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REVIEW

Diagnostic imaging over the last 50 years: research and development in medical imaging science and technology

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Abstract

Over the last 50 years, diagnostic imaging has grown from a state of infancy to a high level of maturity. Many new imaging modalities have been developed. However, modern medical imaging includes not only image production but also image processing, computer-aided diagnosis (CAD), image recording and storage, and image transmission, most of which are included in a picture archiving and communication system (PACS). The content of this paper includes a short review of research and development in medical imaging science and technology, which covers (a) diagnostic imaging in the 1950s, (b) the importance of image quality and diagnostic performance, (c) MTF, Wiener spectrum, NEQ and DQE, (d) ROC analysis, (e) analogue imaging systems, (f) digital imaging systems, (g) image processing, (h) computer-aided diagnosis, (i) PACS, (j) 3D imaging and (k) future directions. Although some of the modalities are already very sophisticated, further improvements will be made in image quality for MRI, ultrasound and molecular imaging. The infrastructure of PACS is likely to be improved further in terms of its reliability, speed and capacity. However, CAD is currently still in its infancy, and is likely to be a subject of research for a long time.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Since the discovery of x-rays by W C Roentgen in 1895, medical imaging has contributed significantly to progress in medicine. The various imaging modalities developed over the last 50 years include radionuclide imaging, ultrasonography, computed tomography (CT), magnetic resonance imaging (MRI) and digital radiography. Therefore, diagnostic imaging

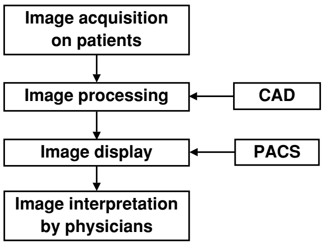


Figure 1. Major components in modern diagnostic imaging.

has grown during the last 50 years from a state of infancy to a high level of maturity. It is very clear that medical imaging has become established as having an important role in patient management, and especially radiologic diagnosis.

From the standpoint of viewing of clinical images, the major achievement in medical imaging might seem to lie in the production of many different types of images. However, modern medical imaging includes not only image production, but also image processing, image display, image recording and storage, and image transmission, most of which are included in a picture archiving and communication system (PACS). Thus, image production is only one of many aspects of modern imaging science and technology.

After medical images have been produced by various modalities, they are presented to a physician (usually a radiologist) for interpretation and a subsequent diagnosis as to the medical condition of a patient. The diagnosis is the result of a decision-making process by the radiologist, who has specialized medical knowledge and experience. Thus, from a physician's standpoint, image interpretation and decision making have been considered as the most important processes in diagnostic radiology. For assisting radiologists' image interpretation, computerized analysis of medical images has recently been implemented clinically for detection of abnormalities such as breast lesions in mammograms; this is generally known as computer-aided diagnosis (CAD).

Major components of modern diagnostic imaging may be illustrated schematically in figure 1. The concepts of these components are applicable to all of the different imaging modalities which may, in some cases, be integrated into a large PACS (Huang 2004). Specific subjects concerning mammography, CT, MRI, MR spectroscopy, ultrasound imaging, SPECT and PET will be discussed in separate articles in this issue of *Physics in Medicine and Biology* (PMB), but some of the major events during the last five decades are summarized in table 1. The content of this review is based primarily on conventional projection x-ray film images and digital images. However, some of the concepts and methods described here will also be applicable to many different types of images obtained with various imaging modalities.

2. Diagnostic imaging in the 1950s

At the time when the first issue of PMB was published, most diagnostic images were obtained by use of screen–film systems and a high-voltage x-ray generator for conventional projection x-ray imaging (Rosenbusch *et al* 1994). Most radiographs were obtained by manual processing of films in darkrooms (Haus and Gullinan 1989), but some of the major hospitals began to use automated film processors. The first automated film processor, shown in figure 2, was a large mechanical system with film hangers, which was designed to replace the manual operation of film development; it was very bulky, requiring a large space, and took about 40 min to process a film.

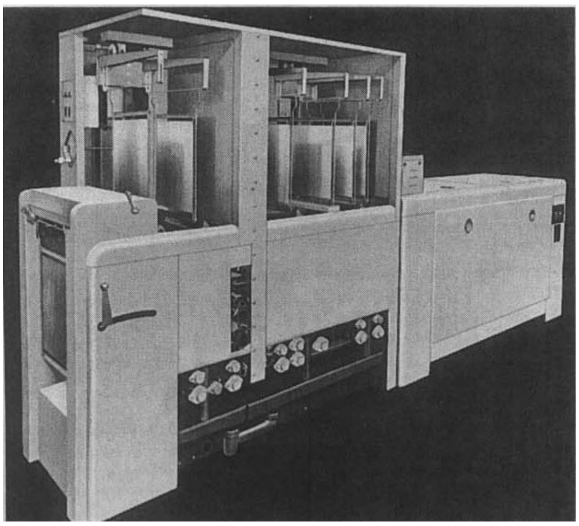


Figure 2. Automated film processor used in the 1950s (permission from Rosenbusch *et al* (1994)).

Table 1. Major events in diagnostic imaging over the last five decades.

1950s	Utilization of an image-intensifier TV system for fluoroscopy Development of a gamma camera for radionuclide imaging
1960s	Development of a 90 s automated film processor Basic research on image quality, MTFs, Wiener spectra and quantum mottle
1970s	Development of rare-earth screen–film systems, digital subtraction angiography (DSA), computed tomography (CT), ultrasound imaging with electronic scan Initial research on ROC analysis, MRI, PET, SPECT, PACS and electronic imaging
1980s	Development of computed radiography (CR), magnetic resonance imaging (MRI), colour Doppler ultrasound imaging Initial research on computer-aided diagnosis (CAD)
1990s	Commercialization and clinical use of a CAD system, flat-panel detector (FPD) systems, multi-detector computed tomography (MDCT), magnetic resonance angiography (MRA), ultrafast MRI, PET and ultrasound harmonic/contrast imaging
2000s	Development and clinical use of real-time 3D ultrasound imaging, cone-beam CT, parallel MRI, PET/CT, full-field digital mammography (FFDM), MDCT with 256 detectors, molecular imaging and PACS

A major new event at that time was the development of image intensifiers (I.I.s) for fluoroscopy, which were intended to replace ‘dark’ fluorescent screens (Deutschberger 1955). The input size of an early image intensifier was only 5 inches, which caused difficulty in viewing of large areas in patients. The input size of the image intensifier was increased gradually over the years, and the image intensifier was combined with a TV camera to provide video images by an I.I.–TV system, which is still used in many hospitals today. Figure 3 shows one of the I.I. systems applied to fluoroscopic examination (Rosenbusch *et al* 1994).

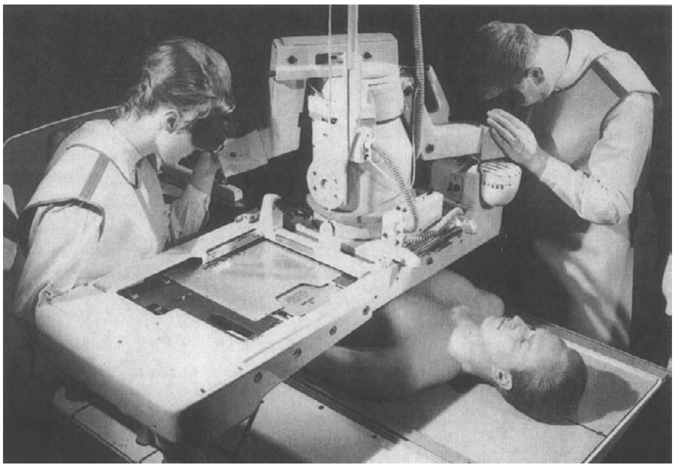


Figure 3. Image intensifier with two optics system for two people in fluoroscopy in the 1950s (permission from Rosenbusch *et al* (1994)).

Garland (1949, 1959) and Yerushalmy (1955) carried out a number of observer studies for detection of pulmonary abnormalities on chest images made by different systems, which included high-quality screen–film images and low-quality minified photofluoroscopic images. They found that radiologists missed on average approximately 30% of actual lesions, and that the size of the recording medium (35 mm or 14″ × 17″ film) was less important than the degree of variation among observers. These observations provided the motivation for further studies, over the subsequent years, on understanding a radiologic diagnosis in terms of detection of abnormalities in medical images, and also eventually for the development of computer-aided diagnosis. Many other studies, some of which were carried out more recently, have confirmed that radiologists and physicians tend to miss many different types of lesions, including breast lesions in mammograms (Schmidt *et al* 1994) and lung nodules in CT images (Li *et al* 2002, 2005a, Armato *et al* 2002) at a rate which is comparable to the rates reported earlier (Garland 1949, 1959, Yerushalmy 1955).

3. Importance of image quality and observer performance

It has generally been believed that diagnostic accuracy, which corresponds to the outcome of radiologic examinations, is related to image quality and other factors (Rossmann and Wiley 1970). However, image quality was a rather vague and difficult concept for quantitation and measurement in the 1950s. Rossmann (1963, 1964, 1966) demonstrated the complexity and importance of the effects of spatial resolution and image noise on simple phantom images by using two different screen–film systems. Figure 4 shows two images obtained with different screen–film systems: system A consists of slow screens with fast film, and system B includes fast screens with slow film. The image with system A is sharp but noisy, and that with system B is smooth but blurred. The two systems have the same overall speed and thus result in the same patient exposure. Test objects included needles and plastic beads, which were used to simulate one-dimensional high-contrast patterns such as blood vessels in angiography and two-dimensional low-contrast patterns such as gallstones, respectively. It is apparent in figure 4 that with system A the needle is visualized clearly, but plastic beads are not seen well, whereas

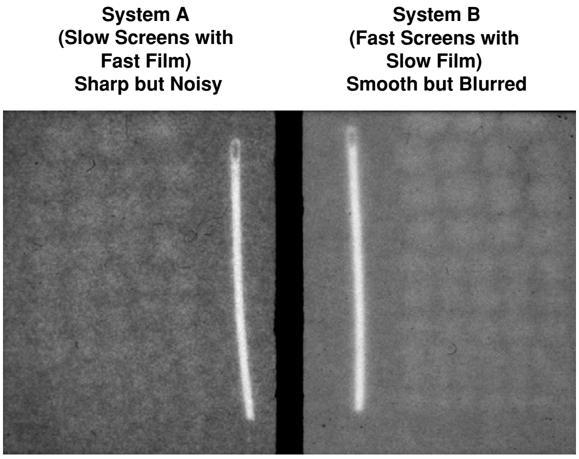


Figure 4. Bead and needle images obtained with two screen–film systems.

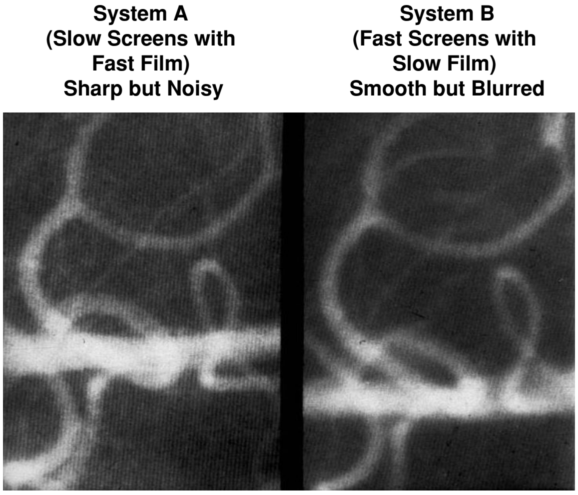
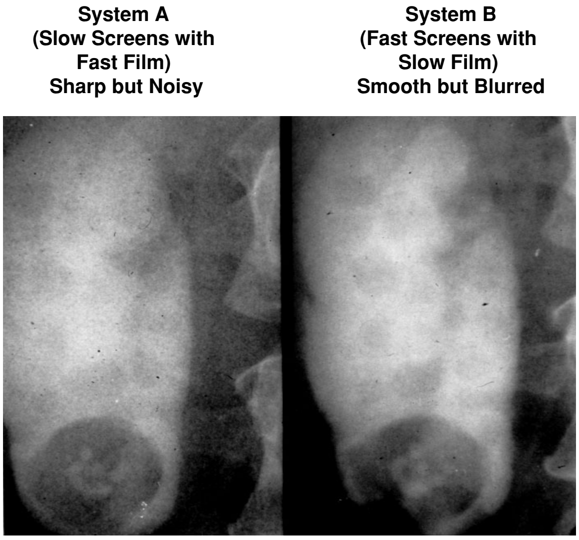


Figure 5. Comparison of blood vessels in angiograms obtained with two screen–film systems.

with system B the needle is blurred but the plastic beads are clearly seen. Therefore, system A is better for visualization of the needle, but system B is better for detection and recognition of the plastic beads. This result implies that a given imaging system would not be suited for all types of objects, and thus a proper imaging system needs to be selected by consideration of specific objects or lesions of clinical interest together with the imaging properties of the system used (Rossmann 1966).

Rossmann applied his findings on these phantom images to practical clinical situations and succeeded in improving clinical images (Doi *et al* 1977), as shown in figures 5 and 6. The comparison of angiograms in figure 5 indicates that small vessel images produced by system A were clearer than those by system B, which had been used in Rossmann's department, and thus was replaced by system A as a result of this demonstration. Similar results illustrated in figure 6 showed that gallstones in a cholecystogram from system B were visualized better



System A
(Slow Screens with
Fast Film)
Sharp but Noisy

System B
(Fast Screens with
Slow Film)
Smooth but Blurred

Figure 6. Comparison of gallstones in cholecystograms obtained with two screen–film systems.

than those from system A, which also had been used in his department, and thus was replaced by system B.

Kundel and Nodine (1975), Kundel *et al* (1978) and Carmody *et al* (1980) carried out extensive investigations on radiologists' performance in the detection of lung nodules in chest radiographs, and then analysed in detail why some lesions were missed. By studying eye movements, they found that 30% of missed nodules were caused by failure of the radiologist to look at the territory of the lesion (search error). In 25% of missed nodules, the eyes looked at the territory of the lesion, but failed to dwell on it (recognition error). Finally, when the eyes dwell on a possible lesion, the radiologist may decide that it is not a lesion (decision-making error); this accounts for 45% of false negative errors. Furthermore, Kundel and Revesz (1976) and Kundel *et al* (1979) found that film reader errors were affected by the adjacent normal background structures, including ribs and vessels, which tend to camouflage nodules in chest images, and thus they called this background structured noise.

Kundel and colleagues also attempted to quantify the conspicuity (Kundel and Revesz 1976, Kundel *et al* 1979), which would indicate the salience or visibility of a lesion affected by structured noise, based on a concept similar to the signal-to-noise ratio. Although the results obtained from the empirical formulation of conspicuity were not successful in relating quantitatively to the performance of observers (Seeley *et al* 1984, Revesz 1985), the concepts of structured noise and conspicuity are still widely considered to be important and useful for understanding the visual detection of abnormalities in medical images.

4. MTF, Wiener spectrum, NEQ and DQE

The three main factors affecting image quality are now generally considered to be contrast, sharpness (spatial resolution) and noise. These basic imaging properties in radiographic images can be evaluated or characterized by the gradient of the H&D curve, the modulation transfer function (MTF) and the Wiener spectrum (ICRU 1986, 1996, 2003). The MTF can be obtained from the one-dimensional Fourier transform of the line spread function (LSF) or from the two-dimensional Fourier transform of the point spread function (PSF) of an imaging

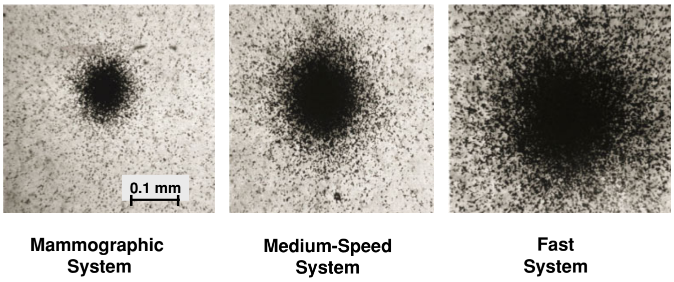


Figure 7. Pinhole images illustrating the PSFs of three screen–film systems.

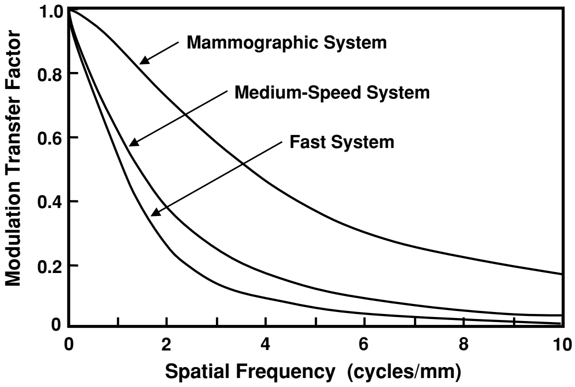


Figure 8. MTF of three screen–film systems.

system (Rossmann 1963, 1969, Morgan *et al* 1964, Metz and Doi 1979, Doi *et al* 1982a, 1986). The MTF represents the spatial frequency response of an imaging system such as a screen–film system and the geometric unsharpness due to the focal spot of an x-ray tube. Figure 7 shows pinhole images obtained with three different screen–film systems, which illustrate the difference in the degrees of sharpness of these systems for an extremely narrow x-ray beam (10 μm square) incident on these screens. The PSF can be obtained from pinhole images. The MTFs of the three screen–film systems are shown in figure 8, where the high-resolution property of a mammographic system is indicated by the high level of the MTF compared with those of the other systems.

The Wiener spectrum represents the spatial frequency content of image noise. It can be determined based on the Fourier analysis of noise patterns obtained from uniform exposure of x-rays to an imaging system. In conventional screen–film systems and in digital radiography, the major source of noise in images is generally due to quantum noise or quantum mottle, which is caused by the statistical fluctuation of x-ray quanta absorbed by the screen–film system or the detector (Cleare *et al* 1962, Rossmann 1963, 1964, Doi 1969).

A theoretical framework for image quality evaluation of medical imaging systems including conventional radiography, digital radiography, CT, MRI, radionuclide imaging and ultrasonography has been provided in *ICRU Report* No 54, ‘Medical imaging: the assessment of image quality’, published in 1996. The content of this report included the definition of noise equivalent quanta (NEQ) and of detective quantum efficiency (DQE) as a function of the spatial frequency (Shaw 1963, Dainty and Shaw 1974, Wagner 1977, Bunch *et al* 1987).

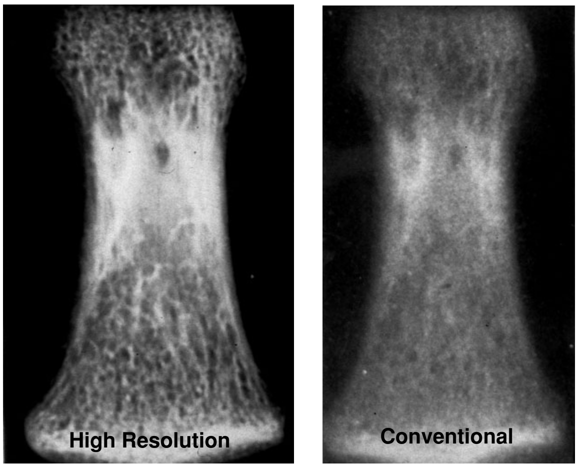


Figure 9. Comparison of bone images obtained with a conventional screen–film technique and high-resolution technique by use of a film without screens.

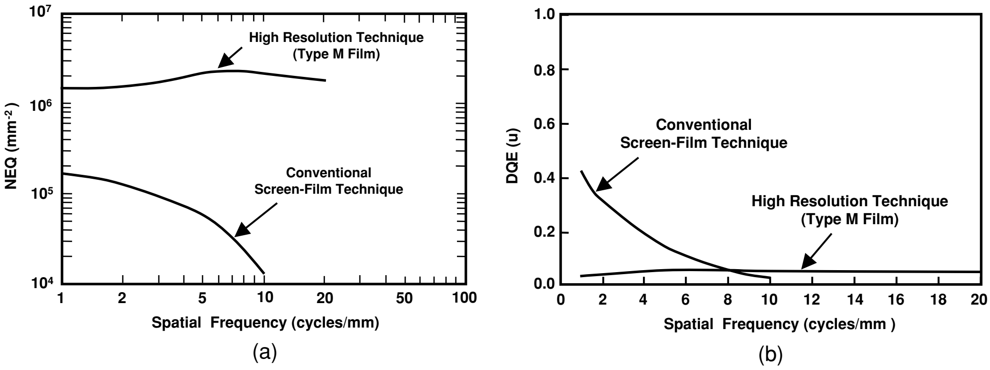


Figure 10. Comparison of the (a) NEQ and (b) DQE of two techniques used for bone images.

The NEQ are defined by taking into account the system's gradient, the MTF and the Wiener spectrum, and indicate the content of an image produced by uniform exposure incident on the imaging system. The DQE is obtained from the ratio of the NEQ to the average number of x-ray quanta incident on the detector, and also from the ratio of the signal-to-noise ratio (SNR) of the output image to the SNR of the incident x-ray exposure. Thus, the DQE is an inherent measure of an imaging system for detecting a known signal, whereas the NEQ provides a measure of the potential quality of a uniformly exposed image in terms of the number of quanta contributing to the image.

Figure 9 shows a comparison of bone images obtained with two different techniques, i.e., the conventional technique by use of a screen–film and a high-resolution technique by use of a film without screen (Genant and Doi 1978). The high-quality bone image obtained with the high-resolution technique is apparent. The NEQ of these images and the DQE of the two techniques are shown in figure 10. It is apparent that the NEQ of the high-resolution technique is much greater than that of the conventional screen–film system, which is consistent with a large difference in image quality between the two systems. However, the DQE of the high-resolution system is very low, but extends to high frequencies. This result corresponds to the fact that the x-ray absorption in film was extremely low, and required a large incident x-ray exposure.

5. ROC analysis

Although the theoretical framework for image quality evaluation is useful for design of the technical parameters of an imaging system, there is a need for quantitative evaluation of the diagnostic performance for many important clinical situations. For example, it is common for many radiologists to question whether a new film, a novel technique or an improved method can really provide a diagnostic performance superior to that with the conventional film, technique or method. Many investigators believe that the answer to this question can be found from analysis of receiver operating characteristic (ROC) curves obtained from observer performance studies which can be carried out with a number of clinical cases and human observers (Metz 1986, 1989, 2000). In fact, ROC analysis has become the standard statistical methodology for evaluating the diagnostic accuracy of imaging systems.

Lusted (1960, 1971) may have been the first to suggest the application of ROC analysis to medical imaging and decision making. The basic concept of ROC analysis was developed during World War II in the field of detecting signals in radar images based on signal detection theory. Goodenough *et al* (1972) reported on ROC curves which were obtained by an observer in the detection of 2 mm lucite beads images, similar to those shown in figure 4, recorded on various screen–film systems. Since then, various aspects of the methodology for obtaining ROC curves and evaluating the results based on statistical analysis have been developed to provide reliable comparisons of new techniques including digital mammography and computer-aided diagnostic schemes. An important development was reported by Dorfman *et al* (1992), who provided the so-called DBM method for analysing multi-reader, multi-case (MRMC) ROC data by taking into account the variations in both readers and cases. With MRMC methodology, the conclusions derived from ROC analysis by use of a sample of cases and a sample of readers can be applied both to populations of cases and readers.

Based on an ROC analysis of the detection of breast cancer in a digital mammography imaging screening trial (DMIST), Pisano *et al* (2005) recently reported that digital mammography is as good as conventional screen–film mammography. It is likely that the conclusion drawn in this study will end the controversy over the last 10 years or more as to whether digital mammography can be used in clinical practice.

6. Analogue imaging systems

The central component of analogue radiologic imaging systems is the screen–film system, which was first employed soon after the discovery of x-rays and is still widely used in many countries around the world, but is being replaced slowly but steadily by digital imaging systems. Over the last 50 years, screen–film systems have been improved substantially by use of rare-earth phosphors instead of traditional calcium tungstate phosphors as the materials used for absorbing x-rays in the screens. Because of the high x-ray absorption and high light conversion efficiency of these rare-earth phosphors (Buchanan *et al* 1976, Wagner and Weaver 1976), it was possible to achieve a significant reduction in patient dose, by a factor of about 2, without a change in image quality as quantified by the MTF and Wiener spectra (Doi *et al* 1982a, 1986), and/or to improve the image quality in radiographs (Bunch 1994, 1995). Although conventional screen–film systems are generally symmetrical in the sense that the same screens and the same film emulsions are used on both the front and back sides, an asymmetrical screen–film system was developed by Eastman Kodak Co. specifically for chest radiography to visualize both fine lung details at high optical densities and low-contrast nodules at the low optical densities that may be located in the mediastinum (Bunch 1992, Swensen *et al* 1993, Gray *et al* 1993).

Substantial progress was made in automatic film processors during the last 50 years (Haus and Gullinan 1989), including 90 s film processors in the 1960s, 30 s film processors in the 1980s and later dry processors without water and liquid components for processing certain types of films.

The effects of other components, which are common to both analogue and digital x-ray imaging systems, on basic imaging properties have been investigated extensively over the last 50 years. The effect of geometric unsharpness due to the finite size of the x-ray tube focal spot was evaluated by use of the MTF and the magnification factor (Doi and Rossmann 1975, Doi *et al* 1975, 1982b), with a precision device developed specifically for accurate measurements of the focal spot distribution. Monte Carlo simulation studies (Chan and Doi 1982a, 1982b, 1983) indicated that the effect of scattered radiation on image quality can be predicted, and also that the effect of antiscatter grids can be evaluated quantitatively in terms of the contrast improvement factor and Bucky factor. These studies have led to the development of high-strip-density grids (Chan *et al* 1985), which have a relatively light weight, but good scatter removal.

7. Digital imaging systems

Potential advantages of digital systems over analogue systems were predicted in the initial phase of digital/electronic imaging research. However, considerable time and effort were needed for understanding the effects of many parameters in digital systems on image quality, and to accept digital images in many areas of clinical practice. One of the important digital parameters is the pixel size, which may substantially affect the quality of digital images (Foley *et al* 1981, Giger and Doi 1984a, 1984b, 1985, MacMahon *et al* 1986). Figure 11 shows a

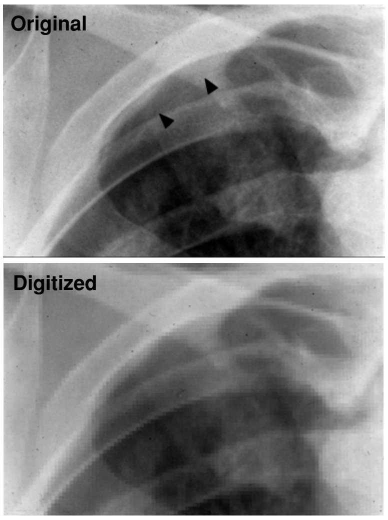


Figure 11. Comparison of an original chest radiograph with a subtle pneumothorax and the digitized image with a pixel size of 1.0 mm.

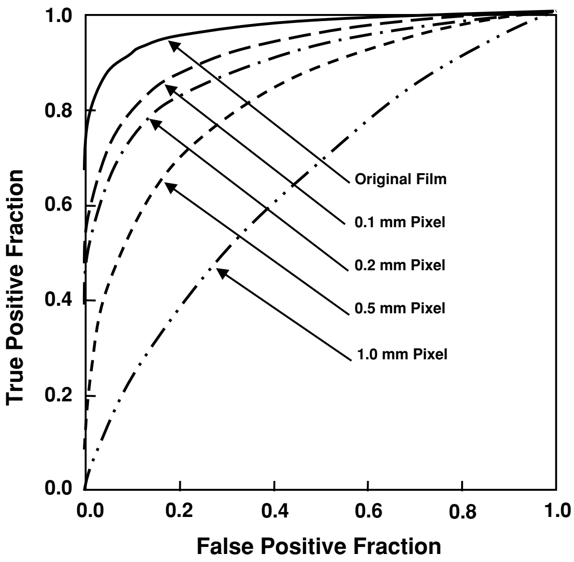
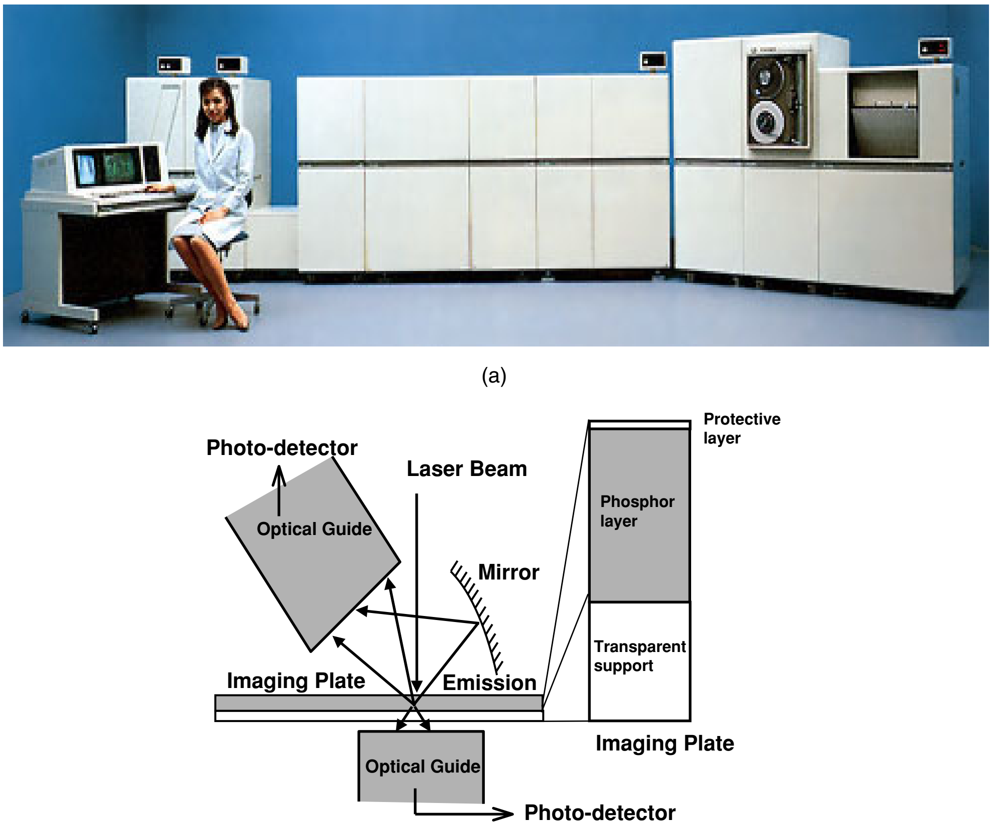


Figure 12. ROC curves for radiologists in the detection of pneumothorax in original chest radiographs and digitized images with various pixel sizes.

comparison of an original chest image with a subtle pneumothorax and the digitized image with a pixel size of 1.0 mm. It is very difficult to detect the subtle pneumothorax on the digitized image. In fact, the ROC curves in figure 12 indicate that radiologists' performance in the detection of pneumothorax in digitized images was degraded substantially as the pixel size increased from 0.1 mm to 1.0 mm.

The first successful digital radiographic system was developed by Fuji Photo Film Co., and was called computed radiography (Sonoda *et al* 1983); the first-generation FCR 101, which included an imaging plate made of a storage phosphor such as europium-activated barium fluorohalide and a laser readout system, is shown in figure 13(a). The image quality of early CR systems was not as good as that of screen–film images, probably due to the relatively low DQE of the detector used (Dobbins *et al* 1995). However, the image quality of recent advanced CR systems has been improved significantly by incorporation of a number of innovative approaches such as dual-side reading of latent images in the imaging plate (Arakawa *et al* 1999, 2003), as illustrated in figure 13(b). Although FCR included digital data storage to allow image processing such as unsharp masking, its output images usually were printed on film as hard-copy images in the initial phase of its development. However, digital radiographic images can now be displayed on high-quality monitors and are often called soft-copy images.

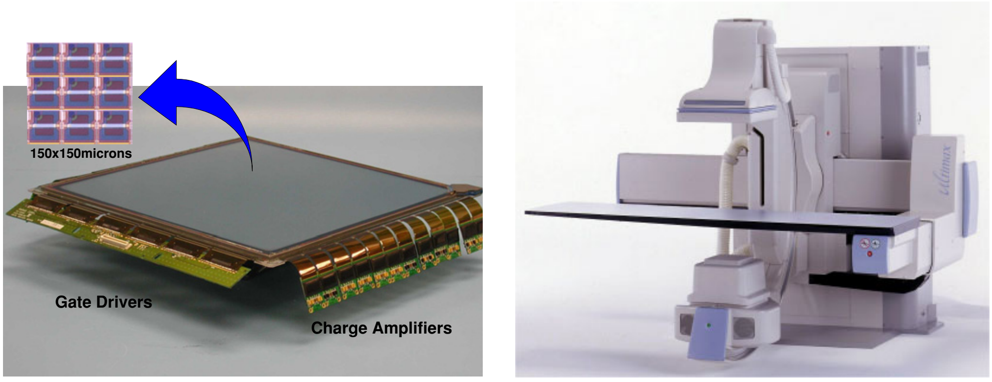
The second generation of digital radiographic systems generally makes use of flat-panel detectors (FPDs) which are self-scanning, two-dimensional solid-state imaging devices, and thus are considered 'ideal' digital x-ray imaging devices. There are two types of FPDs. One, which may be called a direct FPD (Zhao and Rowlands 1995, Lee *et al* 1995), employs an x-ray sensitive photoconductor such as selenium to convert the input x-ray image to a charge image that is then read out electronically by a two-dimensional array of thin-film transistors. Another is called indirect FPD (Antonuk *et al* 1992, Granfors and Aufrichtig 2000, Finc *et al* 2002, Rapp-Bernhardt *et al* 2003, Bacher *et al* 2003); it includes a scintillator layer such as thallium-doped caesium iodide for conversion of x-rays to visible light, which is then detected by an array of amorphous silicon photodiodes for conversion to an electrical charge. The



(a)

(b)

Figure 13. (a) The first-generation FCR system in 1983, and (b) a schematic diagram of a dual reading system in an advanced FCR system (courtesy of Fuji Photo Film Co.).



(a)

(b)

Figure 14. (a) Flat-panel detector system and (b) multi-purpose C-arm diagnostic x-ray system with a flat-panel detector (above the table) (courtesy of Toshiba Medical Systems Co.).

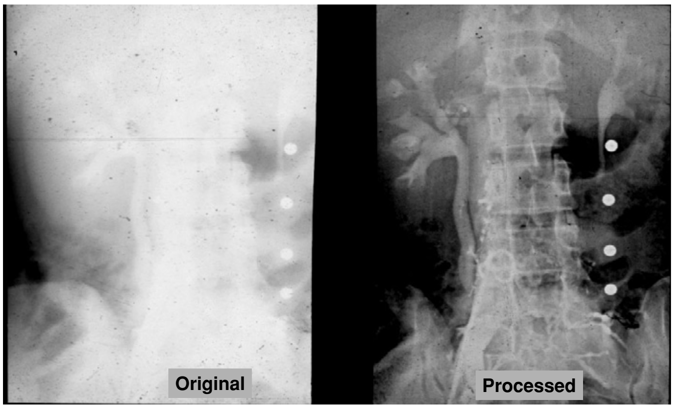


Figure 15. Comparison of an underexposed low-density film image and processed image for enhancement of the underexposed film image.

advantages of these FPDs are a relatively high DQE due to high x-ray absorption by the detector and also, in direct FPD, potentially high spatial resolution. Figure 14 shows (a) a selenium FPD system together with the associated electronic components with a pixel size of 150 μm and a matrix size of 2304 × 2304, and (b) a multi-purpose C-arm system with the FPD installed above the table. This system can be used for fluoroscopic studies with a matrix size of 1152 × 1152 at a frame rate of 30 s^{-1}. It is compact in size compared with conventional systems that include an I.I.–TV system.

8. Image processing

One of the advantages of digital images is that these images can be changed in many different ways by use of various image processing techniques (Bankman 2000). This is a very important advantage, because conventional film images cannot be changed once they have been obtained. For example, if film images were under- or overexposed, additional exposure to patients was necessary in analogue imaging systems. Figure 15 shows an underexposed low-density film image and a digitally processed image which was obtained from the corresponding digitized film image by use of a laser digitizer. It should be noted that the density distribution of the processed image is very similar to that of a properly exposed film image (Yoshimura *et al* 1993).

Although many different image processing techniques are available for different purposes including temporal subtraction (Kano *et al* 1994, Ishida *et al* 1999), the most commonly used processing techniques for digital radiographic images have been aimed at enhancement of the digital images by removal or suppression of noise, and by increasing contrast and/or sharpness, such as the unsharp mask filtering used in FCR. Figure 16 shows a comparison of an original film image with low-contrast objects at three different densities and an image that has been processed to enhance low-contrast objects. Note that only the local contrast in the film image has been increased, whereas a large-area overall density distribution in the processed image was kept the same as that in the original image. The visibility of circular objects in the processed image appears to be superior to that in the original film image. In fact, the ROC curves shown in figure 17 indicate clearly that observers' performance in the detection of simple low-contrast patterns was substantially improved by use of the processed images compared with the original film images (Ishida *et al* 1983, 1984). This improvement

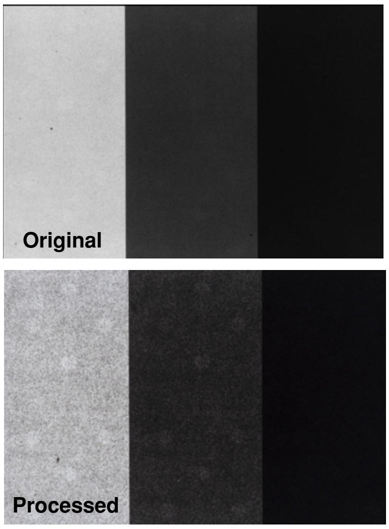


Figure 16. Comparison of an original film image with low-contrast circular objects at three different background densities and processed image for enhancement of local contrast of objects while maintaining the same large-area contrast, i.e., the same background densities.

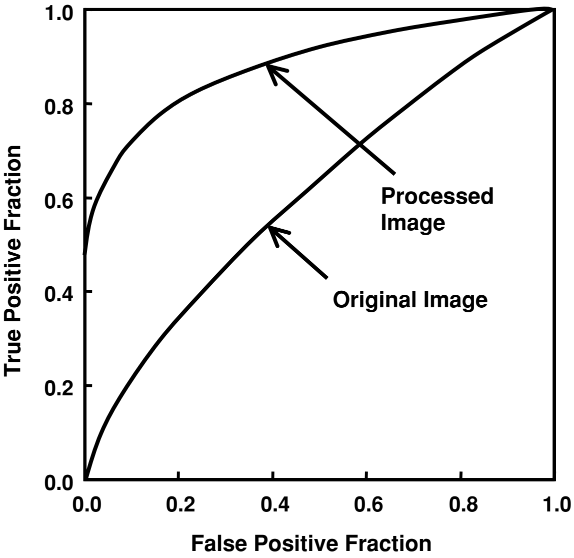
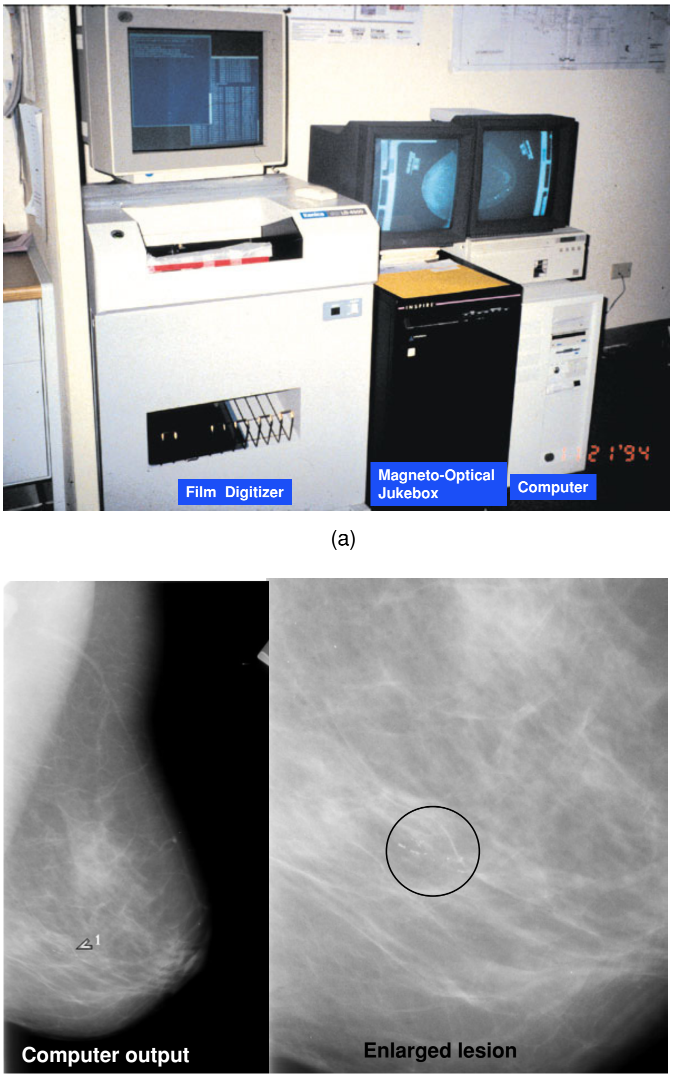


Figure 17. ROC curves for detection of low-contrast objects without and with image enhancement.

in the detection of low-contrast objects by enhancement of local contrast was possible because the contribution of internal noise in human observers can be reduced in the detection of low-contrast objects by increasing the contrast of objects in the processed image, even though image noise is increased as well. The noise level in radiographic images is generally comparable to the level of internal noise in human observers (Ishida *et al* 1984), although human observers may not be aware of this important effect.

9. Computer-aided diagnosis

Computer-aided diagnosis (CAD) is a relatively new concept that has been developed largely during the last 20 years, and that is growing rapidly in diagnostic radiology and medical physics (Doi 2003, 2004, 2005). The aim of CAD is to improve the diagnostic accuracy and the consistency of image interpretation by a radiologist who uses the computer output as a ‘second opinion’. With the computer output pointing to a subtle lesion, the radiologist may be reminded to consider carefully and therefore detect such a lesion, which would otherwise



(a)

(b)

Figure 18. (a) The first CAD system developed at the University of Chicago in 1994 for detection of breast lesions in mammograms, and (b) mammogram with clustered microcalcifications detected by a CAD scheme.

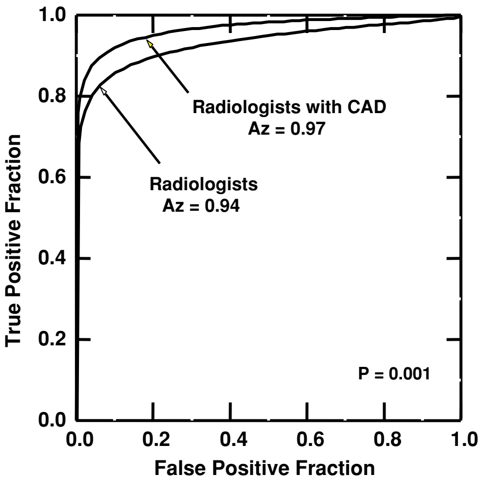


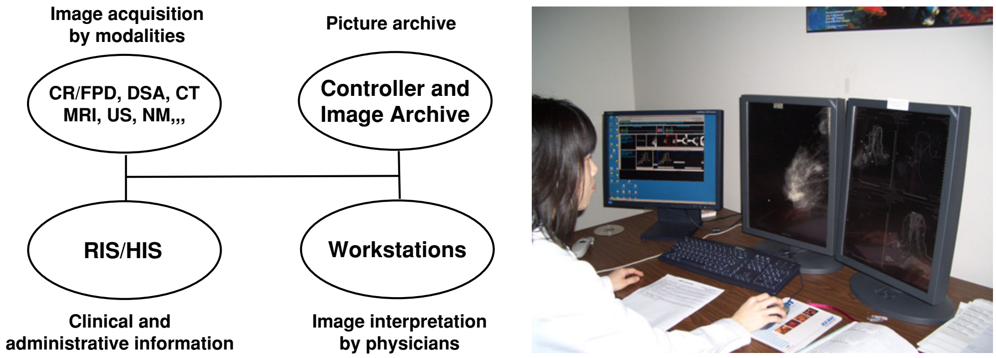
Figure 19. ROC curves for improved detection of clustered microcalcifications on mammograms by use of a computer output.

be missed. In the development of various CAD schemes, it is necessary to employ image-processing and information-processing techniques for quantitative analysis of images. In addition, it is necessary to understand the medically relevant content of the images on the basis of technical features. For example, for detecting lesions by computer, it may be useful to devise approaches that are similar to those which radiologists employ in their clinical tasks. For distinguishing between normal and abnormal patterns (or between benign and malignant lesions), it may be useful to learn from radiologists and to quantify the kinds of image features they recognize and use to make their clinical judgments.

Figure 18 shows (a) the first CAD system developed at the University of Chicago in 1994 for detection of breast lesions on mammograms (Nishikawa *et al* 1995), and (b) a mammogram with clustered microcalcifications detected by a computer (see the arrow). Observer performance studies were carried out for investigating whether the computer output from a CAD scheme can improve radiologists' performance. Chan *et al* (1990) reported the first evidence, shown in figure 19, that the ROC curve for radiologists' detection of clustered microcalcifications was improved significantly when a computer output was available. Because the concept of CAD is broad, CAD is potentially applicable to all imaging modalities and all kinds of examinations of every part of the body. For example, a number of CAD schemes have been developed for detection and classification of various lesions in chest radiographs (Abe *et al* 2004), CT (Li *et al* 2005b, Yoshida and Dachman 2004) and MRI (Arimura *et al* 2006, Hirai *et al* 2005), in addition to breast lesions in mammograms (Freer and Ulissey 2001, Giger 2004).

10. PACS

The concept of a picture archiving and communication system (PACS) was perceived in the early 1980s by the radiology community as an integrated communication network and data management system (Huang 2004), which includes image acquisition devices, storage archiving units, display workstations, computers and databases. Therefore, PACS may be considered as the infrastructure for digital diagnostic imaging. Recently, large PACS have



(a) (b)

Figure 20. Illustration of (a) four major components and (b) high-resolution workstation in PACS.

become a reality, and have been implemented in major hospitals in the United States and in other countries together with radiology information systems (RIS) and hospital information systems (HIS), which are related to administrative and clinical operations concerning patient care. Four major components in PACS are illustrated in figure 20(a), where image interpretations are made by radiologists and physicians on workstations that often include high-resolution LCD monitors with a matrix size of approximately 2000 × 2500, as shown in figure 20(b).

With PACS, it has become possible for radiologists and physicians to use monitors for daily interpretation of radiologic images, which can be manipulated for enhancement by an image processing technique, can be compared with previous images of the same patient together with temporal-subtraction images, can be compared with similar clinical cases retrieved from a large database, and also can indicate the computer output from a CAD scheme for prompting the locations of potential lesions. Advantages of PACS include not only their use in clinical operations, but also their applications to teaching and research.

11. 3D imaging

The need for 3D visualization of medical images became a pressing need when multi-detector CT (MDCT) was developed to produce hundreds or thousands of axial images with almost isotropic voxel data, because image interpretation of all individual image slices by radiologists would be prohibitively time consuming. 3D images from 3D volume data may be created by use of a surface-rendering or volume-rendering technique. Another approach is to view a large number of these images in a stack (cine) mode for images displayed in the axial, sagittal and/or coronal plane by use of a multi-planar reformatting (MPR) technique. For certain organs such as the colon and bronchus, a flythrough or image-navigation technique (Rosset *et al* 2006) may be employed for visualizing the internal surfaces of these organs. For the colon, this has been called virtual colonoscopy, which involves a perceptual task similar to that in optical colonoscopy. Clinical examples of 3D images in cardiac CT (Schoenhagen *et al* 2004), MR cholangio-pancreatography (Morimoto *et al* 1992, Ichikawa *et al* 1998, Koito *et al* 1998, Sai and Ariyama 2000) and ultrasound imaging by fusion of a B-mode image and Doppler image (Fenster and Downey 1996, Ohto *et al* 2005, Yamagata *et al* 1999) are illustrated in figures 21, 22 and 23, respectively. It is likely that the visualization of 3D images would be more useful if it could be combined with CAD schemes for detection of various abnormalities

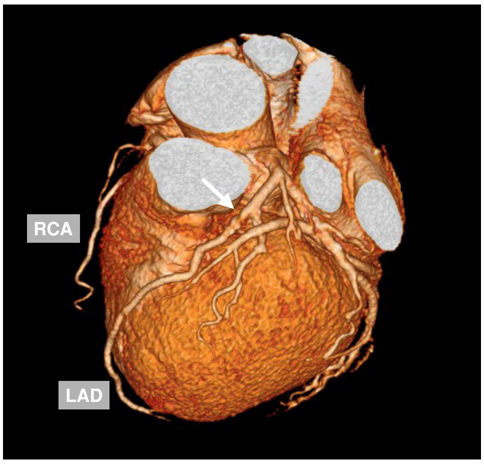


Figure 21. 3D image obtained by cardiac CT, with stenosis in left anterior descending artery (LAD) (courtesy of Fujita Health University).

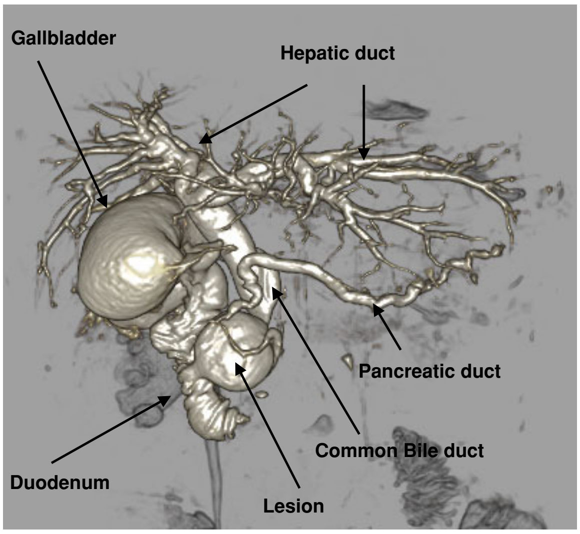


Figure 22. 3D image obtained with MR cholangio-pancreatography (courtesy of Fukushima Medical University Hospital).

and lesions, and also if images from multiple modalities, such as PET and CT images, could be combined (von Schulthess *et al* 2006).

12. Future directions

Over the last 50 years, significant progress has been made in the field of diagnostic imaging. Many new imaging modalities have been developed. Although some of these modalities are already very sophisticated, it is likely that further improvements will be made, especially in image quality for MRI, ultrasound and molecular imaging (Feinendegen *et al* 2003) which is

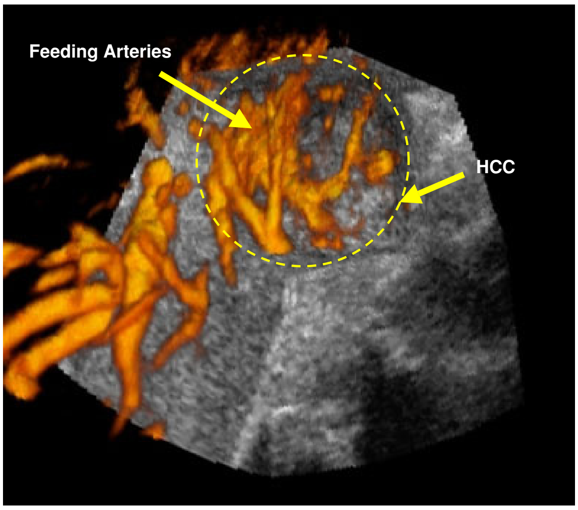


Figure 23. 3D ultrasound image obtained by fusion of a B-mode image for hepatocellular carcinoma (HCC) and a Doppler image with contrast enhancement for feeding arteries (courtesy of National Institute of Radiological Science).

related to the spatio-temporal distribution of molecular or cellular processes for biochemical, biological, diagnostic or therapeutic applications. The infrastructure of PACS is likely to be improved further in terms of its reliability, speed and capacity. However, CAD is currently still in its infancy, and is likely to be a subject of research for a long time because the successful development of CAD schemes depends on a good understanding of the content of medical images. This will probably require establishing a new field of image science that is based on a technical understanding of the contents of medical images. In essence, the major task for this new field of medical imaging science is to translate the knowledge about image interpretation accumulated in radiologists' brains into concepts and terminologies understandable by physicists, computer scientists and engineers. It is, therefore, necessary to have close collaboration among researchers in multiple disciplines.

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References

Abe H, MacMahon H, Shiraishi J, Li Q, Engelmann R and Doi K 2004 Computer-aided diagnosis in chest radiology *Semin. Ultrasound CT MRI* **25** 432–7

Antonuk L E, Boudry J, Huang W, McShan D L, Morton E J, Yorkston J, Longo M J and Street R A 1992 Demonstration of megavoltage and diagnostic x-ray imaging with hydrogenated amorphous silicon arrays *Med. Phys.* **19** 1455–66

Arakawa S, Itoh W, Kohda K and Suzuki T 1999 Novel computed radiography system with improved image quality by detection of emissions from both sides of an imaging plate *Proc. SPIE* **3659** 572–81

Arakawa S, Yasuda H, Kuwabara T, Suzuki H, Suzuki T and Hagiwara T 2003 Compact, high-speed computed radiography (CR) system using a linear CCD with a large-area photodiode (PD) and dual transfer lines *Proc. SPIE* **5030** 778–87

Arimura H, Li Q, Korogi Y, Hirai T, Katsuragawa S, Yamashita Y, Tsuchiya K and Doi K 2006 Computerized detection of intracranial aneurysms for three-dimensional MR angiography: feature extraction of small protrusions based on a shape-based difference image technique *Med. Phys.* **33** 394–401

Armato S G III, Li F, Giger M L, MacMahon H, Sone S and Doi K 2002 Performance of automated CT nodule detection on missed cancers from a lung cancer screening program *Radiology* **225** 685–92

Bacher K, Smeets P, Bonnarens K, De Hauwere A, Verstraete K and Thierens H 2003 Dose reduction in patients undergoing chest imaging: digital amorphous silicon flat-panel detector radiography versus conventional film-screen radiography and phosphor-based computed radiography *Am. J. Roentgenol.* **181** 923–9

Bankman I N 2000 *Handbook of Medical Imaging, Processing and Analysis* (New York: Academic) pp 1–893

Buchanan R A, Finkelstein S I and Wickersheim K A 1976 X-ray exposure reduction using rare earth oxysulfide intensifying screens *Radiology* **118** 183–8

Bunch P C 1992 Performance characteristics of asymmetric zero-crossover screen-film systems *Proc. SPIE* **1653** 46–65

Bunch P C 1994 Performance characteristics of high-MTF screen-film systems *Proc. SPIE* **2163** 14–35

Bunch P C 1995 Comparison of high-MTF and reduced-noise radiographic imaging systems *Proc. SPIE* **2432** 67–95

Bunch P C, Huff K E and Van Metter R 1987 Analysis of the detective quantum efficiency of a radiographic screen-film combination *J. Opt. Soc. Am.* A **4** 902–9

Carmody D P, Nodine C F and Kundel H L 1980 An analysis of perceptual and cognitive factors in radiographic interpretation *Perception* **9** 339–44

Chan H P and Doi K 1982a Investigation of performance of antiscatter grids: Monte Carlo simulation studies *Phys. Med. Biol.* **27** 785–803

Chan H P and Doi K 1982b Physical characteristics of scattered radiation and performance of antiscatter grids in diagnostic radiology *Radiographics* **3** 378–406

Chan H P and Doi K 1983 The validity of Monte Carlo simulation in studies of scattered radiation in diagnostic radiology *Phys. Med. Biol.* **28** 109–29

Chan H P, Doi K, Vyborny C J, Schmidt R A, Metz C E, Lam K L, Ogura T, Wu Y and MacMahon H 1990 Improvement in radiologists' detection of clustered microcalcifications on mammograms: the potential of computer-aided diagnosis *Invest. Radiol.* **25** 1102–10

Chan H P, Frank P H, Doi K, Iida N and Higashida Y 1985 Development of ultra-high-strip-density (UHSD) grids: a new antiscatter technique for mammography *Radiology* **154** 807–15

Cleare H M, Splettstasser H R and Seemann H E 1962 An experimental study of the mottle produced by x-ray intensifying screens *Am. J. Roentgenol.* **88** 168–74

Dainty J C and Shaw R 1974 *Image Science* (London: Academic)

Deutschberger O 1955 The electronically amplified fluoroscopy image *Fluoroscopy in Diagnostic Roentgenology* (Philadelphia, PA: Saunders) chapter 4, pp 38–51

Dobbins J T, Ergun D L, Rutz L, Hinshaw D A, Blume H and Clark D C 1995 DQE (f) of four generations of computed radiography acquisition devices *Med. Phys.* **22** 1581–93

Doi K 1969 Wiener spectrum analysis of quantum statistical fluctuation and other noise sources in radiography *Television in Diagnostic Radiology* ed R D Moseley Jr and J H Rust (Birmingham, AL: Aesculapius Publishers) pp 313–33

Doi K 2003 Computer-aided diagnosis in digital chest radiography *Advances in Digital Radiography: RSNA Categorical Course in Diagnostic Radiology Physics 2003 Syllabus* pp 227–36

Doi K 2004 Overview on research and development of computer-aided diagnostic schemes *Semin. Ultrasound CT MRI* **25** 404–10

Doi K 2005 Current status and future potential of computer-aided diagnosis in medical imaging *Br. J. Radiol.* **78** S3–S19 (Special Issue)

Doi K, Fromes B and Rossmann K 1975 A new device for accurate measurement of the x-ray intensity distribution of x-ray tube focal spots *Med. Phys.* **2** 268–73

Doi K, Holje G, Loo L N, Chan H P, Sandrik J M, Jennings R J and Wagner R F 1982a MTFs and Wiener spectra of radiographic screen-film systems *HHS Publication FDA 82-8187* pp 1–77

Doi K, Kodera Y, Loo L N, Chan H P and Higashida Y 1986 MTFs and Wiener spectra of radiographic screen-film systems, Volume II *HHS Publication FDA 86-8257* pp 1–100

Doi K, Loo L N and Chan H P 1982b X-ray tube focal spot sizes: comprehensive studies of their measurements and effect of measured size in angiography *Radiology* **144** 383–93

Doi K and Rossmann K 1975 Effect of focal spot distribution on blood vessel imaging in magnification radiography *Radiology* **114** 435–41

Doi K, Rossmann K and Haus A G 1977 Image quality and patient exposure in diagnostic radiology *Photogr. Sci. Eng.* **21** 266–77

Dorfman D D, Berbaum K K and Metz C E 1992 Receiver operating characteristic analysis. Generalization to the population of readers and patients with the jackknife method *Acad. Radiol.* **4** 723–31

Feinendegen L E, Shreeve W W, Eckelman W C, Bahk Y-W and Wagner H N Jr 2003 *Molecular Nuclear Medicine, the Challenge of Genomics and Proteomics to Clinical Practice* (Berlin: Springer)

Fenster A and Downey D B 1996 3-D ultrasound imaging: a review *IEEE Eng. Med. Biol.* **15** 41–51

Finc C, Hallscheidt P J, Noeldge G, Kampschulte A, Radeleff B, Hosch W P, Kauffmann G W and Hansmann J 2002 Clinical comparative study with a large-area amorphous silicon flat-panel detector: image quality and visibility of anatomic structures on chest radiography *Am. J. Roentgenol.* **178** 481–6

Foley W D, Wilson C, Keyes G S, DiBianca F A, Scanlon G T, Schleuter D and Lawson T L 1981 The effect of varying spatial resolution on the detectability of diffuse pulmonary nodules *Radiology* **141** 25–31

Freer T W and Ulissey M J 2001 Screening mammography with computer-aided detection: prospective study of 12,860 patients in a community breast center *Radiology* **220** 781–6

Garland L H 1949 On the scientific evaluation of diagnostic procedures *Radiology* **52** 309–28

Garland L H 1959 Studies on the accuracy of diagnostic procedures *Am. J. Roentgenol.* **82** 25–38

Genant H K and Doi K 1978 High-resolution skeletal radiography: image quality and clinical applications *Curr. Probl. Radiol.* **7** 1–62

Giger M L 2004 Computerized analysis of images in the detection and diagnosis of breast cancer *Semin. Ultrasound CT MRI* **25** 411–8

Giger M L and Doi K 1984a Investigation of basic imaging properties in digital radiography: Part 1. Modulation transfer function *Med. Phys.* **11** 287–95

Giger M L and Doi K 1984b Investigation of basic imaging properties in digital radiography: Part 2. Noise Wiener spectrum *Med. Phys.* **11** 797–805

Giger M L and Doi K 1985 Investigation of basic imaging properties in digital radiography. Effect of pixel size on SNR and threshold contrast *Med. Phys.* **12** 201–8

Goodenough D J, Rossmann K and Lusted L B 1972 Radiographic applications of signal detection theory *Radiology* **105** 199–200

Granfors P R and Aufrichtig R 2000 Performance of a 41×41-cm^2 amorphous silicon flat panel x-ray detector for radiographic imaging applications *Med. Phys.* **27** 1324–33

Gray J E, Stears J G, Swensen S J and Bunch P C 1993 Evaluation of resolution and sensitometric characteristics of an asymmetric screen-film imaging system *Radiology* **188** 537–9

Haus A G and Gullinan J E 1989 Screen film processing systems for medical radiography: a historical review *Radiographics* **9** 1203–24

Hirai T, Korogi Y, Arimura H, Katsuragawa S, Kitajima M, Yamura M, Yamashita Y and Doi K 2005 Intracranial aneurysms at MR angiography: effect of computer-aided diagnosis on radiologists' detection performance *Radiology* **237** 605–10

Huang H K 2004 *PACS and Imaging Informatics, Basic Principles and Applications* (New Jersey: Wiley)

Ichikawa T, Haradome H, Hanaoka H, Kassai Y, Nitatori T, Hachiya J and Araki T 1998 Improvement of MR cholangiopancreatography at .5 T: three-dimensional half-averaged single-shot fast spin echo with multi-breath-hold technique *J. Magn. Reson. Imag.* **8** 459–66

ICRU (International Commission on Radiation Units and Measurements) 1986 Modulation Transfer Function of Screen-Film Systems *ICRU Report No 41* (Bethesda, MD: ICRU)

ICRU (International Commission on Radiation Units and Measurements) 1996 Medical Imaging: The Assessment of Image Quality *ICRU Report No 54* (Bethesda, MD: ICRU)

ICRU (International Commission on Radiation Units and Measurements) 2003 Image Quality in Chest Radiography *ICRU Report No 70* (Bethesda, MD: ICRU)

Ishida M, Doi K, Loo L N, Metz C E and Lehr J L 1984 Digital image processing: effect on the detectability of simulated low-contrast radiographic patterns *Radiology* **150** 569–75

Ishida M, Frank P H, Doi K and Lehr J L 1983 High-quality digital radiographic images: improved detection of low-contrast objects and preliminary clinical studies *Radiographics* **3** 325–38

Ishida T, Katsuragawa S, Nakamura K, MacMahon H and Doi K 1999 Iterative image warping technique for temporal subtraction of sequential chest radiographs to detect interval change *Med. Phys.* **26** 1320–9

Kano A, Doi K, MacMahon H, Hassell D D and Giger M L 1994 Digital image subtraction of temporally sequential chest images for detection of interval change *Med. Phys.* **21** 453–61

Koito K, Namieno T, Ichimura T, Yama N, Hareyama M, Morita K and Nishi M 1998 Mucin-producing pancreatic tumors: comparison of MR cholangiopancreatography with endoscopic retrograde cholangiopancreatography *Radiology* **208** 231–7

Kundel H L and Nodine C F 1975 Interpreting chest radiographs without visual search *Radiology* **116** 527–32

Kundel H L, Nodine C F and Carmody D 1978 Visual scanning, pattern recognition and decision-making in pulmonary nodule detection *Invest. Radiol.* **13** 175–81

Kundel H L and Revesz G 1976 Lesion conspicuity, structured noise, and film reader error *Am. J. Roentgenol.* **126** 1233–8

Kundel H L, Revesz G and Toto L 1979 Contrast gradient and the detection of lung nodules *Invest. Radiol.* **14** 18–22

Lee D L, Cheung L K and Jeromin L S 1995 A new digital detector for projection radiography *Proc. SPIE* **2432** 237–49

Li F, Arimura H, Suzuki K, Shiraishi J, Li Q, Abe H, Engelmann R, Sone S, MacMahon H and Doi K 2005a Computer-aided diagnosis for detection of missed peripheral lung cancers on CT: ROC and LROC analysis *Radiology* **237** 684–90

Li F, Sone S, Abe H, MacMahon H, Armato S and Doi K 2002 Missed lung cancers in low-dose helical CT screening obtained from a general population *Radiology* **225** 673–83

Li Q, Li F, Suzuki K, Shiraishi J, Abe H, Engelmann R, Yongkang N, MacMahon H and Doi K 2005b Computer-aided diagnosis in thoracic CT *Semin. Ultrasound CT MRI* **26** 357–63

Lusted L B 1960 Logical analysis in roentgen diagnosis *Radiology* **74** 178–93

Lusted L B 1971 Decision-making studies in patient management *New Eng. J. Med.* **284** 415–24

MacMahon H, Vyborny C J, Metz C E, Doi K, Sabeti V and Solomon S L 1986 Digital radiography of subtle pulmonary abnormalities: an ROC study of the effect of pixel size on observer performance *Radiology* **158** 21–6

Metz C E 1986 ROC methodology in radiologic imaging *Invest. Radiol.* **21** 720–33

Metz C E 1989 Some practical issues of experimental design and data analysis in radiological ROC studies *Invest. Radiol.* **24** 234–45

Metz C E 2000 Fundamental ROC analysis *Handbook of Medical Imaging* vol 1, ed J Beutel, H L Kundel and R L Van Metter (Bellingham, Washington: SPIE Press, The International Society for Optical Engineering) pp 751–70

Metz C E and Doi K 1979 Transfer function analysis of radiographic imaging systems *Phys. Med. Biol.* **24** 1079–106

Morgan R H, Bates L M, Gopalarao G U V and Marinaro A 1964 The frequency response characteristics of x-ray films and screens *Am. J. Roentgenol.* **92** 426–40

Morimoto K, Shimoi M, Shirakawa T, Aoki Y, Choi S, Miyata Y and Hara K 1992 Bilary obstruction: evaluation with three-dimensional MR cholangiography *Radiology* **183** 578–80

Nishikawa R M, Haldemann R C, Papaioannou J, Giger M L, Lu P, Schmidt R A, Wolverton D E, Bick U and Doi K 1995 Initial experience with a prototype clinical ‘intelligent’ mammography workstation for computer-aided diagnosis *Proc. SPIE* **2434** 65–71

Ohto M, Kato H, Tsujii H, Maruyama H, Matsutani S and Yamagata H 2005 Vascular flow patterns of hepatic tumors in contrast-enhanced 3-dimensional fusion ultrasonography using plane shift and opacity control modes *J. Ultrasound Med.* **24** 49–57

Pisano E D *et al* 2005 Diagnostic performance of digital versus film mammography for breast-cancer screening *New Eng. J. Med.* **353** 1773–83

Rapp-Bernhardt U, Roehl F W, Gibbs R C, Schmidl H, Krause U W and Bernhardt T M 2003 Flat-panel x-ray detector based on amorphous silicon versus asymmetric screen-film system: phantom study of dose reduction and depiction of simulated findings *Radiology* **227** 484–92

Revesz G 1985 Conspicuity and uncertainty in the radiographic detection of lesions *Radiology* **154** 625–8

Rosenbusch G, Oudkerk M and Ammann E 1994 *Radiology in Medical Diagnostics: Evolution of X-ray Applications 1895–1995* (Oxford: Blackwell)

Rosset A, Spadola L, Pysher L and Ratib O 2006 Navigating the fifth dimension: innovative interface for multidimensional multimodality image navigation *Radiographics* **26** 299–308

Rossmann K 1963 Spatial fluctuations of x-ray quanta and the recording of radiographic mottle *Am. J. Roentgenol.* **90** 863–9

Rossmann K 1964 Some physical factors affecting image quality in medical radiography *J. Photogr. Sci.* **12** 279–83

Rossmann K 1966 Comparison of several methods for evaluating image quality of radiographic screen-film systems *Am. J. Roentgenol.* **97** 772–5

Rossmann K 1969 Point spread-function, line spread-function, and modulation transfer function: tools for the study of imaging systems *Radiology* **93** 257–72

Rossmann K and Wiley B E 1970 The central problem in the study of radiographic image quality *Radiology* **96** 113–8

Sai J and Ariyama J 2000 *MRCP Early Diagnosis of Pancreatobiliary Diseases* (Berlin: Springer)

Schmidt R A, Nishikawa R M, Schreibman K, Giger M L, Doi K, Papaioannou J, Lu P, Stucka J and Birkhahn G 1994 Computer detection of lesions missed by mammography *Proc. 2nd Int. Workshop on Digital Mammography* (York, UK: Elsevier) pp 289–94

Schoenhagen P, Halliburton S S, Stillman A R, Kuzmiak S T, Nissen S E, Tuzcu E M and White R D 2004 Noninvasive imaging of coronary arteries: current and future role of multi-detector row CT *Radiology* **232** 7–17

Seeley G W, Roehrig H and Hillman B J 1984 A computerized method for the measurement of conspicuity: comparison of film and digital nephrograms *Invest. Radiol.* **19** 583–6

Shaw R 1963 The equivalent quantum efficiency of the photographic process *J. Photogr. Soc.* **11** 199–204

Sonoda M, Takano M, Miyahara J and Kato H 1983 Computed radiography utilizing scanning laser stimulated luminescence *Radiology* **148** 833–8

Swensen S J, Gray J E, Brown L R, Aughenbaush G L, Harms G F and Sears J 1993 A new asymmetric screen-film combination for conventional chest radiography: evaluation in 50 patients *Am. J. Roentgenol.* **160** 483–6

von Schulthess G K, Steinert H C and Hany T F 2006 Integrated PET/CT: current applications and future directions *Radiology* **238** 405–22

Wagner R F 1977 Toward a unified view of radiological imaging systems: Part II. Noisy images *Med. Phys.* **4** 279–96

Wagner R F and Weaver K E 1976 Prospects for x-ray exposure reduction using rare earth intensifying screens *Radiology* **118** 183–8

Yamagata H, Hashimoto S, Ema T and Tanaka Y 1999 Development of a new display method for compound 3D ultrasound images *Toshiba Med. Rev.* **70** 43–6

Yerushalmy J 1955 Reliability of chest radiography in the diagnosis of pulmonary lesions *Am. J. Surg.* **89** 231–40

Yoshida H and Dachman A H 2004 Computer-aided diagnosis for CT colonography *Semin. Ultrasound CT MRI* **25** 404–10

Yoshimura H, Xu X W, Doi K, MacMahon H, Hoffmann K R, Giger M L and Montner S M 1993 Development of a high quality film duplication system using a laser digitizer: comparison with computed radiography *Med. Phys.* **20** 51–8

Zhao W and Rowlands J A 1995 X-ray imaging using amorphous selenium: feasibility of a flat panel self-scanned detector digital radiology *Med. Phys.* **22** 1595–604

Biography

Kunio Doi received his PhD degree from Waseda University, Tokyo, Japan in 1969. He then joined the Department of Radiology at The University of Chicago where he is Professor and Director of the Kurt Rossmann Laboratories for Radiologic Image Research, and Ralph W. Gerard Professor in the Division of Biological Sciences. Dr Doi has served as a Commission Member of the International Commission of Radiation Units and Measurements (ICRU), Director of the Graduate Programs in Medical Physics, Associate Chair for Research in Radiology at the University of Chicago and Associate Editor of *Medical Physics*. He has received numerous honours including the Memorial Lecture Award from the Upstate New York Chapter of the AAPM, the Landauer Memorial Award from the San Francisco Chapter of AAPM, the Eugene P. Pendergrass Lecture at the University of Pennsylvania and the Umetani Award of the Japanese Society of Radiological Technology. Dr Doi has published over 520 papers in Journals and Proceedings.