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Digital Radiography: A Review

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The fully digital radiology department remains a radiologist's dream. The technology necessary for implementation does not yet exist other than in prototype form. When the technology catches up with the radiologist's ideas, many new capabilities will exist. Electronically stored images will be available for viewing wherever a computer terminal exists. The problem of film loss would be nonexistent. Images could be quickly transmitted for interpretation via microwave networks to sites far removed from where they are acquired. Patient radiation exposure would decrease. Computers would help decrease perception errors and would assist in image interpretation. It may be ten years before a working digital radiology department exists. However, many processes developed toward this end are now gradually being incorporated into radiology departments. One must therefore be familiar with digital imaging.

We present a review of the current state of the art in digital radiography. Various methods of image capture are discussed comparing pencil-beam, fan-beam, and area-beam systems. Magnetic tape, digital disk, bubble memory, and other methods of image storage are presented with a brief description of their technical and financial limitations. Teleradiology is also discussed citing current working examples of various systems. An overview of image processing is included.

The technology of diagnostic radiology is rapidly changing. The goals are to minimize costs and to obtain more information using less invasive techniques that expose the patient to less radiation. One way to accomplish these goals is to use computers and digital technology.

Current digital applications in many radiology departments include computed tomography (CT), ultrasound, magnetic resonance, and digital subtraction angiography (DSA). These applications are dependent on electronics and/or computers. However, the bulk of radiologic work is still performed using the analog system in which information is captured and stored on film. Much research is underway to change from analog to digital technology to realize a completely digital radiology department.

Digital imaging uses numeric representation of images as opposed to the analog form used in the current film-based system. Digital radiography can be discussed by organization into three areas: image capture, picture archiving and communications (PACS), and image processing.

Image Capture

Most current radiographic examinations are performed using an X-ray source that produces gamma rays. The image is captured on film using a film-screen combination. The advantages of this system include high-resolution images (4 to 5 lp/mm§ or 2.5 lp/mm with a fast film screen) and relative ease in image transportability and storage. Disadvantages are poor low-contrast discrimination and inflexible display. Also, storage and retrieval can become inefficient and expensive.

Converting to a digital acquisition system would solve some of these problems and offer capabilities not before possible. Potential benefits include low contrast discrimination; flexible imaging display (ie, window and level capabilities); digital storage, retrieval, and transmission; and digital image processing.

Currently several methods are used to acquire an image digitally. One method uses a fan beam, eg, CT scanner, to scan the patient. This method limits the amount of scatter radiation by tightly collimating the beam width, thereby decreasing image degradation.

Kattragadda et al (1), Foley et al (2,3), and Huebner (4), working independently, have investigated the use of the "scout-view" capability of CT scanners to create digital images. Commonly referred to as scanned projection radiography (SPR), these systems use a stationary tube detector, and the patient is passed through the fan beam on a moving gantry (Fig 1). Spatial resolution is on the order of 1 lp/mm.

Kattragadda et al (1) have evaluated a prototype SPR unit. A summary of their conclusions cites the advantages of SPR, which include high-scatter rejection, low patient dose, wide dynamic range, and low contrast sensitivity for large objects.

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§line pairs per mm, a measure of resolution.

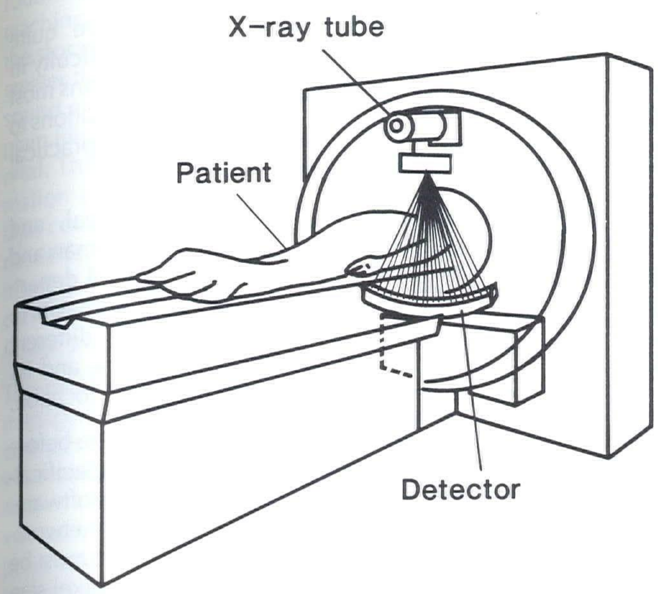

Fig 1
Scanned projection radiography (SPR). Patient passes through thin fan-shaped X-ray beam.

The disadvantages they note are long exposure time and poor high contrast spatial resolution.

The major drawback to SPR is the relatively poor spatial resolution compared with that of a film-based system. To evaluate the acceptable resolution required for digital radiography, Huebner (4) compared 250 chest radiographs obtained using SPR with those obtained using the conventional film-screen system. Using a Somatom SF CT scanner with a 512 crystal detector array, he was able to resolve 1-mm objects of high contrast with a surface dose of 5.9 mRad. He concluded that SPR performed equivalently for objects greater than 2 mm, but significant information was lost when pixel sizes were greater than 1 mm x 1 mm.

Foley et al (2,3) have also investigated the spatial resolution issue in SPR. They used a GE CT/T 8800 unit with 523 Xenon detectors. They compared findings of SPR with those of conventional film-screen radiography in patients who had sarcoidosis, mediastinal adenopathy, and metastatic adenocarcinoma. Their conclusions were similar to those of Huebner. In addition, Foley and colleagues attempted to determine the level of spatial resolution that would allow the detection and discrimination of nodules on chest radiographs. They varied the levels of spatial resolution between 0.3 and 2.5 lp/mm. They concluded that there was no statistically significant difference in observer performance between pixel sizes of 0.2 mm and 1 mm. They commented that in other clinical circumstances this difference in resolving ability would probably be significant. As an example, it appears necessary to use pixel sizes of approximately 0.2 mm to evaluate interstitial lung disease. Although still debated, current research shows that for a digital system to compete with a film-screen system, the pixel size of the digital system will need to be approximately 100 microns. Some specialized needs such as mammography may require pixel sizes of 50 microns.

Rather than modifying existing CT units to become an SPR system, investigators hope that dedicated digital radiographic units will decrease scanning time and improve spatial resolution. Tesic et al (5) have described the Picker dedicated prototype digital unit created for the sole purpose of obtaining digital chest radiographs. This unit uses a vertical detector array consisting of 1,024 scintillator silicon photodiodes optically coupled to a gadolinium oxysulfide screen. Again, this device uses a fan beam to minimize scatter radiation. The initial 12-bit-deep digitization is later compressed to eight bits for easier handling. Scan time is approximately 4.9 sec with a typical entrance dose to the patient of 26 mRad. Pixel size is 0.5 mm x 0.5 mm. This system is essentially limited to chest radiography. Many technical problems occur if this system is used for abdominal or dual-energy imaging (6).

Fraser and others (7) compared the images from the Picker digital chest unit with conventional radiographs of 50 selected patients. Their results indicate that mediastinal structures are better seen on the digital images. However, the major disadvantage is the poor spatial resolution (1 lp/mm). This degree of resolution is not better than that obtained by the SPR units. Other problems they noted included increased tube loading and a skin dose twice that of conventional radiography.

These systems give a glimpse of what digital radiography can offer. American Science and Engineering has created a system with solid-state detectors that creates images in a 1,024 x 1,024 matrix with a resolution of 3 lp/mm. If current attempts to improve resolution to 5 to 6 lp/mm are successful, such a system would be comparable to the current film-based system (8).

Several other methods of capturing digital images are being investigated. Sashin et al (9) described a system with a phosphor strip that is fiber-optically coupled to six self-scanning arrays of light-sensitive diodes spaced 0.025 mm apart. Resolution is determined by the phosphor thickness and not the diode spacing. Phantom results showed a resolution of 3.6 to 6 lp/mm, comparable to the film-based system and the American Science and Engineering system. An advantage of this system is that it moves the detectors out of the primary radiation beam.

Sonoda and colleagues (10) described the Fuji Photo Film Co system that uses a flexible 1-mm plate with photostimulable phosphor crystals and uses an area beam as opposed to the fan beam of the previously discussed systems (Fig 2). The image is stored by the crystals in the plate as energy in quasistable states. The plate is then scanned by a helium-neon laser causing the crystals in the plate to emit luminescent radiation corresponding to the absorbed X-ray energy.

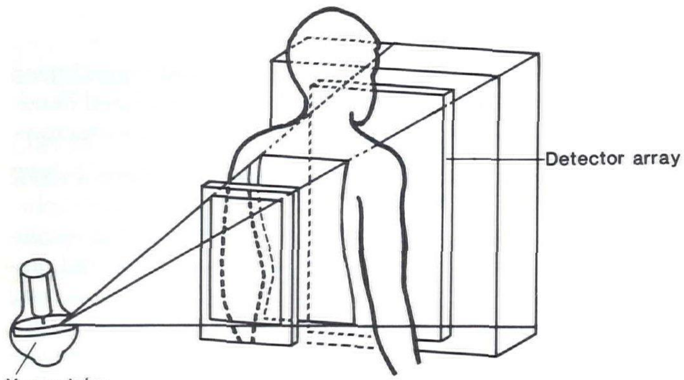

Fig 2
Area-beam geometry showing principle components. Neither patient nor beam move as in SPR.

This luminescence is then converted to a digital signal by a photodetector and A/D converter. Resolution is 1 lp/mm with a skin dose of 2 to 5 mRad. Again, resolution is no better than the SPR systems and the Picker chest unit. The area-beam configuration allows faster scan times but creates more scatter radiation.

Another method for capturing digital images uses an area X-ray beam configuration as described by Papin et al (11). The image is captured on a charged selenium-oxide plate and stored as a pattern of latent electrostatic charges on the plate. The plate is then scanned with multiple electrometer probes to form a 1,024 x 1,024 x 12-bit image. This system, which is still being evaluated for spatial resolution, probably shows the most promise for making digital radiography competitive with film-screen radiography.

Schwenker (12) describes du Pont de Nemour's method that uses the tradition film-screen system to capture the image. The film is later scanned with a laser converting the image into digital form. The du Pont company has developed a wide latitude film particularly suited for this purpose. Their system creates a 2,000 x 2,000 x 12-bit image that is displayed on a 1,050-line video display. However, film is an integral part of their system, where most of the other systems are filmless. In preliminary evaluations, the system appears to have resolution comparable to that of film.

The most well-known system that uses the area-beam configuration is used in DSA. In this system an image intensifier is coupled to a video camera. This configuration allows real-time temporal subtraction, which is not possible with the current film-based techniques.

Stein (13) and Tateno and Tanaka (14) describe systems that use a scanning pencil beam (Fig 3). Exposure can be varied almost continuously over the regions of interest, resulting in an image with proper exposure throughout and an overall decrease in radiation exposure to the patient. This type of beam configuration has not received too much interest because scan times would be inordinately long.

Picture Archiving and Communications

Storage and retrieval of radiographic images are quite cumbersome. The large space requirements and difficulty in locating and retrieving films make these considerations most frustrating. Digital radiography potentially offers solutions to all these problems, although it is not currently practical financially.

PACS refers to the functions of storage, retrieval, and transmission of digitized radiographic images. Bauman and Lodwick (15) listed the advantages of a fully digital department as rapid retrieval of images, transmission of images to other areas, simultaneous viewing of images in different areas, provision for including reports with images, and integration of all of the patients' examinations in one location.

They also listed the problems that must be overcome before radiology departments can become fully digital. Specifically, industry must standardize both hardware and software. Hardware must provide faster processors, improved networking, and a more efficient storage medium. Software must be coordinated with the hardware. Images of proper pixel size and depth must be determined. Interfacing with physicians must be effective, fast, and friendly.

As more and more radiologic examinations are performed in the digital format, an efficient cost-effective storage method will be required. Currently, the cost of storing large amounts of digital data on magnetic tape or disk for any significant length of time is quite expensive. Dwyer et al (16) have estimated the cost of storing digitally acquired images for a 614-bed teaching hospital. Their estimate includes storage of images acquired in the departments of CT, nuclear medicine, ultrasound, and a few digital images acquired during

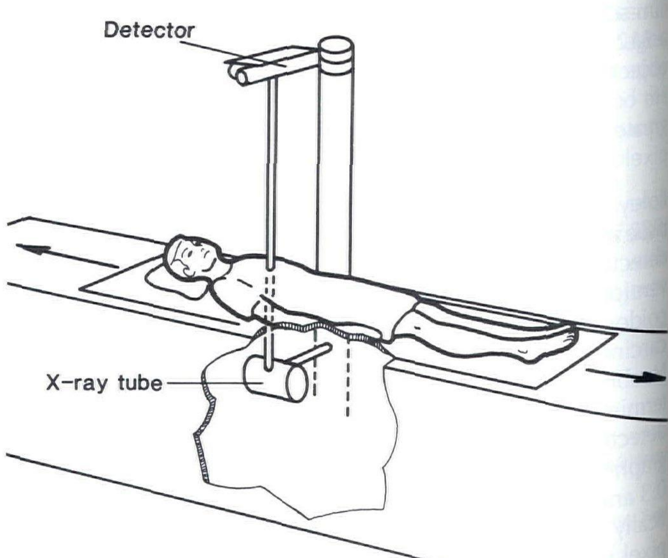

Fig 3
Scanning pencil-beam configuration. Beam and/or patient must move to obtain image.

routine examinations. If Henry Ford Hospital (a 980-bed teaching hospital) used a digital format to acquire all images, the storage costs would be two to three orders of magnitude greater than Dwyer's estimation. Approximately 12,000 ultrasound examinations, 8,400 CT examinations, and 300,000 plain film examinations are performed each year at Ford Hospital. This amounts to approximately 3.6 x 10^{13} bits of information per year. Storing this amount of data on magnetic tape could cost over a billion dollars, which is obviously not cost-effective. Dense and inexpensive methods of storage must be developed before a completely digitized department can become a reality. Even then, there will be a need for image purging.

Templeton and others (17,18) described a digital image-management system that uses networking. The system interconnects CT, nuclear medicine, and ultrasound departments via coaxial cable. Images are stored on magnetic disks. The system can acquire, store, or display images, or can perform various combinations of these functions. Images are stored peripherally rather than centrally. Although expensive, the system exemplifies the potential for the digitized department. Because the microcomputers cannot handle data faster than one megabit/sec, image data throughput on the Ethernet system was limited. Templeton et al suggested that specialized hardware and fiberoptic cables could correct this problem.

Even with faster networking, cheaper and more efficient methods of storage remain the major technically limiting factor in digital radiography. Currently available magnetic tape and magnetic disks cannot store large amounts of digital information cost-effectively.

High-density magnetic tapes that contain 100 tracks with approximately 10,000 bits/inch (as opposed to current tapes that only use nine tracks, often with lower bit densities) are a step in the right direction.

The optical video disk and digital disk offer efficient storage of approximately 10 billion bits of data per side at the estimated cost of 0.001¢ per bit (1/10 that of magnetic tape) (19,20). Information is coded into the disk by a laser that burns miscroscopic pits into the disk surface. The information can later be recovered by the laser beam. Further developments may allow a process whereby the disk can be reused. Also, development of a disk that can hold 100 billion bits of data per side is being investigated.

Bubble memory (21) offers potential solutions to the storage problem. Basically, bubble memory is an integrated circuit that stores data magnetically. Intel has a 128k-byte bubble device that holds a single video frame (480 x 480 x 4) in the prototype system. Eleven seconds are required for storage. Intel is currently developing a 4M-bit device. Further developments may make bubble memory surpass the density of optical disks, making it practical for storing radiographs.

Methods to decrease the amount of information to be saved will also help solve the storage problem. Storage demands will decrease if only selected images are saved and data compression is utilized.

Image compression uses a collection of mathematical techniques to provide compact storage and faster transmission of digital information. Two basic coding schemes exist: noisy compression, which allows compression of data by a factor of 20 to 30 times, but its partial recovery is unacceptable, and noiseless compression (complete recovery), which allows compression only by a factor of three or four, making its worth questionable (22,23).

Although an efficient and cost-effective storage medium presents a problem to digital storage, an equally great technical problem is that of creating a display with sufficient resolution. Most CRTs operate with a 512-line screen with a refresh rate of 60 Hz. The resolution required for diagnostic radiography requires screens with a resolution perhaps as high as 2,000 lines per picture height. However, as video devices are created with resolution above 1,500 lines, scanning at rates to provide flicker-free viewing becomes difficult (24). Multibeam technology may provide the solution to this problem (25). State of the art in CRT resolution is approximately 4,000 lines per picture height.

It is possible that high resolution displays may use an entirely different technology than that of the CRT. A potential medium might be to use liquid crystal displays, although this technology has yet to be developed.

Teleradiology

Teleradiology is the transmission of radiographic images to distant sites via either telephone lines or microwave network. Analog transmission, such as that which allows transmission of television signals, is of insufficient quality for interpretation of diagnostic images (26). Most teleradiologic work currently involves the transmission of digital images.

Regular telephone lines are designed to carry audio signals at a rate of approximately 10,000 bits/sec. A 512 x 512 pixel image eight bits deep would require approximately three to four minutes to transmit. Unfortunately, the error rate on voice-grade phone lines is 10%. In addition, diagnostic images often require resolution of 2,000 x 2,000 pixels x 12 bits deep with a transmission time of a single image considerably longer. Use of dedicated high-speed telephone lines would solve this problem.

Dedicated high-speed telephone lines operate at speeds of 1,200 to 9,600 baud (1 baud = 1 bit/sec) with error rates much less than the 10% error rate of voice-grade lines. Lines that can carry information at 56,000 and 1.5 million bits/sec are less common and are difficult to obtain.

As an example of the necessity of fast transmission, Carey (27) postulates that using a regular phone line at 1,200 baud to transmit 17 skull radiographs of 512 x 512 x 8 bits each would require 36 hours and 16 minutes at a cost of approximately $720. Obviously, teleradiology that utilizes phone lines will require faster results and cheaper rates to be practical.

Gayler et al (28) and Curtis et al (29) have investigated a teleradiology system that uses a 9,600-baud transmission rate for 512 x 512 x 8-bit images. They found that the radiologist's interpretation of findings, impressions, and confidence levels in the transmitted images were less than that when the original radiographs were viewed. Again, transmission times were impractically slow. If the images had a resolution of 2,000 x 2,000, then transmission times would have been approximately 16 times as long.

Greater speed can be gained by microwave transmission of images, which requires the use of transmitting towers in the line of sight. Sol (30) describes a system that allows the radiologist to monitor fluoroscopy procedures remotely by connecting two locations by microwave towers. The angiographic procedure is performed in one location and monitored one-half mile away. This appears to be the most practical method in which line-of-sight towers can be constructed. Only the fastest telephone lines allow practical rapid transmission, yet these special lines are expensive and not readily available.

Image Processing

Although digital image acquisition, storage and retrieval, and transmission offer significant advantages over the current film-based system, the potential to use digital image processing probably offers the most innovative opportunity in digital radiology. Digital image processing gives the radiologist assistance in viewing and in extracting information from the radiologic procedure. This ability is nonexistent in the film-based radiology system.

The simplest forms of digital image processing are used in CT scanners where windowing and level adjustments allow viewing of particular tissues at various levels of contrast. Simple quantitative information is also available enabling the measurement of attenuation coefficients over specific regions of interest.

Computer analysis of pictures has been ongoing by engineers and scientists, particularly in military applications. Image analysis is performed for the improved detection of features in degraded images, for obtaining descriptions of objects in a scene, and for extracting certain objects or parameters while suppressing others. Recently, there has been much interest in applying these techniques to analyzing radiographs.

Image processing is achieved through the use of simple filters, smart filters, pattern recognition and scene matching, and artificial intelligence techniques.

Simple filters are routines such as high-frequency filters that perform edge enhancement. An example is unsharp masking, which enhances high-frequency information, while partially suppressing low-frequency information. An example of unsharp masking performed on digitized images from an air-contrast colon examination is shown in Figure 4. Figure 5 is an example of another simple filter that performs the

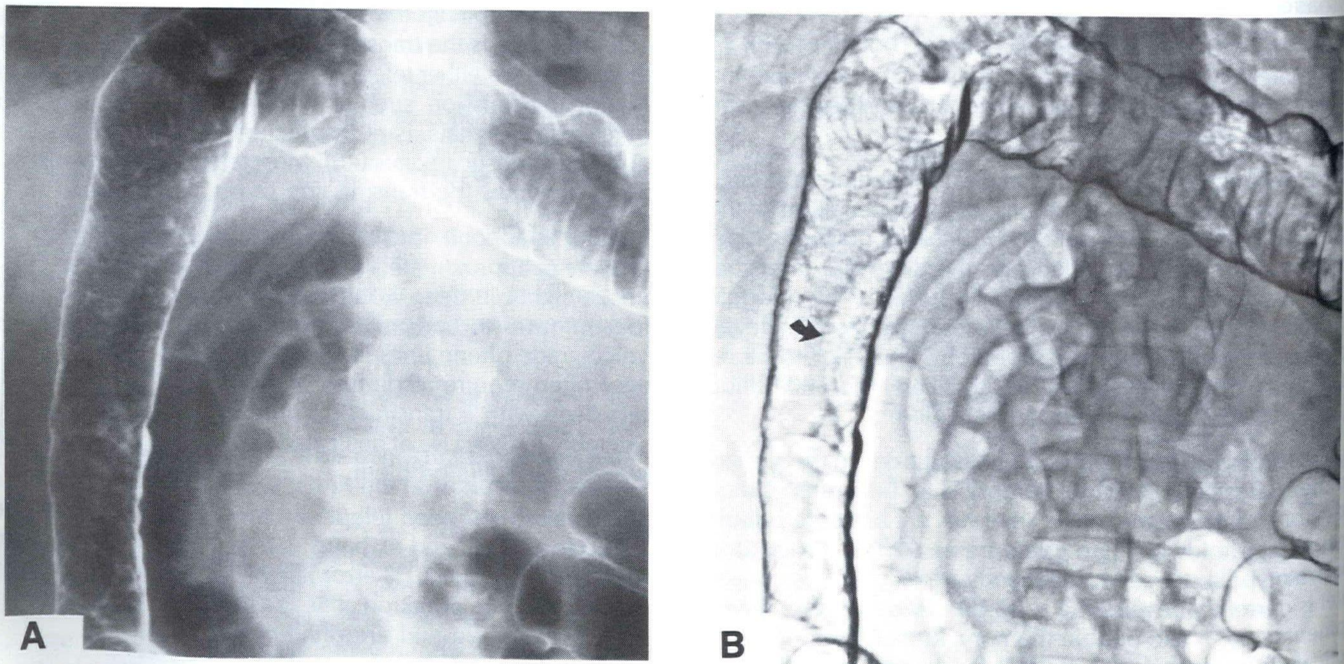

Fig 4
Unsharp masking with gray-scale reversal. Edges are enhanced. Note increased clarity of ulcer in patient with Crohn's disease (see arrow). Original (A); processed image (B). (Images digitized courtesy of E.I. du Pont de Nemours & Co, Inc, Wilmington, Delaware.)

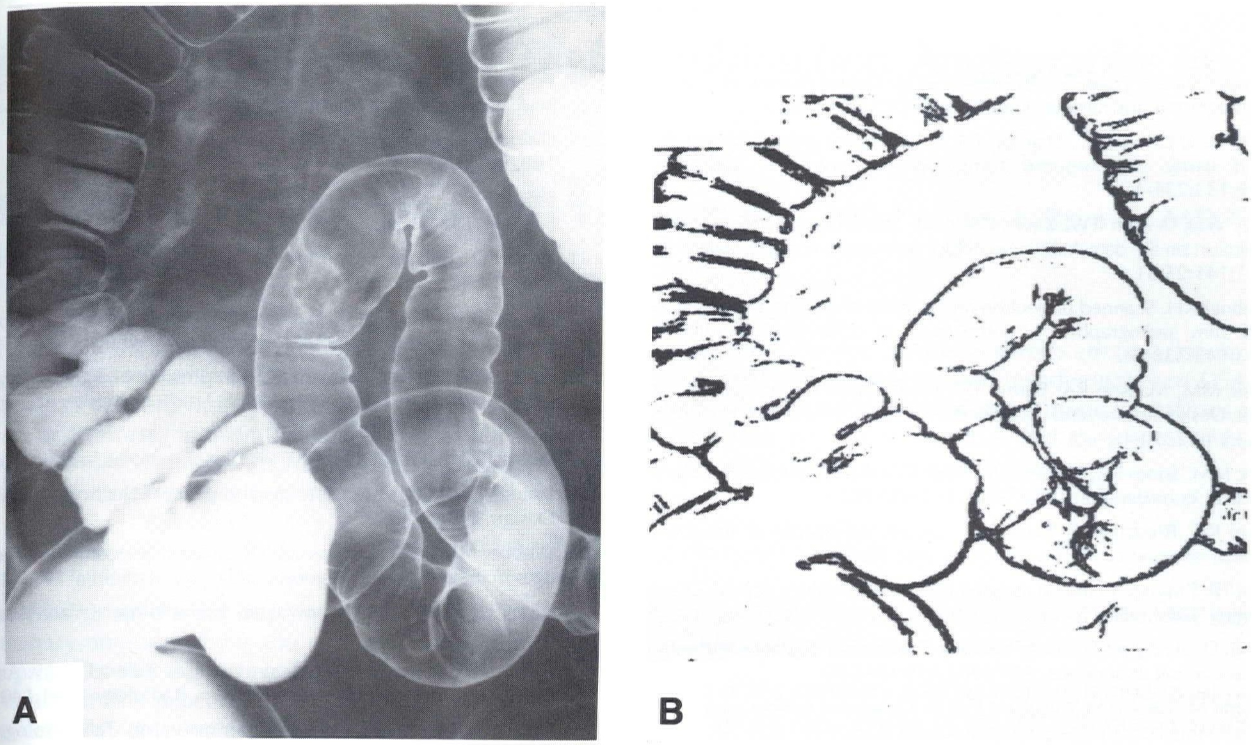

Fig 5
Original image (A). Derivative image (B) creates line drawing of colon of original image. (Distorted size and shape of processed image is technical artifact due to dot-matrix printer.)

derivative of an image, creating a line drawing of the original image.

Smart filters detect characteristics of objects. The program developed by Shadagopan et al (31), which quantifies duct patterns on xeromammograms, is an example of a smart filter. Utilizing this program, Shadagopan found that the computer's duct measurements could be used in ranking cases, providing a system of classification similar to the N1/P1/P2 system described by Wolfe (32).

Mathematics are used in pattern recognition to detect features that correspond to certain shapes such as curves or circles. Tully et al (33) described an attempt at pattern recognition to distinguish between normal, alveolar, and interstitial patterns on chest radiographs. Results of this feasibility study showed that the computer had an overall correct diagnosis rate of 90% for the test cases. Hand and colleagues (34) described an automated system for screening xeromammograms to locate breast abnormalities. Their first generation of routines correctly identified 87% of suspicious areas on xeromammograms with a false negative rate of 13.3%.

The most sophisticated area of image processing couples simple filters, smart filters, and pattern recognition with intelligent search routines using artificial intelligence techniques. Ackerman et al (35) have created a system that identified and correctly diagnosed mass lesions on CT scans of the head. Image processing is attractive because it can reduce costs by decreasing retakes, thereby reducing patient exposure.

Conclusion

It is exciting to imagine a digital radiography department. Logistics would be vastly simplified because images would be electronically stored, immediately available, and infinitely duplicable; the loss of films outside the radiology department would be nonexistent. Technicians could make greater use of imaging rooms because the need for retakes would be eliminated, and interaction with a radiologist could occur over the image network. Computers would help decrease perception errors, and the network would speed the image with a radiologic report to the consulting physician. Exposure also would drop, and diagnostic radiology would be more cost-effective with the ability to analyze images from distant sites sent over microwave.

Exciting! Why not implement it not? The technology needs to catch up with the radiologist's dream. The processes discussed here are just beginning to be formed. It may be ten years before an all-digital radiography department becomes a reality.

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