produce an analog signal which varies continuously and which depends on the amount of radiation received by the detector. In most modern electronic imaging systems, the analog signal from the detector is transformed into a digital signal, that is a signal that has discrete, rather than continuous values. An example of one type of digital image processing system is given in Figure 3-2. In this system an analog-to-digital converter (ADC) performs the transformation from analog to digital. The digital signal is sent to a computer or digital image processor that can analyze, transform, or display the image. The digital image can be recorded on media such as magnetic tape, magnetic disk, or optical disk. The digital image signal also can be transformed back into an analog signal (Figure 3-2), using a digital-to-analog converter (DAC), for display on a conventional video display terminal.

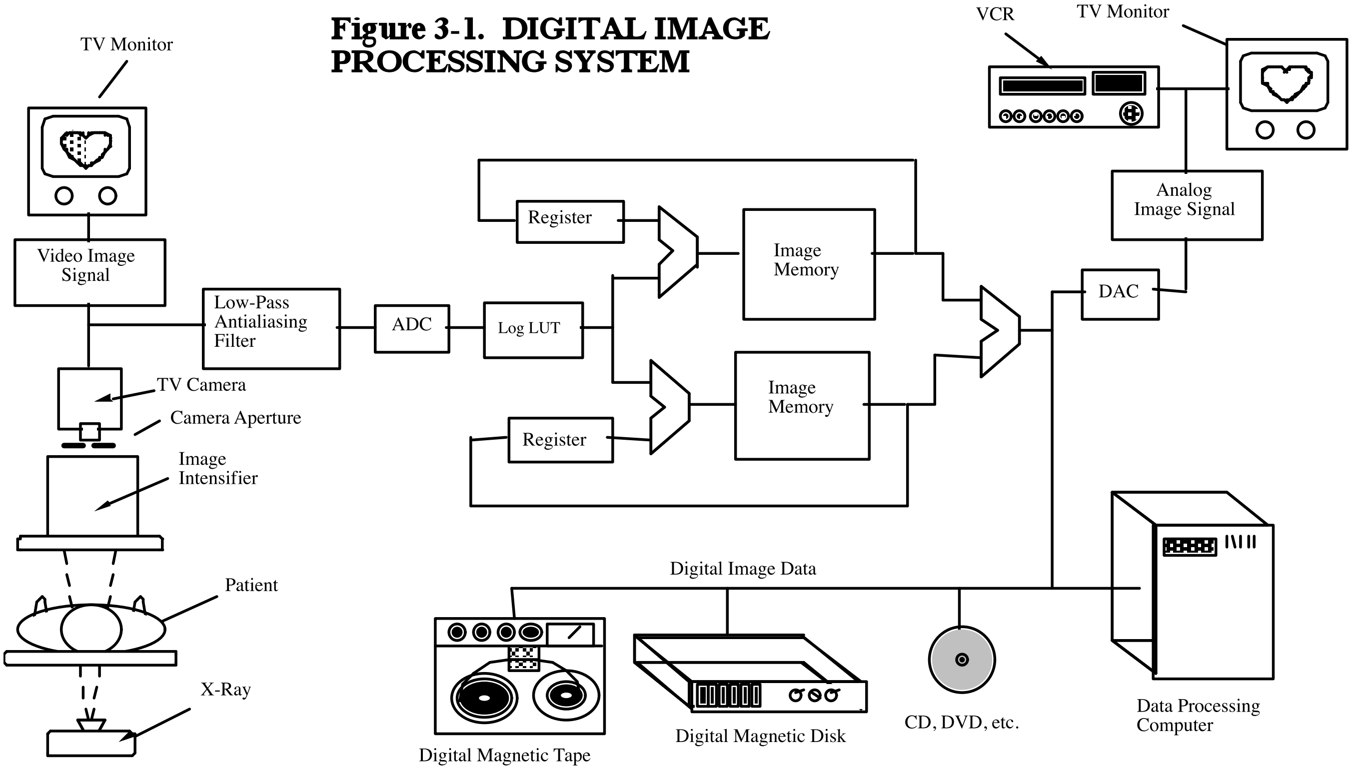


**Figure 3-1. DIGITAL IMAGE PROCESSING SYSTEM**

The image processed and stored in a digital image processor is a two-dimensional array of numbers and is "digital" or discrete in two respects (Figure 3-3). First, the digital image is discrete with respect to its spatial organization. If you look at a digital image with a magnifying glass, you will see it is composed of little gray squares or cells arranged in a rectangular or square array (Figure 3-3). These cells are called "pixels", an abbreviation for "picture element". The pixel is the smallest unit in the image and its size in medical images must be chosen carefully to retain as much detail as possible. An image with M

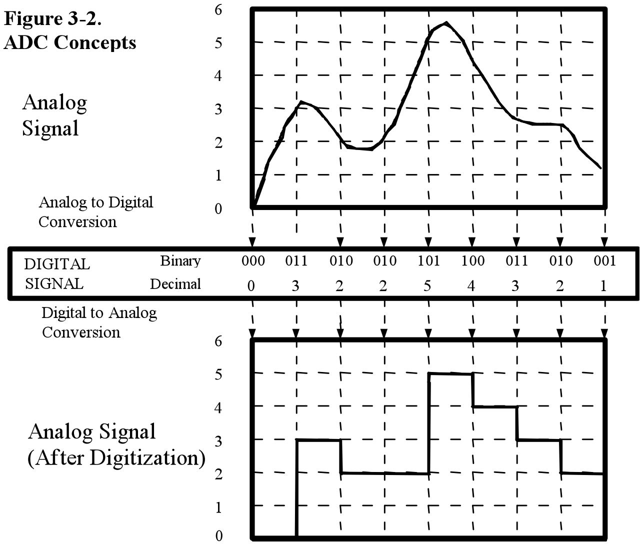
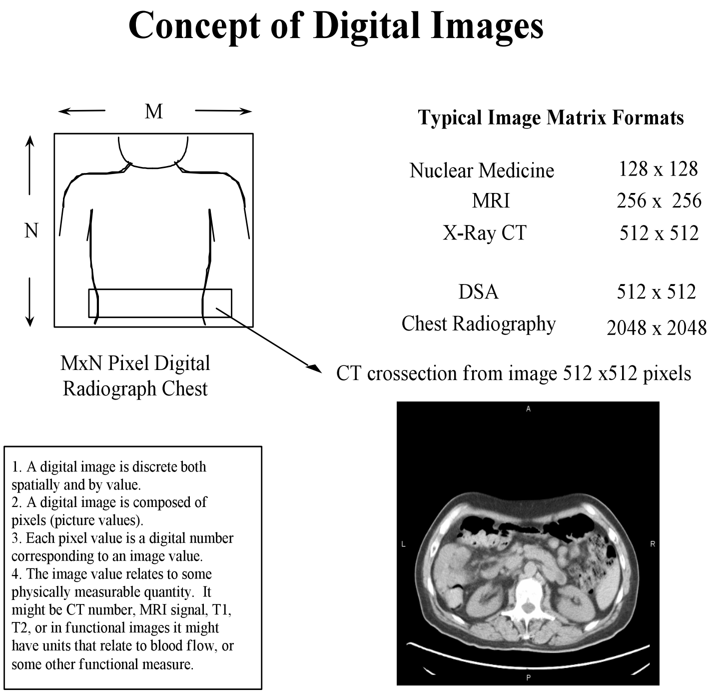


**Figure 3-2.**
**ADC Concepts**

columns and N rows of pixels is commonly referred to as an "M x N" (pronounced "M by N") image. A typical x-ray CT image is 512x512, although some systems now produce 1024x1024 images; many investigators believe that a 2048x2048 or greater array of pixels is required for chest radiography.

In addition to having discrete spatial information, the digital image also is discrete with respect to the pixel (or gray scale) value. The brightness in a digital image does not change from black to white with continuous shades of gray as it does in a normal photograph (Figure 3-3). Rather, the gray scale jumps in small increments of gray from black to white. Each level is represented using an integer value with the smallest number representing black, the largest number representing white, and intermediate numbers representing shades of gray. As in all digital computers, these integers are processed and stored in binary (base 2) form. Therefore, a digital image is an array of binary numbers where each number is a pixel value.



**Typical Image Matrix Formats**

| | |
|---|---|
| Nuclear Medicine | 128 x 128 |
| MRI | 256 x 256 |
| X-Ray CT | 512 x 512 |
| DSA | 512 x 512 |
| Chest Radiography | 2048 x 2048 |

1. A digital image is discrete both spatially and by value.
2. A digital image is composed of pixels (picture values).
3. Each pixel value is a digital number corresponding to an image value.
4. The image value relates to some physically measurable quantity. It might be CT number, MRI signal, T1, T2, or in functional images it might have units that relate to blood flow, or some other functional measure.

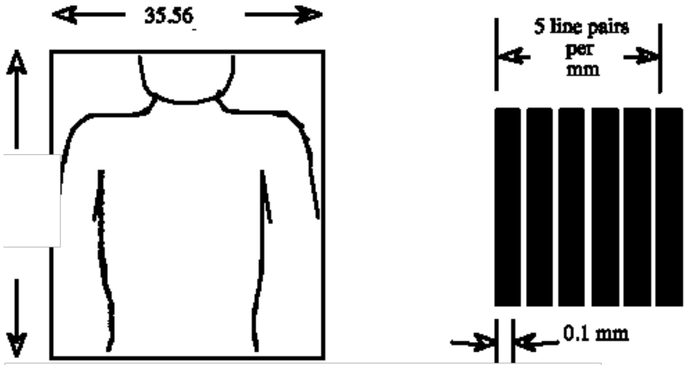
Figure 3-3. Image Pixels

Before continuing with our discussion, we will define the terms "bits", "bytes", and "kilobytes", which are commonly used to describe the characteristics of digital images and image processors (Figure 3-4). A "bit" is a "binary digit", and a binary number system uses only two binary digits (or "bits"), 0 and 1, just as our ordinary decimal (base 10) number system has ten decimal digits from 0 through 9. Typical medical images require 10 to 12 bits per pixel; a 10 bit image has 1024 (or $2^{10}$) different levels of gray while a 12 bit image has 4096 (or $2^{12}$) different gray levels. Instead of talking about bits, often it is more convenient to talk about a "byte" which is 8 bits. You probably have heard the term "kilobyte" and assumed logically (but incorrectly) that a "kilobyte" was 1000 bytes. Actually, a kilobyte (abbreviated "kbyte") is 1,024 ($2^{10}$) bytes, and 327,680 bytes is exactly 320 kbytes. Digital memory requirements for medical radiography usually are specified in terms of megabytes.

**Figure 3-4. ELEMENTARY DEFINITIONS**
1 bit = 1 binary digit
1 nibble = 4 bits
**1 byte = 8 bits**
1 word = 2 bytes (generally)
1 kilobyte (kbyte) = $2^{10}$ bytes = 1024 bytes
1 megabyte (Mbyte) = $2^{20}$ bytes =1024 kbytes
1 gigabyte (Gbyte) = $2^{30}$ bytes =1024 Mbytes

The digital sampling requirement for chest radiography is illustrated in the following example:

> Example 3-1: A chest radiograph is 14 inches by 17 inches in area (Figure 3-5). Assuming that we digitize the chest film with 16 bits (2 bytes) per sample, with a sampling frequency that preserves the inherent spatial resolution in the chest film (5 line pairs per millimeter), calculate the memory required to store the chest radiograph in digital form.



Need 10 pixels/mm to preserve spatial resolution of radiograph

Figure 3-5. Resolving Power

> Solution: A "line pair" consists consists of a dark line adjacent to adjacent to a bright line, and is and is analogous to one cycle of cycle of a square or sine wave. wave. If we want to preserve the preserve the 5 lp/mm (line pairs (line pairs per millimeter) resolution of the chest film, we film, we need 10 samples (or (or pixels) per millimeter (i.e. 5 (i.e. 5 pairs of a bright pixels pixels next to a dark pixels). pixels). With 10 pixels/mm pixels/mm pixel spacing is then 0.1 mm. Converting to metric units, the 14” x 17” chest radiograph has dimensions of 35.56 x 43.18 cm, and requires 3556 x 4318 pixels to preserve the fundamental spatial resolution of film. Since each pixel is represented by 16 bits ($2^{16}$= 65536 gray shades) or 2 bytes, the number of bytes needed to represent the chest radiograph is

$$\text{Number of bytes} = 3556 \times 4318 \times 2 = 30{,}709{,}616 \text{ bytes} = 30{,}000 \text{ kbytes} = 29.3 \text{ Mbytes}$$

> Approximately 100 million chest radiographs are taken every year in the United States, virtually all of which are retained in radiology file rooms for medical-legal reasons. Storage and information retrieval difficulties can arise if chest films are stored digitally without some form of compression.

## 3.2 Sampling Requirements

A digital image is formed by spatially "sampling" an analog or continuous image. Digital encoding of row and column locations of pixels differs for different types of imaging systems. Some form of analog-to-digital conversion (ADC) is used to convert analog image signals to digital pixel values. In scanning systems ADC of time is used to generate a to encode location. For example, in the digitization of a radiograph using a laser scanner, the laser and photodetector are swept across the film with a uniform speed. Spatial-to-temporal encoding occurs because the analog signal from the photoreceptor generated at different times represents density information from different locations on the radiograph. In other imaging modalities such as gamma cameras in nuclear medicine x-y locations are determined in analog form and ADCs are used to convert these to digital x-y locations. Systems using an array of detectors provide image row/column sampling based on the spacing and size of individual detectors.

An important consideration in digital imaging is that the sampling frequency (samples or pixels/distance) must be high enough to preserve important information in the image. In other words, how many pixels do we need per unit distance so that important spatial information in the analog image is not lost when it is digitized? Theoretically, this question is rather easy to answer. If we represent image information in the frequency domain by taking the Fourier transform of the image, we can determine the maximum spatial frequency containing important image information. Shannon's Sampling Theorem specifies the sampling frequency needed to preserve this information.

> Shannon's Sampling Theorem: If the maximum spatial frequency in an analog signal is $f_{max}$ (**cycles/mm**), then the signal must be sampled with sampling frequency ($f_s$) of at least $2f_{max}$ (**samples/mm**).

Note the difference in how we specify the analog signal as cycles/mm and the sampling frequency as samples/mm. Also, in medical imaging we often use line pairs/mm (lp/mm) instead of cycles/mm when referring to the analog frequency. The rationale for the 2X sampling requirement can be seen intuitively by considering sampling of sine waves. Assume we have a sine wave of frequency $f_0$ that is sampled at a sampling frequency of $f_s$. As can be seen in Figure 3-6, when the sampling frequency equals the frequency of the sampled sine wave, values of all sampled points are equal. Our digital signal in this case has spatial frequency of zero. The magnitude of the sampled value depends on the amplitude of the sine wave where the samples are started. Similarly, if the function is sampled at some frequency $f_s$ where $f_0 < f_s < 2f_0$, the sampled sine wave will have a frequency lower than $f_0$. Only when $f_s \geq 2f_0$ will we correctly capture the frequency of the original sampled sine wave. Additionally, to accurately sample the amplitude of the sine wave oversampling (4-10X) is often used, which is common practice for audio CD recordings.

The sampling frequency needed to preserve the spatial frequency information of the sampled signal is called the "Nyquist rate", and the necessity of sampling at twice the maximum frequency of the signal is called the "Nyquist condition". These follow from the Shannon Sampling Theorem. If the Nyquist condition is not met a complex signal after sampling will contain false periodic signals (called aliases). The frequency of an aliased signal is always less that that in the analog signal. It can be shown (Chapter 6) that if $f_S$ is the sampling frequency and f some frequency in the analog signal, then f will alias to a lower frequency $f_{alias}$ when $f_s < 2f$, and the lower frequency is determined from the following equation:

$$f_{alias} = |n \cdot f_s - f| \tag{3-1}$$

where n is an integer applied to ensure that $f_{alias} < f_s/2$. For example, if an analog signal with a frequency of 60 Hz is sampled at a rate of 70 Hz (here n = 1), the aliased signal will have a frequency of

|70-60| = 10 Hz. So what would $f_{alias}$ be if $f_{sample}$ were 40 Hz? For this example the analog signal must be sampled at twice its frequency (i.e. 60x2 =120 Hz) to prevent aliasing. We will return to the issue of aliasing later, after we have developed more mathematical tools to model the effect of aliasing in digital medical images.

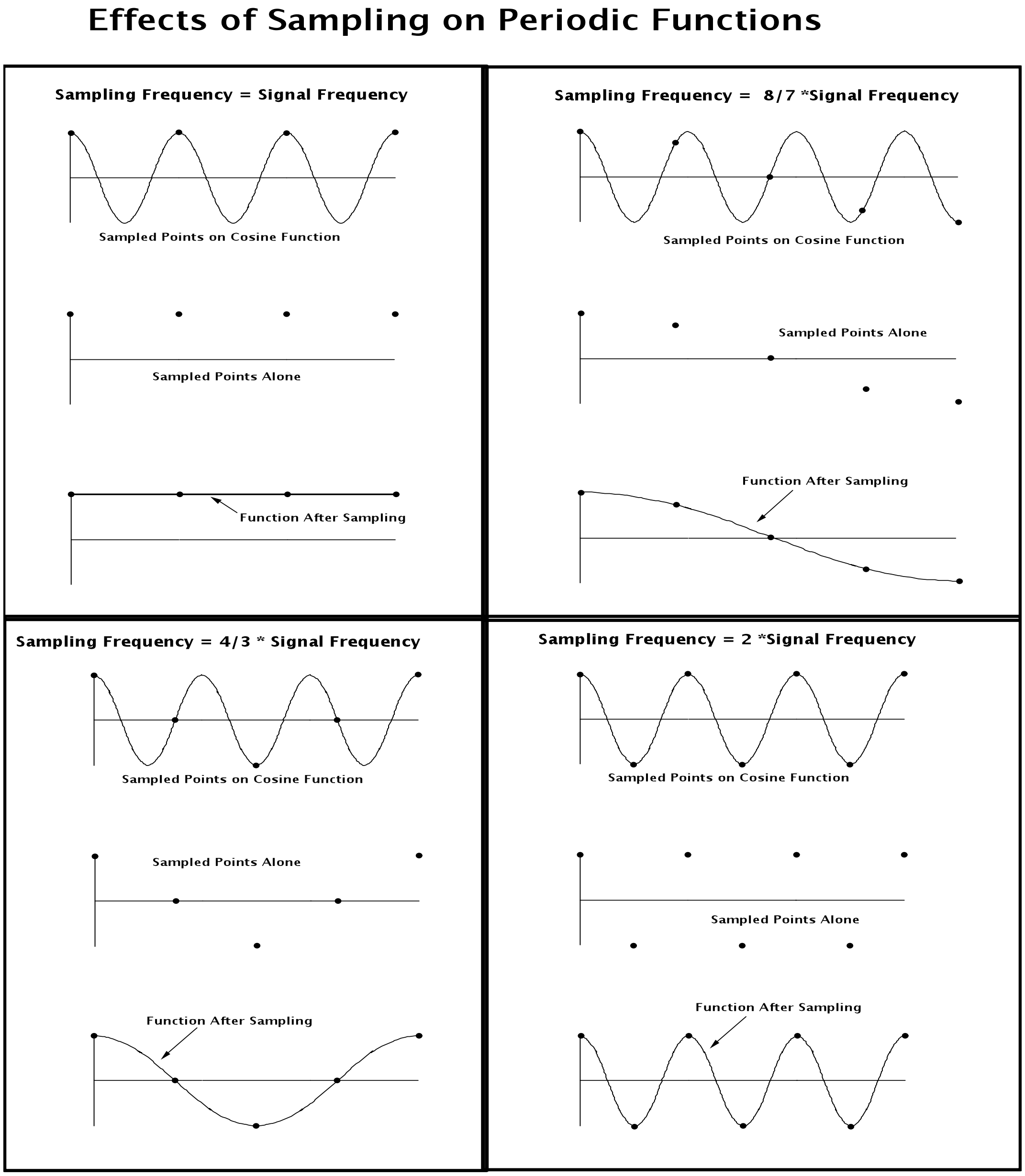


**Figure 3-6**. In digital sampling, the frequency of an analog signal is faithfully reproduced only if the sampling rate is at least twice that of the maximum signal frequency. At lower sampling rates, the approximated function will contain false signal frequencies. The introduction of these false frequencies is called “aliasing”.

In this example the signal frequency is 3 cycles/mm. Sampling for upper left example is 3 samples/mm; upper right is 3-3/7 samples/mm; lower left is 4 samples/mm; and lower right is 6 samples/mm, i.e. sampling to preserve the analog signal’s frequency.

## CHAPTER 3: HOMEWORK PROBLEMS

1. The Japanese revere Beethoven's Ninth Symphony, especially Beethoven's musical rendition of Schiller's great "Ode to Joy" in the fourth movement which celebrates the potential of humanity living together with love and peace. It is not a coincidence that the compact disc was designed by Sony so that Beethoven's Ninth Symphony would fit on a single side, providing a recording that could be played without interruption. For purposes of this analysis, we will assume that the compact disc stores a digital record of the amplitude waveform forming the musical sound.

   (a) Technical specifications indicate that most compact disc players are capable of a signal-to-noise ratio of 96.3 dB. It is more accurate to state that the dynamic range (ratio of loudest possible sound to softest sound) is 96.3 dB, and that this dynamic range limitation is provided by the digitization of the signal. Show that this dynamic range requires 16 bits assuming that 1 bit is used to record the softest sound and 16 bits is used to record the loudest sound.

   (b) On a compact disc, the music is digitized at a sampling frequency of 44 kHz. Why is this sampling frequency required if the human auditory system is capable of hearing sounds only in the range of 20 Hz to 20 kHz?

   (c) How many bytes does it take to record Beethoven's Ninth Symphony (approximately 1 hour) on a compact disc?

   (d) How much compression would be needed to completely store this symphony on a 64-Mbyte USB RAM storage device in MP3 format? How might the quality of the sound differ when compared to the uncompressed version?

2. In the plane of the detector, what spatial frequency can be recorded by a 512x512 pixel digital fluoroscopy system with a 150 mm by 150 mm receptor?

3. Most radiographs are obtained by placing a "grid" between the patient and image receptor. The grid is composed of thin strips of lead separated by a material (plastic, aluminum, or carbon fiber) that are transparent to x-rays. Therefore, the grid reduces scattered radiation emerging from the patient which would degrade the image, while allowing the primary photons to be transmitted to the film.

   A 14" by 17" chest radiograph is recorded with a grid having 100 lines per inch where the width of the lead strips is equal to the width of the material between the lead strips.

   (a) If the chest radiograph is digitized with a 2048 x 2048 image matrix, explain why aliasing will be produced. What will be the frequency and the appearance of the aliased signal?

   (b) What is the spatial frequency of the digital sampling that will avoid aliasing? What is the digital image format and the pixel size (in inches) that corresponds to this digital sampling frequency?

4. In digital subtraction angiography, an analog video signal is converted to a 10-bit digitized signal. However, the video signal can have a bandwidth which exceeds 7.5 MHz, requiring the use of a low-pass "antialiasing filter" to condition the signal before it is digitized to a 512x512 format with an analog-to-digital converter. Assume that the video frame (one image) consists of 525 lines, with a frame time of $\frac{1}{30}$ sec, and that each line of the frame is digitized with 512 samples.

   (a) If no antialiasing filter is used, calculate the temporal frequency of the aliased signal produced in the digitized signal.

   (b) Calculate the bandwidth of the low-pass filter which can be used to prevent aliasing in the digital image.