Digital radiology at the 1996 RSNA Congress

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Substantial progress in digital imaging in radiology has been made over the past 10 years. Despite this and the many theoretical advantages, digital radiography has yet to supersede conventional X-ray film. One of the reasons for this is the lack of a single clearly superior digital system. This deficiency drives a great deal of current commercial and academic research and development.

The main reason for attending this congress was to obtain information on the latest developments in digital imaging, with particular attention being paid to digital radiography. Throughout the six day congress scientific and technical papers and exhibits with a bearing on digital imaging were attended. The recently introduced Inforad section, which covers exclusively computer and network-related topics in Radiology, was particularly rewarding.

More computers and network appliances than ever before were evident, with high-end Silicon Graphics and Sun workstations widespread throughout the manufacturers exhibits, and the scientific and Inforad displays.

The interest and activity in the digital imaging field was such that there was invariably a presentation connected to the topic during every session. The majority of these presentations and exhibits dealt with technical issues, although a few did take the clinical perspective. There was a particularly strong research emphasis on the various methods of direct digital image acquisition.

An introductory presentation by Doug Tucker (Houston, Texas) proposed the ideal scenario of a computer-based patient record allowing full integration of all relevant information for that patient, including medical records, radiology images, laboratory and pathology results, and scheduling and billing information. The HL7 guidelines dictate patient information standards, whilst the DICOM 3 (Digital Imaging and Communication in Medicine) standards cover image-related information and communication. DICOM 3 evolved from the earlier American College of Roentgenology / National Electronic Manufacturers Association (ACR/NEMA) standard.

Measures of image quality

The major steps of any imaging process are:

- Acquisition
- Transfer
- Storage and retrieval
- Processing
- Display

The conventional analogue radiographic film-screen cassette is a well matched and effective combination. Optical density varies smoothly as a function of position with such an analogue image, whereas this change occurs in discrete steps in a digital system. Spatial resolution and contrast resolution are two important image quality criteria for either type of image. Spatial resolution (also known as high contrast resolution) is the area of signal represented, while contrast resolution is the number of different levels represented. Spatial resolution can also be considered the resolving power; "the ability of an optical system to distinguish images of objects that are separated by small angular differences" (dictionary definition). Spatial resolution is measured by the maximum number of detected line pairs per millimetre. Contrast can be measured by densitometer. The most important information-bearing part of the image was felt to be the medium lp/mm component. Image noise is a further important element. The human eye needs at least a signal- to-noise ratio (SNR) of 1.5 to 1.7 to detect information.

The Fourier theory regards the spatial and frequency domains as equally valid representations of an image. Nyquist sampling theory links the limiting frequency to the spatial domain by the equation f=1/2 delta, where f is the frequency and delta is the sampling period or pixel size. In practice one should be able detect one level poorer than the theoretical Nyquist limit. Aliasing artefacts arise when high frequency information is spuriously represented as low frequency information. Insufficient contrast resolution can lead to "banding" or contour artefacts.

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Digital imaging

Image acquisition

Digital radiological images can be obtained by:

1. Digitising a conventional analogue image such as a radiograph;or
2. (a) Indirectly, or;
   (b) Directly capturing the pattern of X-ray photons in a digital format.

Indirect capture takes place with computed radiography (CR), while direct radiography (DR) provides direct conversion of X-ray photons to electrons.

Digitisers

These are a compromise interim option, allowing some of the benefits of digital radiography to be experienced.

Digitisation of conventional analogue radiographs relies largely on either (a) laser or (b) charge-coupled devices (CCD) types.

In laser digitisers, a laser beam scans across the film and is measured by a light collector. The CCD type uses a uniformly illuminated row of lenses focusing on an entire line, reading out the data serially in a "bucket-brigaded" CCD sequence.

Transmitted light is converted to optical density by an inverse logarithmic function. A log lookup table or logarithmic amplifier (log amp), together with an analogue digital converter (ADC) are used. Log amps are difficult to design and build, and are expensive and inherently unstable. It is technically advantageous to have the log amplifier precede the ADC. This arrangement avoids "blocky" images with posterisation artefacts, although it may be more noisy and less effective for dark film. Binary counts from 0-4000 map to optical densities from 0-4. At density levels above 2, one percent or less of the light is transmitted. Antiblooming technology has been developed to prevent the spillover of light from adjacent areas affecting the readings.

Comparison between laser and CCD digitisers

The laser digitiser offers variable resolution while the CCD digitiser usually has a fixed resolution. Both the optical density (OD) range and resolution are better for laser type digitisers. The laser provides better density accuracy and signal-to-noise ratio (SNR)- the CCD type is approximately twice as noisy. CCD-based digitisers are less able to accurately digitise very dark films and generally cut off at optical densities of 3.0 or 3.2 as compared to 3.5 for laser scanners. This is less problematic in the lighter areas of the image.

Testing digitisers

The simplest test of accuracy is comparing the known OD with the resultant pixel value obtained after digitisation. Contrast-to-noise ratio is another useful measure of performance. Other parameters which can be evaluated include contrast and spatial resolution, pixel size and glare. One test object for evaluating digitiser performance consists of a radiograph of 5 rows of 32 optical step wedges each increasing in contrast by 3%. A test step wedge radiograph can also be created by stepped exposure of film. Further items include contrast resolution and modulation transfer function tests, a variety of test patterns, blacked-out regions and sets of line pairs.

A rectangle cut out of dark film is a useful test for glare. Glare is normalized as the percent of the film square's values less than the peak quantity. Glare is seen at edges of the square, and as a tail due to detector signal spill-out causing CCD "blooming".

Charge transfer function is measured by digitising 14 inch black and white squares and counting the pixels. A large 3 step wedge is useful to test uniformity of response from side to side. Signal "pegging" and "flatlining" may be seen where the system reaches its limits of tolerance.

An additional test for accuracy uses a modified Society of Motion Picture and Television Engineers (SMPTE) pattern printed onto mylar.

Automated measurements of digitiser parameters by computer are possible. Scanned images can be saved as a file and analysed by computer in under 5 minutes.

Computed radiography (CR)

Three manufacturers at present offer computed radiography systems. These are Fuji, Kodak and Agfa. All three of these companies are also major film manufacturers.

Computed radiography (CR) initially acquires the latent radiographic image (i.e. the pattern of x-ray photons) into a storage (or photostimulable) phosphor plate of similar dimensions to X-ray film. The image is recorded by radiation boosted electrons being caught in electron traps in the storage phosphor (SP). The SP plate is subsequently processed using a cabinet-sized laser reading device. This releases the stored image, converting it into a digital format. SP plates were introduced in the 1980s, and dominate the digital radiography market. The Fuji system has been available for the longest period.

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Technical details

The storage phosphor plate structure has a support base, the phosphor layer containing BaFBrI:Eu2+ (barium fluorohalide doped with europium) and a protective coating. A unique bar code for identification of the plate is included. Standard Fuji plates cover a 2k by 2k matrix with approximately 100 micron pixels. This allows visibility of up to 2.5 to 5 lp/mm compared with 6 or 7 lp/mm for regular x-ray film. Contrast resolution is 10 bits deep. The new high resolution HQ model has a 4k by 5k matrix and 43 micron size pixels. This appears to reduce image noise but otherwise provides similar image quality to the standard plate. Digital image sizes vary from 8-32 MB.

The phosphor plate has a k-edge lower than conventional film, at approximately 40 kV, which increases sensitivity to scatter. Scatter can be limited by a lead back-scatter layer either within the cassette or layered onto the plate.

CR has an exposure range of 4 compared to that of 1.6 for conventional film, i.e. it has greater latitude. CR avoids entering into toe or shoulder regions of the photographic H and D curve.

Two operations are performed during the laser readout. A helium neon laser light scans transversely across the film it is slowly fed into the reader by small increments. Laser light has a different spectrum from the emitted light, allowing filtration and exclusion of laser light from the detectors of the photostimulated photons. This method of scanning and feeding give rise to two different resolutions; one in the transverse plane, the other in the longitudinal direction.

The CR system then needs to identify image-bearing data in the raw digital output. High and low ranges are defined, and a pixel frequency histogram is evaluated. This can be a cumulative or integral histogram. The shape of histogram is largely determined by the radiological study being undertaken. The computer checks the histogram and attempts to exclude irrelevant data. Agfa uses the "Musica" technique, based on a square root transform of the digital data, to analyze images before optimising processing. Kodak uses "multitonal analysis". Air, metal or contrast material can confuse the readout algorithm causing an overshoot artefact.

Some CR systems operate at 12 bits of contrast resolution, but may reduce to 10 bits during processing. Most CR systems are set to deliver a finite number of pixels in the final image for a specific study. This can give rise to poor detail when multiple images are taken on a plate intended for a single image. Each image then only uses a portion of the available pixels.

Clinical applications

Current usage is dominated by portable (mobile), intensive care unit (ICU) and paediatric radiography. Emergency room work is problematic during peak periods where a throughput exceeding 30 to 110 films per hour is required as the unit is fairly slow, processing 70 films per hour at best.

In practice the patient is positioned, the beam is collimated and the exposure made. Radiographic factors are typically 75 kV using a phototimer with a 0.5mm Cu filter. Aluminum filtration is recommended for high kV chest images. A change of mAs affects only mottle, not image density. Pale CR films are not usually due to underexposure but are often the result of over-collimation. The kV is used to control film density.

Under or over exposure is less of a problem with CR. Retake rates drop from 5-7% with conventional film to 1% with CR. Up to twice the conventional exposure may be required, however. CR tolerance to overexposure gives rise to mAs "creep" as radiographers learn to opt for higher doses to ensure a usable film. It is possible to track exposures by using Agfa's Sensitivity number (S), which is an exposure indicator. This should ideally be approximately 200. Kodak uses an Exposure Index, defined as 2000+1000xlog(x)mR. Dose reduction with CR is felt to be impossible by most. Others feel that normal film screen cassettes are often overexposed and that with CR, exposures can be reduced by 60 percent.

A grid should be used for large patients as the phosphor plate is a scatter sponge. Digitised images are prone to develop Moiré patterns with grids. The exposure should be reduced by 50 percent without a grid.

The major cause of error in CR is patient positioning. Collimation has become more critical. Double exposures are more likely with the higher latitude. Choosing a smaller cassette is important to provide better detail.

The type of study performed is entered into the machine. The subsequent processing largely depends on this information e.g. a mammogram needs dark areas to be visible. The S value is the amplification factor required to adjust the image to viewable levels with the Fuji system. A variety of HD curves can be chosen to attempt to compensate. Individual

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adjustments of machines in a department should be avoided to enable consistent configuration management.

Identification terminals and HL7 compatibility are important patient information considerations.

Initially CR images were printed onto small 8" by 11" films to reduce apparent image noise, leading to early doctor resistance. Larger films are now available.

Musculoskeletal work is well suited to digital radiography. Problem areas conventionally include:

- The "swimmers view" of the lower neck is notoriously difficult and is repeated 50 percent of the time when using normal radiographs.
- Shoot-through lateral hip views are another challenging area.
- Limited dose is important for paediatric and scoliosis patients. For scoliosis, fine detail is not critical, the patients are frequently young and often need examinations at regular intervals.
- Ribs, low density foreign bodies, calcifications, air, masses and arthrograms are all well demonstrated by CR. For detection of subtle fractures and subperiosteal resorption a spatial resolution of up to 5 lp/mm is required.
- Thick areas such as the lumbar spine perform poorly with CR, possibly largely due to noise. Excessive processing only serves to increase the noise; the solution is to boost the dose.

Dual energy imaging is possible by switching kV. Portal films from radiotherapy units are feasible.

CR is a fairly mature technology, but it raises a new quality control dilemma in that optical density and dose are no longer related. Noisy images are often the clue to underexposure.

Problems

1. Operational

a) Computed radiography is more complex than conventional film radiography.

b) Slow throughput is a problem. Seventy plates can be processed per hour.

c) The 8" by 10" film initially provided required a learning curve of months to view adequately.

2. Physical

a) The plates are susceptible to dirt scratches.

b) The plates wear out physically, lasting on average 1000 exposures or one year.

c) The current generation of Fuji plates (model ST Va) have a thicker protective layer to prevent cracking when fed through the curved rollers of the laser reader.

3. Physics

a) Image noise is a major issue.

b) Specific artefacts may be encountered.

c) Thicker phosphor screens spread light, limiting spatial resolution.

d) Erasure of phosphor plates is necessary to avoid double exposure.

e) Fogging and charge depletion can be problematic.

f) The plates have low quantum detection efficiency.

g) Europium emits light at 400 nm wavelength, while helium neon laser stimulation occurs at 650 nm. Solid state lasers are not suitable for use with Europium as the wavelengths are too close together.

4. Software

a) The need to choose a particular processing algorithm can lead to errors.

b) Aggressive purging of patient and examination data are essential to avoid mislabeling.

c) Masking collimation borders and backgrounds is required to avoid misleading the analysis program. Attempts are being made to automate this.

d) Images may fall outside the area of computer analysis especially if a number are exposed on one plate, causing inappropriately processed images.

e) Gas, metal and contrast agents can confuse the image analysis program.

Testing and quality control of CR

This covers both acceptance testing of new equipment and ongoing quality control. Hardware, software and operator factors all need consideration. Exposure index reporting, uniquely identifying and logging each machine and each plate, calibration testing and flat field uniformity are important elements. The NCRP 99 publication covers quality control issues. The American Association of Physicists in Medicine (AAPM) task group 10 are publishing acceptance testing and quality control protocols shortly. The ACR teleradiology standards have some areas of relevance.

Testing methods

1. Leeds test objects (TO): Leeds TO, Leeds TOR, Leeds TO.16, Leeds TO.CR and Leeds spatial resolution test phantoms. These are frequently used by UK-based Faxil unit. Low contrast resolution appears to be a major issue in testing. The Leeds TO.16 is widely used for this purpose.
2. ACR phantom.
3. University of Birmingham, Alabama phantom.
4. Nuclear Associates phantom.
5. Anthropomorphic phantoms.
6. The Durham C phantom is a quality control phantom for digital

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chest radiography. This resembles the human chest spatially and on the attenuation histogram.

7. A prototype phantom using 0.5mm copper and 6mm aluminum plates, 25mm Lucite front and back, copper elements and a test object was presented. Details are published in January 1997 *Radiology*.

8. A phantom of beef brisket in alcohol with embedded aluminum wires is used to simulate breast calcifications.

9. Imaging plate dark noise is measured by analysing an unexposed plate.

10. Contrast resolution and dynamic range are best evaluated with a step-wedge type test object, directly comparing the area mean pixel value against the corresponding block number.

11. Spatial resolution can be measured using a bar or star pattern. A test plate should not be imaged at 45 degrees as this can falsely improve lp/mm measures. It should be positioned at 90 degrees.

It is important to test resolution in both directions as the method of readout for each direction differs. Transversely the readout occurs as a result of scanning, while the perpendicular resolution arises from progressively feeding in the detector plate.

Quality can be tested on the final hard copy, or by setting the window width to 1 while viewing a test object or step wedge, and taking the limit of spatial resolution at the point that bridges form between the lines on the MTF plate. Beads on lines are due to noise.

Modulation transfer function (MTF) can be determined with a straight edge. Film readout, software, image readout and frequency reduction all need to be evaluated.

CR quality improvement (QI), quality assurance (QA) and performance improvement (PI) are all similar concepts. QI protocols are not yet firmly established.

ROC curves are frequently used. ROC areas are calculated by the trapezoidal rule.

Dynamic quantum efficiency (DQE) is commonly quoted. It is a percentage measure of how effectively the system converts inherent information, and is charted as percentage versus frequency in cycles per mm. DQE typically ranges from 20 to 5 percent at 4 lp/mm.

High quality focal spot analysis is possible with a Nikon slide digitiser. It accepts dental film and has a resolution of 10 microns, producing 2500 dpi digitisation. The focal spot has a "double banana" configuration. Blurring of the focal spot, including the oscillating magnetic field, are well seen.

A new MOSFET dosimeter is being explored. A luminance meter is required for monitor brightness testing.

New computed radiography developments include:

1. A barium fluoro bromide plus iodide phosphor which shifts the output spectrum, allowing use of a solid state laser detection device. Cerium or Kb R:Cu doping are encouraging for fast emission. These new detectors have better DQEs at all spatial frequencies. Terbium doping is not felt to be a good choice as it delays the electrons' return to lower energy levels, interfering with the scanning readout.

2. Attempts have been made to manufacture transparent phosphor materials to reduce blur, but it has proven difficult to match the phosphor refractive index to that of the binder. It is also problematic to create a phosphor with a crystalline structure or to increase the z value of the phosphor.

3. Normally 5 photomultiplier tubes are used to detect output in the plate reader. By using fibreoptic guides all the output can be fed into a single photomultiplier tube.

Direct digital radiography (DR)

Direct digital radiography is potentially the most exciting alternative to the storage phosphors.

This involves the direct capture of a digital image on an image receiver, either using:

1. A self-contained indirect readout, selenium-based system such as the Philips Thoravision, or;

2. (a) Phosphors optically coupled to CCD cameras, or;

(b) An active matrix photoconductor system.

Thoravision

This dedicated chest radiography device uses an aluminium drum coated with selenium. Once exposed, the drum with the activated selenium rotates and is read out in a similar fashion to storage phosphor plates. Selenium is felt to have better long term potential than CR phosphors. Pixel sampling occurs every 200 microns, corresponding to 2.6 lp/mm, half that of normal film. However, it is felt that spatial resolution is not as important as contrast resolution, and that this is acceptable. An additional 12:1 grid is felt by some to be important as the existing 15 cm air gap does not fully eliminate scatter. The Thoravision (Philips, Holland) can accommodate

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any size patient by adjusting the image geometry to fit standard film output. The equipment is fairly bulky and expensive.

Chest examinations account for 30 to 50 percent of an average radiology practice. Groups of radiologists were asked to compare conventional analogue films with the film generated by the Thoravision. They were asked which images they preferred in the following anatomical areas: Vertebrae, lung, right paratracheal stripe, subdiaphragmatic lung, retrocardiac pulmonary vasculature, disc spaces, carina, azygous vein and azygous recess. Speed of access to image information was also evaluated. Thoravision digital radiography was felt to be as good as or better than conventional film in all these areas.

Phosphor/CCD

After irradiation, **stimulated phosphors** deliver light photons via optical couplings to **CCD cameras,** which in turn produce electrons. These are known as prompt phosphors as the electrons very quickly return to baseline, releasing light photons. A variety of scintillation screens and substances such as cesium iodide (CsI) and zinc cadmium telluride have been used. CsI can be made with a 5 micron, needle-shaped, fibreoptic structure which funnels photons preventing light diffusion and blurring. The phosphor screen is coupled to CCD cameras either by means of lenses or fibreoptic tapers. Lens coupling is inefficient and very difficult to set up, especially for a full field view. The fibreoptic tapers are less efficient where minification occurs, leading to large light losses. Some designs use fibreoptic coupling without any taper to avoid these light losses.

Photoconductor/array

An **active matrix photoconductor system** directly converts x-rays to electrons. Many use similar technology to laptop computer displays, incorporating thin film transistors and storage capacitors. Various photoconductor detectors include amorphous silicon, amorphous selenium or compound metal oxide silicide (CMOS). Amorphous selenium is the most commonly used. It is prone to forming ghost images and therefore needs to be annealed between exposures. The edge enhancement seen in xerography is due to the toner particles and is not inherent to selenium. Practical problems include making the plate large enough, the difficulty of "stitching" smaller plates together, coating the finished plates and the need to protect the electronics from excessive radiation.

Dark field subtraction is useful to eliminate temperature-induced background plate activity. Field inhomogeneity subtraction compensates for variable detector sensitivity.

Many of the new DR systems are being tested with digital mammography because of the smaller area required, despite the greater spatial resolution requirements of at least 4k by 4k matrices. It is interesting to note that as far back as 1975 proposals for the creation of a full field digital mammography unit were being made. An intriguing suggestion of performing digital subtraction angiography with mammography to detect tumour blush was made, based on the observation that breast carcinoma enhances well on magnetic resonance imaging. Temporal subtraction has also been used to detect subtle changes in the mammogram. Magnification digital radiography of mammogram specimens have been useful.

Newer technologies

Phosphor/CCD

1. Swissxray have a commercially available multipurpose C-arm radiography machine incorporating a built-in scintillator coupled to a CCD array.
2. Use of CsI-coupled CCDs mounted in a 6x8 mosaic checkerboard pattern, with non-tapered fibreoptic couplings to reduce light loss. Similar configuration lead apertures above and below the breast are aligned to the CCDs. The image is acquired in 4 stages, with patient radiation limited by lead filtration. A high precision stepping motor is used to rapidly and accurately reposition the X-ray beam and detector arrangement. The checker-board pattern is built up to cover the entire area by rapidly moving the lead filters and detectors in a square pattern, with collimated exposures at every quadrant. It requires 0.33 sec to move the CCDs on their mechanical carrier. The mechanical translation errors are less than 2 microns, with angular errors of less than 25 microradians. The entire mammogram takes 4-5 seconds to perform. The 15 micron pixels are binned (combined) to 30 microns. Seamless imaging without stitching is obtained. As no magnification or demagnification is used, a direct pixel representation exists, matching screen film resolution at 16 lp/mm or better. Scatter rejection is good as the lead filters are mounted both above and below the breast. There is less than 7% overlap of radiation in adjacent squares. No grid is needed, but an air

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gap of 49 mm results in a 19% scatter to primary radiation ratio. The quantum gain is calculated to be 24 electrons per photon. It can be retrofitted to current machines. The breast can be compressed as normal. The dose to the patient is approximately the same as for a normal mammogram. The ACR mammography phantom is the standard phantom used for testing.

3. A slot-scanning digital mammography unit is commercially available as the Fischer Sennoscan. The CCD being used in the unit is a two phase, time delay integrated (TDI) CCD which is front illuminated and whose output is binned. The use of CsI with its 1 ms decay time is felt to be advantageous. The phosphor MTF dominates. Fifty micron pixels are used in a 4k by 5k matrix. It produces 10 lp/mm and takes a total of 4.5 seconds. The scan speed is 1260 lines per second. Problems were initially experienced with a mismatch of the TDI frame transfer speed. Scan degradation occurs as a result of regional areas of nonisotropic magnification.

4. Binary optical techniques have been used to address some of the problems of lens coupling to CCD cameras. In general a lens has poor efficiency and far field aberration (far from the optical centre). Binary optics allows production of computer generated lenses similar to the Fresnel lens. These microstructures can be diffractive as well, and are lightweight and compact with better off-centre function. Binary focusing mirrors may also be possible. Whether it is possible to make a UV lens, mirror or beam splitter is at present unknown.

Photoconductor/array

1. Dupont has sold its direct digital photoconductor matrix technology to Sterling. A replacement for the conventional radiographic cassette based on this is due for commercial release this year. The cassette will be able to plug into network points, and may contain an optical disk drive to store images acquired remotely with mobile units. A dielectric layer in their design prevents the cassette from being used for fluoroscopy.

2. A similar design by John Rowlands (Toronto, Canada) without this layer is used for fluoroscopy, achieving 30 frames per second.

3. The Xerox active matrix flat panel imager (AMFPI) has begun clinical testing. Amorphous silicon (a-Si:H) and indirect x-ray detection are used. This is a 26 cm square, full size monolithic panel receptor with 508 micron squares. An alternate hi-resolution version has 127 microns squares. Pixel sizes under 100 microns on a full chest size panel are anticipated soon. It can achieve 1 frame per second in fluoroscopic mode. This operates at 112 kV and 0.05 mAs. The calibration of the panel remains valid over reasonable periods of time. There is a need for better pixel fill factors and the use of multiplexers.

4. The Faxil unit in Leeds is also testing a selenium based system. This covers a large area and provides a good DQE of approximately 30 percent down to 5 percent. MTF is measured using a 20 micron wide slit angled to the scanning plane. Measure of noise power density *vs* spatial frequency was found to be useful.

5. A linear array microstrip silicon detector has been developed and tested in Trieste, Italy. It uses a 200x300 micron size pixel. Single photon detection is possible with 16 bit density resolution, and achieves 10 lp/mm in the scan direction. A 600 micron slit is used to precollimate the X-ray beam, which reduces the usual dose to one third. The X-ray beam strikes the side of the detector to improve absorption. Resolution is increased by scanning in steps smaller than the pixel size. Total acquisition time is 6 minutes. It is able to accept high count rates. A linear artefact due to lack of normalization of the detector channels has been problematic.

6. Trex, a company recently formed by the amalgamation of Bennett, Continental and Lorad, are releasing a slit scanning digital mammography machine. The flat panel detectors use CsI layered over a glass panel, with a self scanned array made by photolithography. Initial work had focused on Schmidt optical coupling of phosphor to 12 CCDs.

7. General Electric (GE) have a direct digital system available as well, based on selenium layered into an array. A scanning control and multiplexer are incorporated into the device.

8. Massachusetts General Hospital are currently working on a GE flat field mammography unit using a solid state device made with monolithic silicon and a CsI photodiode. The 5 micron needles of CsI need to be sealed from the atmosphere as they are hygroscopic. A microchannel is incorporated within a 2mm thick layer. This panel has 4 million pixels and requires 1/3 second to acquire images. A good S/N ratio is obtained. They use either 100 or 50 micron size pixels (the latter is achieved by repeating the exposure with a half-pixel shift). At present they are unable to comment on clinical image quality. The dynamic range of 1000 compares well with the value of 100 for film screen.

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9. Gas microstrip photon counting detectors are constructed with drift electrodes and charge collection strips etched onto the detector. These are fairly kV dependent, using xenon/methane gas or argon/isobutane. The system is able to achieve 4 lp/mm, and accepts high photon counts. Better resolutions of up to 5.5 line pairs per millimetre are anticipated with higher pressures. A keystone detector geometry is planned.
10. Indium bumps such as used in night sights may offer a new type of detector system.
11. A prototype microchannel gated laser-driven device is being tested at Stanford University.
12. Digital tomosynthesis makes use of arc rotation and a step-and-expose method with 7-15 low dose exposures. A GE 17 x 23 cm digital radiography panel with rapid readout is used. Subtraction with a 1-D blur filter eliminates streaking. Slice thickness is determined by the angles used and cannot be altered after acquisition.
13. Lorad offer a new cellular mammography grid with a grid ratio of 11 cells per square centimetre. This reduces scatter in both axes.

Fluoroscopy

Cardiovascular imaging requires a high frame rate of up to 90 fps, as well as high spatial resolution. Interventional radiology does not need the high temporal resolution but does need a last frame hold facility. Good spatial and contrast resolution are needed and should be approximately 20 lp/**inch** (approximately 1 lp/mm). A 3% contrast difference should be visible, and can be tested with a Leeds test object. CsI predominates as the image intensifier phosphor, with 10 000 times or better intensification overall.

It is really only in fluoroscopy that radiation dose reduction appears to be an issue. Otherwise, there seems to be very little initiative to reduce radiation doses in diagnostic imaging. There is an increasing feeling that the linear, no threshold model of radiation damage should be abolished. Dose assessment of fluoroscopy is fairly complicated in practice.

Various methods are currently in use to limit dose during fluoroscopy. These include:

a) Feedback to the user by means of audible warnings or a speedometer or odometer type dial.
b) Image stacking where sequential images are combined.
c) Maximum opacification, where the DSA program identifies and retains the peak opacification image.
d) Matched filtering.
e) Finite impulse response. This is best for reducing contrast use.
f) Region of interest (ROI) fluoroscopy where only the central area of interest receives the full radiation dose.
g) Binary mask ROI fluoroscopy, an electronic equivalent.
h) Grid-controlled pulsed fluoroscopy from Philips. A grid in the X-ray tube controls X-ray production to within one millisecond. Each beam is a 20 millisecond long pulse. A last-image-hold function is used to fill in the spaces. Screen refresh rates can be adjusted from 3 to 12 fps. At 12 fps a "Charlie Chaplin" effect is noticeable, but the images are well accepted down to 6 fps. This leads to dose reductions of 15 to 60 percent. The dose is measured by the machine during the rise time of 0.01 milliseconds. Tube life is extended and blurring or blooming of the image intensifier (II) is limited.

New developments

A laser driven X-ray source for high speed dual energy subtraction coronary angiography is being developed. A replaceable metal tape is to be used as the anode. A 10 micrometer laser beam creates a plasma on the target. This ejects a fountain of electrons. These return to the positively charged anode producing incoherent X-rays by brehmstraling. The tube moves in a circle, and a crystal monochromator deflects two different energy X-ray beams. Logarithmic subtraction is used. The final product is expected to meet the spatial resolution requirements of 0.5mm, with a pulse duration of 1 nanosecond and a SNR of 3.

Image storage/transmission

A digital radiology department in a typical hospital will generate 8 gigabytes of plain film information per day. It is arguably not necessary to store all these images digitally; rather, the films produced may be kept as permanent records. If storage is to be in the digital format, long term retrieval, speed of access, communications, quality control, integration, medicolegal issues and the DICOM standards are all important considerations. Simple problems such as losing images, image slice localization and lack of implementation of devices such as the redundant array of inexpensive disks (RAID) to speed up image retrieval are presently at the forefront.

The previous radiology report should ideally be available automatically on a separate screen, together with a record of all prior imaging. Intelligent prefetching of images should

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only collect relevant prior investigations. Interruption of the viewing of the current set of images to display a new series of images is desirable. Image quality control is not complete until the radiologist has finished with the image.

The DICOM 3 standard consists of 13 parts with additional sections. It is object oriented, contains entities, objects, conformance statements, services and server-object pairs. DICOM 3 is not yet integrated with other standards.

Integration

Doug Tucker feels that the current picture archival and communication system (PACS) is still very immature. At present imaging information is only shared, and is not integrated with the existing medical information infrastructure. PACS is essentially telemedicine. Image acquisition, data processing and image rendering are presently catered for. Integration of PACS with the radiology information system (RIS) and hospital information system (HIS) is finally being addressed.

The current arrangement is vertically oriented. Components are tuned to complement or compensate for each other. A single individual is responsible for the entire infrastructure. Tomorrow's PACS will be more horizontal, with looser coupling, using a LAN or WAN throughout the whole organisation. All components in the system will not necessarily be known at the time of image acquisition. Manual data exchange, usually through the user at present, will need to be eliminated to reduce redundant and error prone data entry. Patient scheduling should preferably be an automated exchange of data between systems.

An interface engine complying with well defined standards may in future coordinate data. Data is normalized to the context of its use at present; in the future data will be normalized to the context of the entire system.

The new gold standards will be the pixel value, luminance, acquisition devices, CR, digitized film, rendering devices, system behaviour and application definition rather than component, diagnostic task, clinical review, specialty review and device interactions. A well defined pixel value will be supported. Digital data rather than film will be analysed. Established protocols for testing and maintenance will be in place. Standard testing routines using well known phantoms and imaging conditions will provide objective measures. Quality control components, image rendering, film, paper, cathode ray tubes, analogue, digital and others will be the future issues.

Despite all of these potential areas of technical improvement, most problems arise as a result of human error. Careful evaluation of the ways in which humans interact with machines and software will eventually lead to less hostile interfaces with built in error-trapping.

Image presentation

Morphological analysis, consultation and advising relevant investigations are critical components of the radiologist's job. At the human level the usual cause of missing lesions on radiographs is "satisfaction of search", where the detection of one abnormality leads to lowered vigilance for other abnormalities. To avoid this, the "gestalt" search is replaced by a dedicated area-by-area search. Similarly, radiologists will need to view digital radiology images dynamically by adjusting the window levels. Typically, over 45 seconds is required to report from a monitor, which is longer than the time required for plain film reporting. Monitor displays do not show the full dynamic range that film does, although there is work in progress on this aspect. Perceptual linearization implies that equal steps of input should map to equal steps of observer perception.

Robert Allman described what he felt were the "Windmills" in digital radiology; those areas perceived to be problems which would be easily resolved. These non-problems included:

a) Spatial resolution
b) Contrast resolution
c) Image compression
d) Lesion conspicuity
e) Cost justification
f) Radiologist adaptation
g) Diagnostic enhancements, and
h) Grey scale windowing.

What he classified as "Dragons" were the major problems, which included:

a) Availability and adequacy of clinical information
b) Ergonomics, including manual and visual aspects
c) The interactive system including keyboard, keypad, trackball and icon management
d) The excessive hand-eye coordination required
e) Slow monitors
f) Network access
g) Long term retrieval and speed of access
h) Quality assurance
i) Standards
j) Communications, and
k) DICOM integration.

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Monitors

Monitors may be based on analogue, digital or hybrid designs. They need to be reliable, artefact free and consistent. Technical components include the controller, cathode ray tube (CRT), CRT optics, surface coatings and electronics. A 10 bit digital to analogue converter is recommended to prevent overlap of grey levels. Maximum and minimal luminance, characteristic curves and consistency vary from unit to unit and from vendor to vendor. Over time monitors drop approximately 2 candelas per metre square per month. A photometer is needed for good QC. The calibration target is the human visual system, based on the Barten eye model. ACR NEMA "just noticeable difference" (JND) standards are used. The JND is measured on a scale from 0 to 500. Calibration entails measuring a response, defining a goal and confirming the response. It may require creation of a non-linear correcting lookup table (LUT).

Portrait orientation monitors are preferred, but occasional landscape films are a problem to display; a rotating monitor may be the best solution. The use of 4 monitors is ideal, although 2 should suffice for plain film viewing. For CT and MR 4 are needed. Secondary review monitors such as those in ICUs do not require as high resolution as diagnostic monitors.

New display technologies being developed include the use of micromirrors (Texas Instrument) or microprisms on a display matrix, allowing very high intensity displays. New flat panel displays with point electron emitters are also being explored.

Extremely high resolution displays using head mounted, low power microlasers which scan the image directly onto the retina are in use for image-guided procedures, and may expand to other fields.

Image processing

Types of image processing vary from **point** related functions such as windowing, **area** type functions such as edge enhancement and **image** based operations, such as subtraction.

Lookup tables need to be introduced on a large scale. Edge enhancement techniques have not yet been fully evaluated. Modulation transfer function can be boosted by unsharp masking.

Realistic organs can be recreated by considering the tubular structures in the human body as being constructed on splines with adjustable springs and attached cross sections. Adding a wire frame and texture map permits life-like simulations.

More effective 3D reconstructions are possible by defining the following zones in a structure:

- Reflective
- Visible
- Critical
- Transparent

A flight path algorithm can be used to automatically navigate the lumen of a 3D reconstructed vessel or bowel as one virtually flies through it. Start and end points are user selected. The computer identifies the surface, then erodes it, performing automatic segmentation and cross correlation. Thereafter expansion and border detection provide the best path.

A neuroendoscopic simulator allows training on a computerized robotics system. Specific procedures such as lower third ventriculoscopy can be practised. Complications can be included.

A computerised training system for teaching intravenous line insertion, angioplasty and stent placement was also presented. This system has 6 degrees of freedom and uses force robotics to provide tactile feedback. Guidewire, sheath and catheter are incorporated. Contrast can be injected, as can urokinase. Fluid flow is computer-modeled on a Silicon Graphics Onyx Reality Engine. Physics principles will in future be more accurately applied to allow more accurate modeling.

It was predicted that robotic surgery may be able to perform procedures 1000 times faster than the human equivalent.

Laser film printers

A polygonal mirror spins at 5000 rpm, deflecting the variable intensity laser spot across the surface of a film. This film conventionally requires wet chemicals for processing.

New developments:

1. Imation (ex 3M) now produce a dry laser film printer which has almost the equivalent image quality and cost as a conventional "wet" laser film printer.
2. A binary film printer from Helios.
3. Other manufacturers use a dry silver salt and developer mixture embedded in the emulsion.
4. Fuji use microcapsules on the film surface which are activated by heating.

Computed radiography has served to establish digital radiography as a viable alternative to conventional film screen radiography. Whether direct radiography will eliminate the latter is still subject to much speculation.