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Digital radiography detectors – A technical overview: Part 2

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Abstract Digital X-ray detector technologies provide several advantages when compared with screen-film (SF) systems: better diagnostic quality of the radiographic image, increased dose efficiency, better dynamic range and possible reduction of radiation exposure to the patient. The transition from traditional SF systems to digital technology-based systems highlights the importance of the discussion around technical factors such as image acquisition, the management of patient dose and diagnostic image quality. Radiographers should be aware of these aspects concerning their clinical practice regarding the advantages and limitations of digital detectors. New digital technologies require an up-to-date of scientific knowledge concerning their use in projection radiography.

This is the second of a two-part review article focused on a technical overview of digital radiography detectors. This article provides a discussion about the issues related to the image acquisition requirements and advantages of digital technologies, the management of patient dose and the diagnostic image quality.

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Introduction

The transition from traditional screen-film (SF) systems to digital technology-based systems highlights the importance of the discussion around technical factors such as image acquisition, the management of patient dose and diagnostic image quality. Radiographers should be aware of these aspects concerning their clinical practice. New digital technologies require an up-to-date of scientific knowledge concerning their use in projection radiography.

This is the second of a two-part review article focused on a technical overview of digital radiography detectors. This article provides a discussion about the issues related to the image acquisition requirements and advantages of digital technologies, the management of patient dose and the diagnostic image quality.

Image acquisition requirements and advantages of digital technologies for projection radiography

A digital X-ray detector is the key component of a digital radiography system. It has to fulfil several requirements^{1,2} concerning field size, pixel size, sensitivity, dynamic range, internal noise and readout.

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In DR (Digital Radiography), the field or detector size must be large enough for all radiographic examinations. Ideally, it should have an active area of at least 43×43 cm to allow both vertical and horizontal imaging orientations without detector rotation. In CR (Computed Radiography), different cassette sizes with standard dimensions for typical plain radiography are available (e.g. 18×24 ; 24×30 ; 35×43). These cassettes contain the correspondent IP which is used for the appropriate region to be examined.

The maximum spatial resolution of an image is defined by pixel size and spacing (i.e., the pitch or the distance between centres of pixels). Pixel size affects the system resolution and ranges typically from $100\text{--}200\ \mu\text{m}$ in CR (depending on the cassette detector size) and $127\text{--}200\ \mu\text{m}$ in DR detectors. In SF systems, spatial resolution is higher ($25\text{--}80\ \mu\text{m}$) but these systems are limited in their sensitivity and dynamic range, when compared with digital systems.

Sensitivity or latitude must be high enough to allow low-dose operation. Digital detectors that have higher sensitivity or higher detective quantum efficiency values, allows better image quality at all frequencies showing the ability to represent both small and large image structures.

The dynamic range must be enough to cover a wide range of intensities. Typically, digital detectors have a dynamic range of 1:10.000 which is considerably higher than SF systems (1:30). This wide dynamic range allows the digital systems to maximize the number of grey values on the digital image (Fig. 1). This characteristic is a key feature concerning exposure errors. A marked reduction of repeated radiographs and consequent reduced radiation exposure to the patient² is a positive consequence of wide dynamic range in digital detectors.

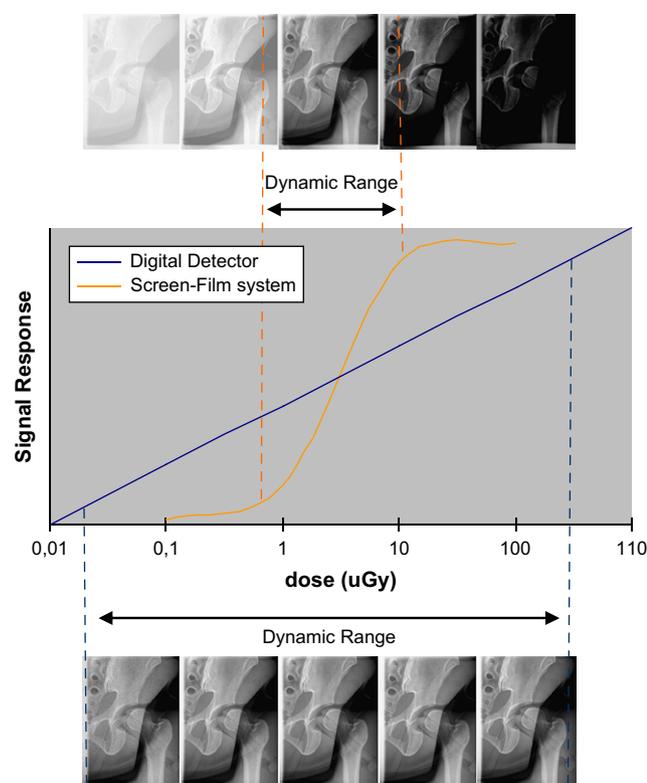


Figure 1 Dynamic Range in digital and SF systems.

Internal noise sources must be small enough to preserve image quality. These noise sources could be related, for example with the capture element, the coupling element, and the collection element of the digital detector.³

The readout time must be fast enough to allow efficient workflow and this will depend on the type of technology: in CR, bigger IPs will have a slower readout than smaller IPs (e.g. 30–40 s); in DR, the readout process could take about 1.3 s.⁴

These requirements are very important in digital X-ray technology because they will affect image quality, dose efficiency and workflow. In fact, digital technologies for projection radiography can offer several advantages when compared with SF systems. The fundamentals and advantages of digital systems are stated by ICRP⁵ and were discussed before in this review.

Management of patient dose

The development of an adequate radiographic technique involves the management of the exposure parameters, the patient's radiation exposure and the exposure on the imaging detector to produce the most accurate diagnosis. This should be accomplished with an optimization of exposures and image quality. When a new digital system or post-processing software is introduced, an optimization programme (for radiation dose) and continuing training should be conducted in parallel.⁵

Exposure optimization should contribute to protect patients from unnecessary exposures and ALARP (*As Low As Reasonable Practicable*) principle should be always kept in mind. This is an important principle because in digital radiology – both CR and DR – examinations can be performed over a wide range of doses and the best images (low noise) are obtained with higher doses.⁵

DR technology based on solid state detectors can achieve a dose reduction in chest and skeletal radiography of up to 33–50% without loss of image quality when compared with a traditional screen-film radiography system^{6,7} due to its high detective quantum efficiency and wide dynamic range. In the field of thoracic and skeletal radiography, flat-panel detectors have the potential for dose reduction compared with conventional SF systems with the same imaging quality.⁸

In a study comparing radiation dose delivered to patients undergoing clinical chest imaging in three different detector technologies, significant differences in the patient radiation dose were found.⁹ The flat-panel detector radiography system allowed an important and significant reduction in both entrance skin dose and effective dose compared with the film-screen radiography ($\times 2.7$ decrease) or computed radiography ($\times 1.7$ decrease) system. In addition, image quality produced by the flat-panel detector radiography system was significantly better than the image quality produced by the film-screen or computed radiography systems, confirming that the dose reduction was not detrimental to image quality.⁹

With a reduction in mAs which is possible in CR systems rather than in FS systems, the CR systems will be able to produce quality diagnostic images with less patient dose than FS systems.¹⁰ These results were recently confirmed in a study where digital techniques allowed diagnostically adequate images to be obtained with substantially lower patient doses than used for SF radiography.¹¹

Image quality in diagnostic radiology

Digital detectors are often cited as offering higher sensitivity, lower intrinsic noise and greater dynamic range rather than traditional SF systems, which opens up new possibilities for dose reduction in clinical applications.² Beyond the characteristics of detectors, the imaging capabilities of digital systems are also determined by signal processing, digital image post-processing and documentation.¹² Although several advantages over SF systems are identified, considerable variations in image quality and effective dose can be achieved among different digital detectors.¹³

Image quality could be evaluated combining the physical characteristics of the imaging system, the overall system performance and observer performance studies.¹⁴ However, a recent review¹⁵ states that the relationship between the results of physical measurements, phantom evaluations and clinical performance is not fully understood.

Table 1 shows a wide spectrum of methods for image quality evaluation.¹⁴ Some of these methods focus on the physical characteristics of the imaging systems and others on subjective assessment of image quality; some are used for the whole imaging chain including the human observer (observer performance) while others are used for parts of the system (typically physical measurements).

This leads to the discussion of the image quality concept in diagnostic radiology. This concept could be virtually understood as a good quality image that fulfils its diagnostic purpose and comprises several methods for image quality evaluation. A good quality image is of major importance to assure an accurate diagnosis and this is – in general – determined by three primary physical image quality parameters¹⁶: contrast, spatial resolution and noise. These quality parameters can be evaluated by objective image quality measurements such as signal-to-noise ratio (SNR), modulation transfer function (MTF) and Wiener spectra (WS). Together they form a basis for the description of image quality which encompasses the three primary physical image quality parameters (Fig. 2).¹⁷

These factors contribute for the measurement of *Detective Quantum Efficiency* (DQE) which is well established as the most suitable parameter for describing the imaging

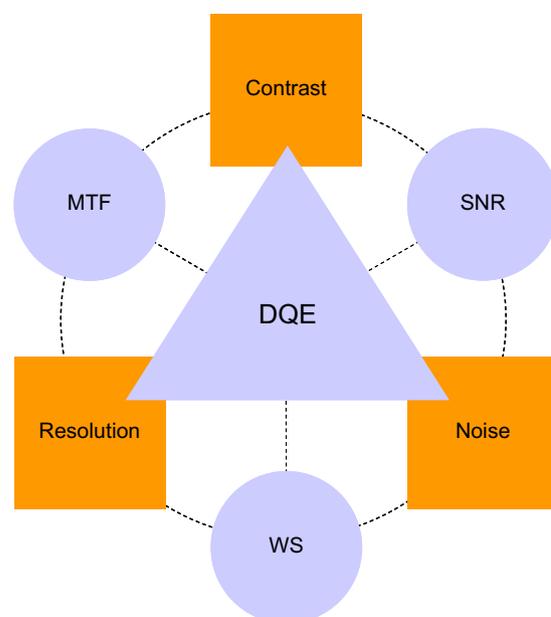


Figure 2 Image quality triangle: relationships between image quality parameters and physical image measurements (adapted¹⁷).

performance of an X-ray digital imaging device.^{18,19} DQE is the measure of the combined effect of the noise and contrast performance of an imaging system, expressed as a function of object detail. DQE combines spatial resolution (i.e., MTF) and image noise (i.e., WS) to provide a measure of the SNR of the various frequency components of the image.¹

Primary physical image quality parameters

Contrast is defined as a measure of the relative brightness difference between two locations in an image.²⁰ The contrast of an imaging system is described by the characteristic response curve of the system. This curve has a typical S-shape for a SF system but in digital systems the characteristic curve is generally linear. SF systems have a characteristic curve that is in relation with the logarithm of incident

Table 1 Methods for quality evaluation of diagnostic imaging procedures¹⁴

Level of ambition	Investigation	Measurement
Lowest	Radiographic technique	<ul style="list-style-type: none"> Equipment characteristics Exposure parameters
	Primary physical characteristics	<ul style="list-style-type: none"> Contrast Spatial resolution (MTF) Noise (WS) Signal-to-noise ratio (SNR)
	Overall system performance	<ul style="list-style-type: none"> DQE Image quality index (IQI) Contrast-detail resolution
	Images of anthropomorphic phantoms	<ul style="list-style-type: none"> ROC ROC related methods Visual grading analysis (VGA)
Highest	Images of patients	<ul style="list-style-type: none"> ROC ROC related methods Visual grading analysis (VGA) Image criteria (IC)

intensity, while digital systems measure their characteristic response directly with respect to exposure (rather than the log of exposure as with film).²¹ If the user is not properly trained, there is an obvious risk that the patient exposure can be unnecessarily high since a digital detector does not set the limit as film does with respect to film blackening^{14,16} and thus the risk of over or underexposure could be present.

The *spatial resolution* concept refers to the ability of the system to represent distinct anatomic features within the object being imaged.²² It could be defined as the ability of the system to distinguish neighbouring features of an image from each other and is related with sharpness. Sharpness of an image is related to (a) the intrinsic sharpness of the detector employed; (b) the subject contrast, as determined by object characteristics, beam quality, and scatter, as well as the blur caused by the finite size of the X-ray focal spot; and (c) the patient motion during the acquisition.³ The sharpness of an imaging detector or system is best characterised in terms of its MTF.

Noise arises from a number of sources – such as quantum and electronic noise – that produces random variations of signal that can obscure useful information in a diagnostic image. Random noise means fluctuations of the signal over an image, as result of a uniform exposure, and can be characterised by the standard deviation of the signal variations over the image of a uniform object. Wiener spectrum has to be used to get a more complete description of the spatial correlation of the noise: it measures the noise power as a function of spatial frequency.²³ Noise is a major limiting factor in object detection because it remains constant in a given system unless dose is increased. The noise in images is recognized as an important factor in determining image quality. Image noise may be characterised by the WS – or noise power spectrum (NPS). WS provide the means of characterizing image noise and play a central role in the ultimate measure of image quality.²⁴ WS is the noise variance of the image, expressed as a function of spatial frequency, i.e., represents noise power at various spatial frequencies.

Objective image quality measurements

Physical measurements of signal-to-noise ratio (SNR), modulation transfer function (MTF) and Wiener spectra (WS) form together a basis for the description of image quality which encompasses the three primary physical image quality parameters.¹⁷ Establishing a complete characterization of the physical properties of the digital image system requires the determination of MTF, SNR, WS and DQE.²⁵

Unlike analogical screen-film detectors, which are contrast limited in operation, digital acquisition devices are signal-to-noise ratio limited, which means that the image quality is usually dependent on the quantum statistics of the image formation process combined with contrast and spatial resolution enhancement methods.²⁶

DQE is the measure of the combined effect of the noise and contrast performance of an imaging system, expressed as a function of object detail. DQE combines MTF and WS to provide a measure of the SNR of the various frequency components of the image.¹

The *MTF* is a measure of the ability of an imaging detector to reproduce image contrast from subject contrast at various spatial frequencies.²² In other words, MTF

represents how well an imaging system reproduces high contrast objects of varying size in the resulting image, and, therefore, represents the relationship between contrast and spatial resolution.¹⁷ Blurring and unsharpness introduced by the imaging system results in higher spatial frequencies not being transmitted as well as lower spatial frequency information. As a result, the MTF progressively decreases with increasing spatial frequency.²⁶

The *SNR* represents the relationship between contrast and noise in an image for large scale objects.¹⁷ While signal sensitivity (contrast) and image noise properties are important by themselves, it is really the ratio between them that carries the most significance and constitutes the most significant indicator of image quality.^{14,21} This relation shows that SNR needs to be a ratio of about 5:1 for a reliable detection by human observers.²¹ In digital X-ray systems, as noise decreases and SNR increases, object detection increases very rapidly.

The *WS* represents the noise power in an image as a function of spatial frequency. It, therefore, represents the relationship between noise and spatial resolution.¹⁷ WS (or NPS) may be understood in several but equivalent ways²¹: it may be thought of as the variance of image intensity (i.e., image noise) distributed among the various frequency components of the image; or may be pictured as the variance of a given spatial frequency component in an ensemble of measurements of that spatial frequency.

Observer performance methods

Observer performance methods could be grouped in two categories¹⁴: observer performance methods based on lesion detection; and observer performance methods based on visibility of anatomical structures. Both methods are used to evaluate the whole imaging chain and give a measure of the clinical image quality of an imaging system.

The first category includes the methods used to detect lesions either in real patients or in phantoms: receiver operating characteristic (ROC) analysis and ROC related methods, such as free-response ROC (FROC), alternative free-response ROC (AFROC) and free-response forced error (FFE). ROC analysis offers several advantages as a measure of the accuracy of a diagnostic test²⁷: (a) it includes all possible cut points, (b) it shows the relationship between the sensitivity of a test and its specificity, (c) it is not affected by the prevalence of disease, and (d) from it we can compute several useful summary measures of test accuracy (e.g. ROC curve area, partial area). These methods were found to be in good agreement with one another.²⁸ ROC analysis provides the most comprehensive description of diagnostic accuracy available to date.²⁹

The second category includes the methods used to evaluate the visibility of anatomic structures such as visual grading analysis (VGA) and image criteria (IC). In VGA analysis, the aim is to compare the visibility of defined structures in the image to be evaluated with the same structures in a reference image. This evaluation is often based on a 5-level grading scale for image comparison.¹⁴ In IC analysis, the aim is to decide if the image criterion – based on a reference frame – is present or not in the image giving a score for that purpose. The criteria can be used to highlight optimum radiographic technique in terms of image quality and patient dose.³⁰

Conclusions

Digital detector technologies can offer several advantages when compared with SF systems. These advantages include better diagnostic image quality and better management of patient exposure. Also, a digital environment can offer better workflow and several other functionalities that are intrinsic to digital technology.

Radiographers should be able to work with these technologies and specific training is needed. The transition from a SF environment to a digital environment requires the attention of radiographer's practices concerning the optimization of image quality and dose. This could be done through the implementation of dose management and clinical image evaluation programs for digital techniques. There is a considerable potential for the optimization and improvement of performance levels of digital detectors available at the present time.

Conflict of interest

No conflict of interest is declared.

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