

Chapter 4

Digital Radiography and Its Limitations

Digital radiography (DR) is a term used to describe general radiography when the radiographic images are in digital form and are capable of being displayed on a computer monitor. There are several methods of capturing DR images. These methods include computed radiography (CR), digital fluoroscopy (DF) and flat panel radiography systems such as direct radiography and indirect radiography. CR is currently the most commonly used method of capturing DR images (MacMahon *et al*, 1991; Samei *et al*, 2001; Wilson *et al*, 1994). The basic principles of CR have been discussed in Chapter 2. These principles and the principles of direct radiography, CT projection radiography and DF are further described by Bushong (2001), Bushberg *et al* (2002), Fauber (2000) and Gunn (2002).

An advantage of CR over film/screen (F/S) radiography is the increased dynamic range and linear response of CR images (Artz, 1997; Balter, 1990; Bushberg *et al*, 2002; Dowsett *et al*, 1998; Schaetzing *et al*, 1990; Weiser, 1997). A brief discussion of this can be found in Chapter 2. According to Vuylsteke & Schoeters (1994), F/S has an exposure range in the order of 100:1. When the linear response section of the S-shaped curve is considered, the exposure range is ten times as small. In contrast, CR has a dynamic range of nearly 1000:1 (Vuylsteke & Schoeters, 1994). These dynamic range advantages also exist for DF and for direct and indirect digital radiography.

A further advantage of DR over F/S is that it provides the facility to perform post-processing functions or manipulate the image after it has been acquired. These functions are discussed more fully in Chapter 5. So called “hard copy” display of F/S does not allow the image to be altered once acquired.

4.1 Clinical Uses and Clinical Advantages of Digital Radiography

DR has been in clinical use since the late 1980s. Clinical experience with DR systems has been widely reported (Busch, 1997; de Silva, 1997; Kudo *et al*, 1997; Lindhardt, 1995; Smith *et al*, 1995; Williams, 1997). The use of DR is now extending into non-clinical areas of non-destructive testing (Barber, 2001). The transition from a F/S based general radiography system to DR based general radiography systems has had an impact on many areas of radiographers' practice and roles. These include training, new skill attainment and changes to work patterns (Artz, 1997; Cesar, 1997; Dzingle, May & Garland, 2001; Schaetzing *et al*, 1990; Williams, 1997). Computed radiography and other DR systems are now widely accepted as image recording media in general radiography.

The clinical use of DR imaging techniques is also well accepted. Comparisons between various DR and F/S general radiographic techniques have been undertaken in many anatomical regions. General radiographic comparisons of the chest have been undertaken by several authors. Müller *et al* (1996c) and Kundel *et al* (1997) suggested that significant improvements in diagnostic performance in chest radiography were evidenced by DR compared to F/S. High attenuation differences in the chest make chest radiography with F/S a highly challenging examination. CR can better meet these challenges with its increased dynamic range over F/S and the potential to manipulate the image after it has been acquired (MacMahon & Vyborny, 1994). Kido *et al* (2000) concluded that DR performed better than F/S in detecting low contrast pulmonary nodules. Both Weatherburn *et al* (2002) and Strozer *et al* (2000) discussed some advantages of DR systems over F/S systems but concluded that there was no significant difference of observers' diagnostic performance between the two systems. Nickoloff *et al* (2002) compared high peak kilovoltage (kVp) techniques for paediatric chest radiographs. They concluded that high kVp chest examinations using CR were comparable to F/S examinations when the latter involved appropriate beam filtration and there had been use of post-processing functions for the CR examinations.

Skeletal anatomical areas have also been the subject of comparisons between DR and F/S imaging systems. In 1991, Wilson *et al* (1991) concluded that CR should not be used exclusively for trauma radiography of the extremities. In a study by of trauma x-ray examination of the cervical vertebra, Wilson *et al* (1994) concluded that CR had distinct advantages in diagnostic performance over F/S. However, no significant differences in diagnostic performance of DR over F/S were found by Strozer *et al* (1998) and Wu *et al* (2000). Strozer *et al* (1998) also stated that dose reduction potential existed with the DR systems of up to 75% with no loss of image quality. Volk *et al* (2000) also concluded that direct DR of the skeleton produced good image quality at a reduced dose over CR and F/S. Both Piraino *et al* (1998) and Ludwig *et al* (2000) examined the image quality of direct DR systems. Piraino *et al* (1998) concluded that the majority of observers (four out of five) preferred the DR image quality to that of F/S. It has also been found that that direct DR image quality was comparable to that of CR and F/S (Ludwig *et al*, 2000). It is now generally agreed that the diagnostic performance of DR is at least equal to that of F/S.

Other anatomical regions have been the basis of comparisons. Comparison between direct DR and CR in radiographic urography examinations was undertaken by Zähringer *et al* (2003). Equivalent image quality and observer performance was reported between two imaging modalities even when DR was undertaken at half of the dose of the CR examinations. Urography was also the basis of comparison undertaken by McCollough *et al* (2001). The main purpose was a comparison of CR and F/S to computed tomography (CT) projection radiography. McCollough *et al* reported that CR and F/S were comparable to each other and superior to CT projection radiography for the delineation of small areas of anatomy and pathology.

Colin *et al* (1998) provided a comprehensive review of the literature on comparisons between CR and F/S systems across all general radiographic examinations. One of their foci between the two systems was diagnostic accuracy. At that time, no clear distinction could be made as to which system provided the higher diagnostic accuracy.

Digital radiography provides either similar or improved clinical performance to that of F/S general radiography. Other advantages of DR over F/S such as dose reduction and post-processing functions add to the clinical improvements.

4.2 Objective Evaluation of Digital Radiography Systems

Low contrast detectability comparisons of CR and F/S using a chest phantom have been undertaken by several authors. Low contrast detectability is evaluated by subjectively determining the smallest objects that can be visualised in a group of objects. All objects in the group have low contrast differences between the object and the background. It is expected that as the contrast between object and background increases, keeping the objects' size the same, detectability will increase. It is also expected that, while keeping the contrast differences the same, as the object's size increases, detectability will increase.

Cook *et al* (1993) used a Lucite phantom with holes of various sizes drilled into layers of the phantom as a low contrast detectability tool. Images of the phantom were subjectively evaluated. CR images were printed to film so that these and the F/S images could be compared side-by-side. Objective measurements of the signal to noise ratio (SNR) were also made. The conclusion was that there was no significant difference in low-contrast detectability between CR and F/S. Rong *et al* (2001) compared direct DR, CR and F/S systems. No significant difference was observed between F/S and CR. The direct DR system showed a significant improvement over both CR and F/S. Images from each system were displayed on film. The DR images were printed using standard clinical chest settings. So-called soft copy viewing was not used. These two studies did not allow observers to view the images under typical clinical conditions, and observers did not have the opportunity to manipulate the DR images.

Lu *et al* (2003) also undertook comparisons of CR and F/S using a contrast-detail phantom. Here CR images were displayed in soft copy format so as to allow post-processing manipulation of the CR images. Low contrast detectability was greater using CR than F/S. A further comparison by Weatherburn & Davies (1999)

compared CR and F/S using a contrast detail test object and allowing CR image manipulation. It was again shown that the wider latitude of CR over F/S provided greater low contrast detectability.

Beute *et al* (1998) compared CR, direct DR and F/S when a chest anthropomorphic phantom was radiographed. The authors used a chest anthropomorphic phantom to simulate clinical chest radiography. Clinical chest radiography exhibits a wide range of exit x-ray intensities due to the large attenuation differences that exist within the chest anatomy. The authors concluded that the greater dynamic range of DR and the image processing operations of contrast and spatial frequency manipulation provided improved image quality over F/S. Schaefer-Prokop & Prokop (1997) also evaluated direct DR, CR and F/S in the radiographic examinations of the chest. In their study both anthropomorphic phantom images and clinical images were compared. Image processing functions were an advantage of direct DR and CR over F/S when assessing chest radiographs. The direct DR method, a selenium based system, was significantly better than other imaging methods in the detection of micronodular opacities. Overall, DR imaging methods were preferred over F/S imaging of the chest. In a wide review of the literature, Freedman & Artz (1997a) also concluded that DR was the preferred radiographic method of imaging the chest.

4.3 Disadvantages of Digital Radiography

Several disadvantages of DR have been reported. The spatial resolution of an imaging system is its ability to accurately represent small objects (Baxes, 1994). Spatial frequencies in F/S general radiography are limited by factors external to the image recording system. Some external factors are the finite size of the focal spot where x-rays are produced and the geometric relationship between the focal spot, the object being imaged and the image recording system (Bushberg *et al*, 2002; Bushong, 2001; Curry *et al*, 1990; Dowsett *et al*, 1998; Thompson *et al*, 1994). A digital image's spatial resolution is determined by the number of rows and columns of pixels in the image (Baxes, 1994). The spatial frequencies of a DR image are also limited by the external factors discussed above. The spatial resolution of a DR image can be measured in pixels per millimetre or in line pairs per millimetre (Bushberg *et*

al, 2002; Bushong, 2001). The spatial resolution of DR image recording systems is lower than that of F/S image recording systems (Schaetzing *et al*, 1990; Artz, 1997; Balter, 1990; Bushberg *et al*, 2002; Bushong, 2001; Weiser, 1997). This lower spatial resolution impacts on the overall spatial resolution of radiographic examinations. Specifically, the sampling frequency of the DR recording system is the limiting factor in determining the spatial resolution of the DR system (Bushberg *et al*, 2002; Bushong, 2001).

The impact of such a lower spatial resolution system on clinical performance is not significant. Clinical performance when using DR compared to F/S was previously discussed and no effect of spatial resolution was reported. The physical spatial resolution of a system cannot be altered once an image has been acquired. The perceived spatial resolution of the digital image can be altered so as to enhance edges or smooth areas within the image. This is described fully in the next chapter.

Another reported disadvantage of DR relates to the displayed image size (Artz, 1997; Buckwalter & Braunstein, 1992). F/S radiographic images are similar in size to the objects being examined, but there is small magnification of the image. Common radiographic practice is to minimise the magnification of the image (Bushong, 2001; Fauber, 2000; Gunn, 2002; Thompson *et al*, 1994). In DR, the viewed image size is a function of the display software and the monitor. Murphey *et al* (1992) explained that reduced size of the displayed image can obscure structures in the image. The use of the zoom function to enlarge the image can overcome this problem.

Direct radiographic image noise results from either internal system noise or from scattered radiation. Inherent system noise is greater in DR than in F/S and is reduced through software algorithms prior to the display of the image. CR and other DR systems are more sensitive to scattered radiation than F/S. The amount of scattered radiation is a function of the energy of the x-ray beam and the anatomy which attenuates the x-ray beam. Scatter can be reduced prior to reaching the image receptor in both F/S and DR systems. The effect of scattered radiation in DR can be further reduced through the use of scatter correction algorithms (Bushberg *et al*, 2002; Bushong, 2001;).

Quantum mottle is an appearance of noise in the radiographic image due to low SNR of the information reaching the image recording system. Statistical fluctuations of exit photon intensities exist when an x-ray beam of homogeneous intensity irradiates a uniform object. When the exit intensity is low, the fluctuations are relatively large compared to the x-ray intensity. The SNR is therefore low. When the exit intensity is high, the fluctuations are relatively small compared to the x-ray intensity, and the SNR is then high. Mottle or so-called “salt and pepper” appearance is seen on the image when the SNR is low. Quantum mottle appearances are present with both F/S and CR systems when the photon exit intensities are low (Bushberg *et al*, 2002; Bushong, 2001; Fauber, 2000; Gunn, 2002).

Artefacts are a potential problem that can reduce the quality of images. DR has artefacts that are not found in F/S systems. Artefacts in CR fall into four main categories (Cesar *et al*, 2001):

1. image plate artefacts
2. plate reading artefacts
3. image processing artefacts
4. operator errors.

An artefact that mimics pathology can result from the use of spatial resolution enhancement. In DR images, edge enhancement is used to help visualise small anatomical regions within the bone. The edges of a metal prosthesis exhibit a halo effect and appear ill-fitting or loose within the bone when edge enhancement has been used (Cesar *et al*, 2001; Murphey, 1992; Murphey *et al*, 1997; Vuylsteke and Schoeters, 1999). These artefacts are discussed further in Chapter 5.

4.4 Digital Radiography and X-ray Dose

Digital radiography has been the subject of many studies evaluating the radiation doses received by patients as compared to doses received in F/S radiographic examinations. The consensus of the findings is that the dose received by the patient in CR is similar to that of F/S radiographic examinations. Neofotistou *et al* (2005), in a clinical study in Europe, reported that dose comparisons between the use of DR and

F/S were difficult, and no formal conclusions as to dose reduction capabilities of DR over F/S could be drawn. In paediatric radiographic examinations, doses received by the child were lower in F/S than in CR imaging examinations according to Nickoloff *et al* (2002). In an earlier study, Hufton *et al* (1998) stated that dose reduction in the order of 40% could be made by using CR compared to when F/S was used. In that study, image quality comparisons were not made.

A general consensus of recent articles is that the wide latitude of CR compared to F/S has not provided the expected dose reductions for CR. It has been suggested that quantum noise from low exposures used in CR systems limits its dose reduction capabilities. However, dose advantages are gained in direct DR imaging examinations over those of CR and F/S. The reduced dose of direct DR is attributable to the lower noise levels of direct DR over CR and the wider latitude of direct DR compared to F/S (Chotas *et al*, 1993; Dobbins *et al*, 2002; Fischbach *et al*, 2002; Marshall, 2001; Marshall *et al*, 1994; Seibert, Shelton & Moore, 1996; Seifert *et al*, 1998; Vassileva, 2002).

4.5 Limitations of Digital Radiography

DR has many advantages over F/S radiographic techniques. The two main advantages are the increased dynamic range of DR over F/S and the possibility of manipulating the images once they have been acquired. However, spatial resolution is the main disadvantage of DR compared to F/S (Bushong, 2001; Siebert, Shelton & Moore, 1996; Weiser, 1997).

DR has shown improved examination quality over F/S when imaging anatomical regions with large density differences such as the chest, thoracic spine, shoulder, facial bone, cervical spine, thoraco-lumbar spine, hip/neck of femur, femur, feet, hands and horizontal ray examinations of the abdomen. The improved observer performance in such anatomical regions is largely attributed to the increased dynamic range and image manipulation ability of DR (Artz, 1997; Freedman & Artz, 1997a).

The increased dynamic range of DR images implies that all of the anatomy has density values that can be displayed and visualised. Using a broad scale contrast display, all anatomy can be visualised in the image within the displayed range of optical densities. Such images will exhibit low displayed contrast. According to Vuylsteke & Schoeters (1994), the dynamic range is large enough to catch all diagnostic information but this wide range cannot be displayed with acceptable image contrast. Van Metter & Foos (1999) also claimed that with DR imaging it is possible to capture a wide range of x-ray information on a single image. They further stated that the problem of displaying DR images, such that information is adequately visualised while maintaining adequate contrast for diagnostic detail, has remained.

Displayed densities can be altered so as to adjust the contrast and brightness of the image. The basic adjustment of contrast and brightness of the image is achieved through look-up functions in medical imaging called window width (WW) and window level (WL). Changes to WW change the displayed contrast. Changes to WL change the displayed brightness. These functions are fully detailed in Chapter 5.

Narrowing the WW increases the displayed contrast of the image, allowing greater differentiation of small anatomical density differences. With increased contrast, small density differences between areas of anatomy can be visualised with greater ease. The disadvantage is that anatomy with density values outside of the range of the WW will appear either white or black, because the displayed optical density range is narrowed. Anatomical regions with different density values outside of the WW will be indistinguishable from each other. The WL therefore needs to be altered to visualise these anatomical regions at that WW. Multiple manipulations of the WW and WL must be undertaken by the viewer to visualise all the anatomy in the image at an optimal displayed contrast.

Other processing functions may need to be used by the viewer to fully examine the DR image. The use of zoom and pan functions can overcome the display size issues previously noted.

In a study by Kruminski (2002) of medical imaging perception, it was found that radiologists seek a “global impression” of digital radiographic images when they first

examine the image. According to Kruminski, digital displays have the disadvantage of being more complex than F/S images. Although many tools are available to manipulate and process DR images, the manipulation takes time and impedes workflow. Kruminski concluded that presenting high quality images initially to the radiologist would reduce the amount of manipulation required and improve workflow. Koenker and Grover (2002) found that image manipulation on a DR viewing station was time-consuming and hindered radiologist productivity. Kido *et al* (2000) also commented that in daily clinical practice several problems exist with the use of WW and WL functions. They found that the use of these functions increased the time required for diagnosis and also led to an increase of reported false-positive results.

Digital radiographic images are often printed on film, so-called hard copy, for viewing by clinicians who do not have access to DR viewing programs and hardware (Cook *et al*, 1993; Hildestad & Morin, 2002; Kundel *et al*, 1997; Müller *et al*, 1996b; Rong *et al*, 2001; Weatherburn & Davies, 1999; Weatherburn *et al*, 2002; Williams, 1997). The characteristics of display monitors differ from those of film. Printing of the image requires optimisation of its contrast and brightness to display all anatomy at the highest possible contrast (Hildestad & Morin, 2002). Optimisation of the image for printing on film is subjective.

Hard copy display film has disadvantages similar to those discussed in Chapter 2 for F/S radiography. Hard copy devices used in medical imaging are typically multi-format video cameras and multi-format laser cameras (Bushberg *et al*, 2002; Bushong, 2001). The respective films differ in characteristics from each other (Bushberg *et al*, 2002; Bushong, 2001; Siegel *et al*, 1991). The similarity of hard copy films to F/S film is that they all exhibit a characteristic curve. This implies that a limited range of optical densities can be viewed on the hard copy film (Lo *et al*, 1990; Siegel *et al*, 1992; Teslow, 1997; Yin *et al*, 1992). Automatic calibration of the displayed brightness and contrast to match the characteristics of the laser film has been the prime purpose of some studies (Escarpinati, Costa Vieira & Schiabel, 2002; Teslow, 1997).

Spatial resolution is a limiting factor in DR. Spatial enhancement techniques can be used to improve perceived spatial resolution within the image. Care must also be taken to display the image without the enhancement present, to identify any possible artefacts that may be present in the image.

An appropriate method of optimising the displayed or radiographic contrast in an F/S image is to use an appropriate physical tissue compensation filter (TCF). The use and advantages of physical TCFs are fully discussed in Chapters 2 and 3. The use of physical TCFs in DR has not been fully investigated in the literature. Artz (1997) stated that acrylic wedge filters are used for CR imaging where they would be routinely used in F/S imaging.

It is generally accepted that in clinical practice when CR examinations are performed, TCFs are not used (N. Emanuel, 2002; G. Menzies, 2002; A. White, 2002; personal communications). The main reason is that physical TCFs may produce an artefact on the image. The edge of the physical TCF or the air/TCF material interface produces a line on the CR image, and this appearance may be mistaken for an area of anatomy or a pathological appearance. It was also expected that contrast and brightness manipulation tools were available and would be used by the viewer. It was felt by these practitioners that WW and WL functions should replace the need for a physical TCF to be placed in the x-ray beam. The use of WW and WL does, however, have some drawbacks. According to Vuylsteke & Schoeters (1999), a disadvantage of the use of physical TCFs is that they are designed for a single well-defined anatomical shape. When the anatomy deviates from that shape, physical TCFs provide sub-optimal performance.

In the work reported in subsequent chapters, algorithms were developed to overcome the limitations of DR in anatomical regions where large attenuation differences exist. Anatomically shaped radiographic contrast-enhancement masks (RCMs) mimic the features of physical TCFs. The shape and thickness of a RCM is adjustable by the user. The placement of a RCM in the image can be adjusted to suit the anatomy. RCMs are not spatial enhancement algorithms that could produce artefacts in the image. An artefact in shoulder images is produced outside of the anatomy by the RCM. Such artefacts are easily identifiable and would not be confused with

pathology. The use of RCMs and their effect on DR images are more fully discussed in subsequent chapters.

The use of RCMs allows images to be displayed initially with a high level of contrast. Image adjustment and manipulation can still be undertaken as required to further enhance the image. The initial optimisation should reduce the time taken to manipulate the image. The RCM also allows for optimisation of the image prior to printing it to film, and the printed image is at a higher level of displayed contrast than without the use of the RCM. Viewers of the film have an advantage of viewing an image that has a high level of contrast while still showing all of the anatomy.

The potential for manipulation of DR images once they have been acquired, called post-processing, is considered an advantage of DR over F/S methods. Post-processing methods are discussed in Chapter 5.