1.1 Introduction to Digital Radiography

Digital radiography (DR) involves the electronic measurement of the pattern of X-ray transmission through the patient with subsequent conversion of this electronic transmission into a digital file that is viewed on a computer workstation. The term DR is often applied incorrectly to any image that is generated electronically. Although the process is similar to a digital photograph, obtaining a digital photograph of radiographic film is not DR. DR involves the use of two major types of technology: computed radiography (CR) and DR.

The advantages of DR over conventional film radiography include financial, image quality, and technical benefits. In general, there is a large capital expense when making the transition to DR. However, there will be subsequent financial savings on films and processing equipment/maintenance. Less physical space is required for archiving stored images and there is no requirement for a dark room resulting in square footage savings in the hospital. Digital images are capable of displaying a wide range of attenuation of tissues on the same image. This will translate into fewer images needed compared to analog (conventional) film. In addition, DR has greater tolerance to exposure factors, resulting in fewer retakes due to suboptimal technique.

Patient throughput is often increased with DR compared to analog systems. The digital radiograph can be manipulated (post processing, e.g. zooming, gray-scale adjustments) with the viewing software to maximize diagnostic quality. Lastly, digital images can be viewed at any location in the hospital or transmitted off-site for rapid interpretation or referral. The main disadvantage with direct digital format is the tendency of personnel holding the patient to not follow proper radiation safety protocols. Human hands should never be in the primary beam even when lead gloves are worn. Personnel should not crop hands out of an image prior to sending it to a viewing station. Care should be taken to correctly position patients to avoid excessive retakes and unnecessary exposure to radiation.

The following sections will give a brief overview of DR. This will include the components of the digital file, digital radiographic hardware, comparisons of digital versus analog imaging, and image storage.

1.2 Digital Image File

The digital radiographic image is a computer file that contains the pattern of X-ray transmission from the patient. This file is commonly stored in a DICOM format. DICOM is an acronym for Digital Imaging and Communications in Medicine. This format was derived for consistency and to ensure connectivity between imaging devices [1,2], and contains embedded information, including the manufacturer of the device, date, and time of image acquisition, patient demographics, acquisition parameters, operator identifiers, and various other image information needed for medico-legal reasons [2,3]. This added information is referred to as the DICOM header (Figure 1.1) and helps to ensure security and prevent fraud. Some less expensive digital equipment may produce images in other formats, but these are typically inferior for viewing and their use is discouraged for diagnostic interpretation due to liability concerns.

A digital image is composed of picture elements, termed pixels. Pixels are arranged in rows and columns into a geometric matrix (Figure 1.2). Each pixel has a specified shade of gray. The more pixels in a digital file, the larger the matrix size and ultimately the larger the file size [4].
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A typical uncompressed digital thoracic radiograph has a size of approximately 12 megabytes (MB) [3].

The spatial resolution of a digital image is directly related to the size of the pixels and how small an object can be detected. The pixel size is determined by the digital radiographic hardware. For a same size image, the more pixels available, the greater the spatial resolution (Figure 1.2). Thus pixel size and number are important factors in image quality. A way of measuring the spatial resolution of an image, acquisition equipment or viewing station is to compare the pixels per inch value (total number of pixels divided by the surface area of the image). In addition to pixel size, the bit depth of the pixel is important to image quality. Bit depth refers to the number of gray shades that can be stored in a pixel. Computer files use a binary notation to assign a gray shade to a pixel. A one‐bit system would use only digits 0 and 1, assigning black to 0 and white to 1. The maximum number of shades of gray that could be stored is equal to \(2^n\), where \(n\) is the number of bits of computer memory. For example, an 8-bit system could store 256 shades of gray per pixel \((2^8)\) whereas a 16-bit system could store 65,536 shades of gray \((2^{16})\) [1,4,5]. Many digital systems are 12–14-bit systems. The human eye can only perceive about 50–100 shades of gray. However, the digital image can be manipulated to make use of all of the shades of gray, thus improving the diagnostic yield of DR.

1.3 Digital Radiographic Hardware

There are two main types of digital radiographic acquisition hardware: CR and direct DR [6]. Both types make use of the conventional X-ray tube and X-ray table.

1.3.1 Computed Radiography

Computed radiography was the first digital radiographic system to come to market. Like film-screen radiography, CR makes use of an imaging cassette which contains a photostimulable phosphor plate (PSP) rather than film. They are used with X-ray machines just as a regular film-screen cassette is used on a table top or in the Bucky tray (Figure 1.3).

During exposure, the X-ray attenuation pattern of the patient is stored as a latent image within the PSP. Following exposure, the CR cassette is then placed in a plate reader (Figure 1.3), which is similar in size and appearance to a small automatic film processor. The PSP is extracted from the cassette and scanned to produce a digital image. “Processing” also restores the PSP to its previous state. The cassette is then ejected from the reader and ready to use on the next patient [1,4,5]. The “processing” time for typical veterinary systems is in the range of 1–2 minutes.

Computed radiography systems can provide good-quality digital radiographic images and are typically less expensive than DR systems. Furthermore, if a cassette is damaged, it can be replaced inexpensively, unlike a DR plate. Because CR makes use of a cassette, it is familiar to those who have been using film-screen systems and provides greater flexibility than many DR systems. The biggest perceived disadvantage for CR is the requirement for processing and the noninstantaneous display of the image after acquisition [1].

1.3.2 Direct Digital Radiography

Digital radiography involves technology that produces an almost instantaneous image without the need for a processing stage. This provides time savings compared to conventional film radiography as well as CR. There are three main types of DR systems: indirect flat panel, direct flat panel, and charge couple device (CCD) detectors [1,4,5].

Indirect flat-panel detector systems use light as an intermediate step in image formation. A scintillator (usually cesium iodide or gadolinium oxysulfide) is built into the flat-panel detector [5]. When struck by X-ray photons, the scintillator will emit light which is ultimately converted to a digital image [4,5]. These systems are capable of good resolution and bit depth in the range of 14.
Direct flat-panel detector systems use a semiconductor material that stores energy in proportion to the incident X-ray intensity (Figure 1.4). The absorbed X-ray energy is directly converted into charge in the detector with no intermediate step (i.e., light) [1,4,5]. This stored energy (charge) is read, processed, and digitized. Like the indirect flat-panel systems, these systems usually have a bit depth in the range of 14.

Charge couple device detectors (CCD systems) form images from visible light. A scintillator produces light when struck by X-ray photons. This light is then coupled and channeled on to smaller light-sensitive sensor (CCD chip).

Figure 1.2  Lateral radiograph of a feline patient showing a changing matrix and pixel size. As the size of the pixels is reduced and the matrix size is increased, image resolution improves. For the same size image, the more pixels that are present, the greater the spatial resolution. Image (a) is severely limited by the large pixel size and small matrix, being nondiagnostic. There is a gradual increase in the number of pixels and decrease in the pixel size from image (a) to image (d). Notice how the L marker in the lower right corner of image (d) has sharper margins and is more clearly delineated compared to image (b) and (c), emphasizing the importance of pixel and matrix size.
Figure 1.3  CR system. The CR cassette containing the photostimulable phosphor plate (PSP) is in the plate reader ready to be processed. During processing, the PSP containing the latent image will be exposed to a helium–neon laser resulting in light emission. The emitted light will be collected, filtered, and converted to an amplified signal that is ultimately digitized by the computer into a digital image. The PSP is erased and then inserted into the cassette and ejected from the plate reader.

Figure 1.4  Direct flat-panel DR system. The DR plate in this case is wireless and housed in the Bucky tray during exposure. With direct flat-panel DR systems, the absorbed X-ray energy is directly converted into a charge in the detector with no intermediate light step. The stored energy is then read out directly by the thin-film transistor (TFT) array and converted to a digital image. This results in near-instantaneous image after exposure.
The CCD chip accumulates electronic charge from the light which is read out and converted to an electronic file. The CCD chip is small relative to the light output from the intensifying screen and thus the light needs to be focused onto the CCD chip [1,4]. Because of the geometry of this system, there will be light distortion that leads to image degradation. As a result, image quality is typically inferior to a flat-panel DR system or good-quality CR system. Furthermore, due to the design features of this system, it cannot easily be retrofitted into existing radiology equipment. This necessitates purchase of a new X-ray machine if this technology is chosen.

1.4 Review Monitors (Image Display)

In DR, the image is viewed on a computer screen. Monitor quality will influence the accuracy of interpretation of the digital image. The majority of modern computer monitors are flat-panel detectors; these include a variety of technologies such as liquid crystal display (LCD), light-emitting diode (LED), or thin-film transistor (TFT) monitors. Flat-panel monitors can be monochrome (gray scale) or color. Dedicated medical-grade monochrome monitors are characterized by superior brightness, contrast ratio, and resolution (Figure 1.5). Unfortunately, this comes with a cost which may be prohibitive in some circumstances. This cost can range from $5000 to $15000 (www.necdisplay.com/solutions/healthcare/5).

The brightness of a monitor is termed luminance [1,4,7]. Conventional view boxes for film-screen radiography are about 10 times brighter than a high-luminance medical gray-scale monitor and 30 times brighter than a typical color monitor [4]. The monitor brightness relates to how bright a white screen is. This translates into a bright screen being able to display a wider dynamic range of shades of gray. The contrast ratio is a ratio of the luminance between the whitest shade displayed and the blackest shade displayed. Usually a higher contrast ratio is preferred [7]. The spatial resolution (pixel matrix) of a monitor can affect how well an image will appear on the screen. It is usually expressed in terms of megapixels (MP). Most personal computer monitors range from 0.75 to 2 MP. Medical-grade

Figure 1.5 Radiology viewing station. There are two flat-panel 21 in. gray-scale medical monitors showing a feline thorax. The additional adjacent computer station is used to access medical records.
monitors range from 2 to 6 MP [7]. A 21 inch 3 MP monitor will commonly have a 2048×1526 pixel matrix. This level of resolution approximates the average resolution of most digital radiographs. This means that all the digital information is displayed fully without having to magnify the image.

Although there is a clear advantage to medical-grade gray-scale monitors, due to the expense it is difficult to justify having them throughout the hospital. Consumer-grade color LCD monitors are generally considered adequate for viewing images in exam rooms and surgery suites [7]. It is advisable to have at least one medical-grade gray-scale monitor in a dedicated reading area of the hospital for diagnostic interpretation of radiographs.

1.5 Comparison of Digital Versus Analog Imaging

There are many advantages to digital imaging when compared to traditional screen film systems such as reduced expendable supply cost, consolidated image storage, and increased image portability and rapid referrals. In addition to these more obvious benefits, perhaps more importantly are the advantages in the image themselves. These include exposure latitude and contrast along with image processing [1].

With conventional radiography, the relationship between exposure and optical density (blackness of the film) is known as the characteristic curve. This curve is sigmoidal in shape (Figure 1.6a). If the film is under- or overexposed, information is lost. The characteristic curve defines the useful exposure range to achieve the appropriate optical density [4,5]. With a digital system, the characteristic curve is linear rather than sigmoidal, meaning that there is no toe or shoulder region of the curve where information is lost (Figure 1.6b). This equates to a greater exposure latitude resulting in fewer image retakes due to improper technique [1,4,5]. This wide exposure latitude does not mean that over or underexposure is not a problem, however. If a digital image is underexposed, the image will appear grainy (Figure 1.7a). If the image is significantly overexposed, the detector will become saturated (Figure 1.7c). At this point, the computer will assign this the maximum pixel value (black) which will result in some parts of the image being absent. Fortunately, these errors in technique are usually only evident with extreme technical errors.

Contrast resolution or contrast optimization is the ability of a system to display thick and thin regions of anatomy suitably in one image [1]. With conventional radiographs, it is very difficult to radiograph a patient’s body part that had a variably thick anatomic region. For example, if the technique is set to image the lumbar spine/pelvis, the detail in the abdomen is often decreased due to overexposure (too dark) and conversely, if the technique is set for the abdomen, the detail for the osseous structure is often decreased due to underexposure (too white). With DR, the wide range of anatomic thickness can be compensated for by the computer system. This translates into a single radiograph that shows adequate detail for both the thicker and thinner

Figure 1.6 Diagram illustrating the principle of exposure latitude. In both examples, film blackness is plotted as a function of exposure. The area in yellow represents underexposure, the green one adequate exposure and the red one overexposure. (a) Because the exposure (characteristic curve) for screen-film radiography is sigmoidal in shape (blue curve), small changes in exposure technique result in marked changes in film blackness. There is only a narrow range of exposure technique that leads to suitable images. (b) The exposure (characteristic curve) for digital radiography (red curve) is linear with a much shallower slope. This allows for a much wider range of exposure technique that results in adequate film blackness.
1.6 Image Storage

Once the digital image is made, it must be stored. This can be either off-line (CD, DVD, external hard drive) or online (central storage). An online archiving system known as a picture archiving and communications system (PACS) is used for secure storage, transfer, and retrieval of images (Figure 1.8) [2,8]. The basic components of a PACS system include the imaging modality (X-ray machine, ultrasound, CT, MRI), an archive server, routing software, and associated viewing stations. This setup is variable, customizable, and expandable to accommodate the size of the clinic and the workflow [8]. Some PACS systems can be integrated into the practice management systems. Although this is an ideal situation, it is not widely available at this time.

For safety purposes, it is highly recommended to regularly back up the PACS information to a remote online location or an off-line storage such as a hard drive. Such recovery files may be needed in case of computer, network, or hard drive failure. Keep in mind that these files are likely to contain part of the patients’ legal medical records.

anatomic parts simultaneously. This is perhaps one of the biggest advantages of DR.

While conventional film cannot be “post processed” beyond the use of a hot light or magnifying glass, post-processing features of the DICOM viewing software allow the user to make changes to the appearance of the final image. These features include the scale of contrast, magnification, image orientation, and many other features, depending on the software. This flexibility maximizes the viewing options for the clinician and in doing so, improves interpretation accuracy. There are a variety of DICOM viewers available such as eFilm®, K-PACS®, ClearCanvas®, and OsirX, to name a few.

Figure 1.7  Digital radiograph of an anatomy skull showing exposure variation. Although digital radiography allows for wide exposure latitude, the images can still suffer from exposure errors. (a) Underexposure results in fewer photons interacting with the digital plate. As a result, system noise becomes more apparent and the image appears grainy. Any attempt to manipulate the image through the viewing software will amplify the system noise and the graininess will persist. (b) Correct exposure. (c) Overexposure (extreme) results in the digital detector becoming saturated. At this point, the computer will assign the maximum pixel value (black). This translates to areas being displayed without any discernible anatomy. This is often referred to as a clipping artifact. No amount of post processing will recover this information.
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Figure 1.8  Components of a PACS system. Images in DICOM format are transferred from the acquisition device to the central server. Clinicians at remote locations (exam room) can retrieve the images from the server for interpretation or to show the client. The central computer should not be relied on as the sole image storage device. An offsite back-up is essential in case the server crashes.
References
