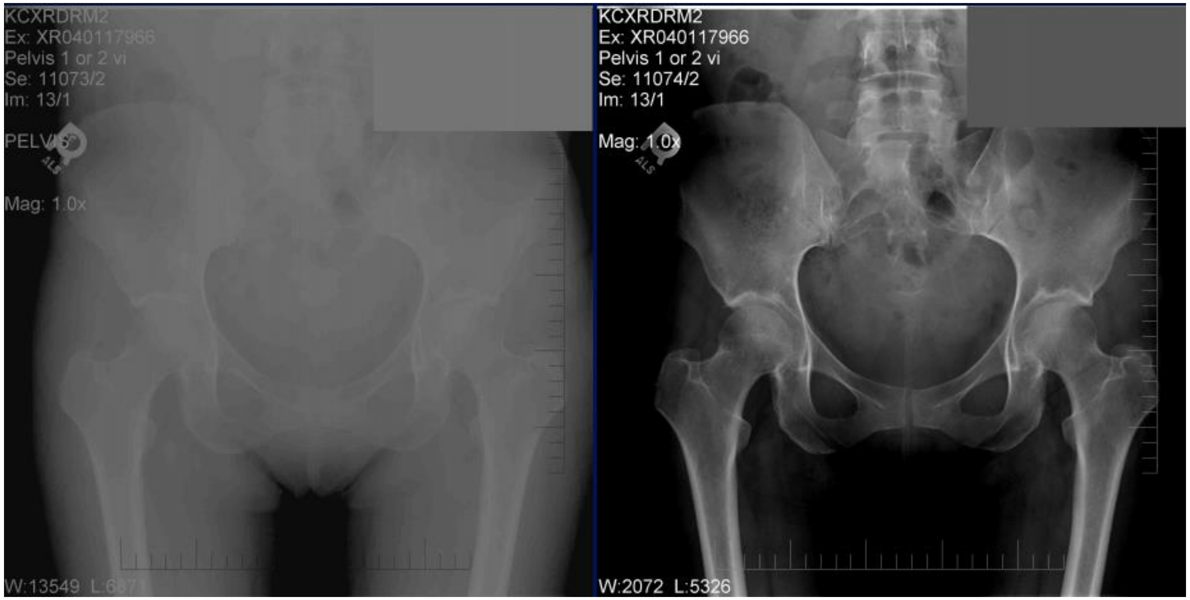
Medical Imaging Systems

Medical Imaging

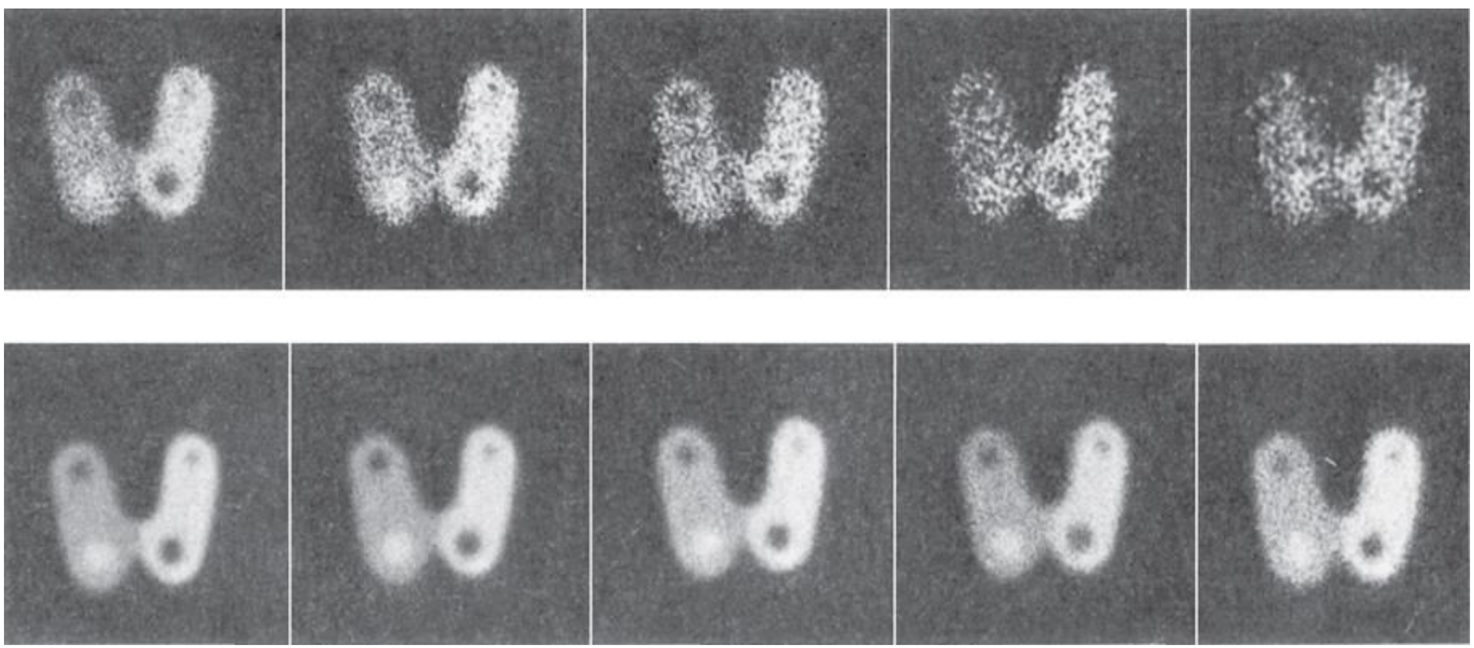
- The overall objective of medical imaging is to acquire useful information about physiological processes or organs of the body by using external or internal sources of energy.

Image properties

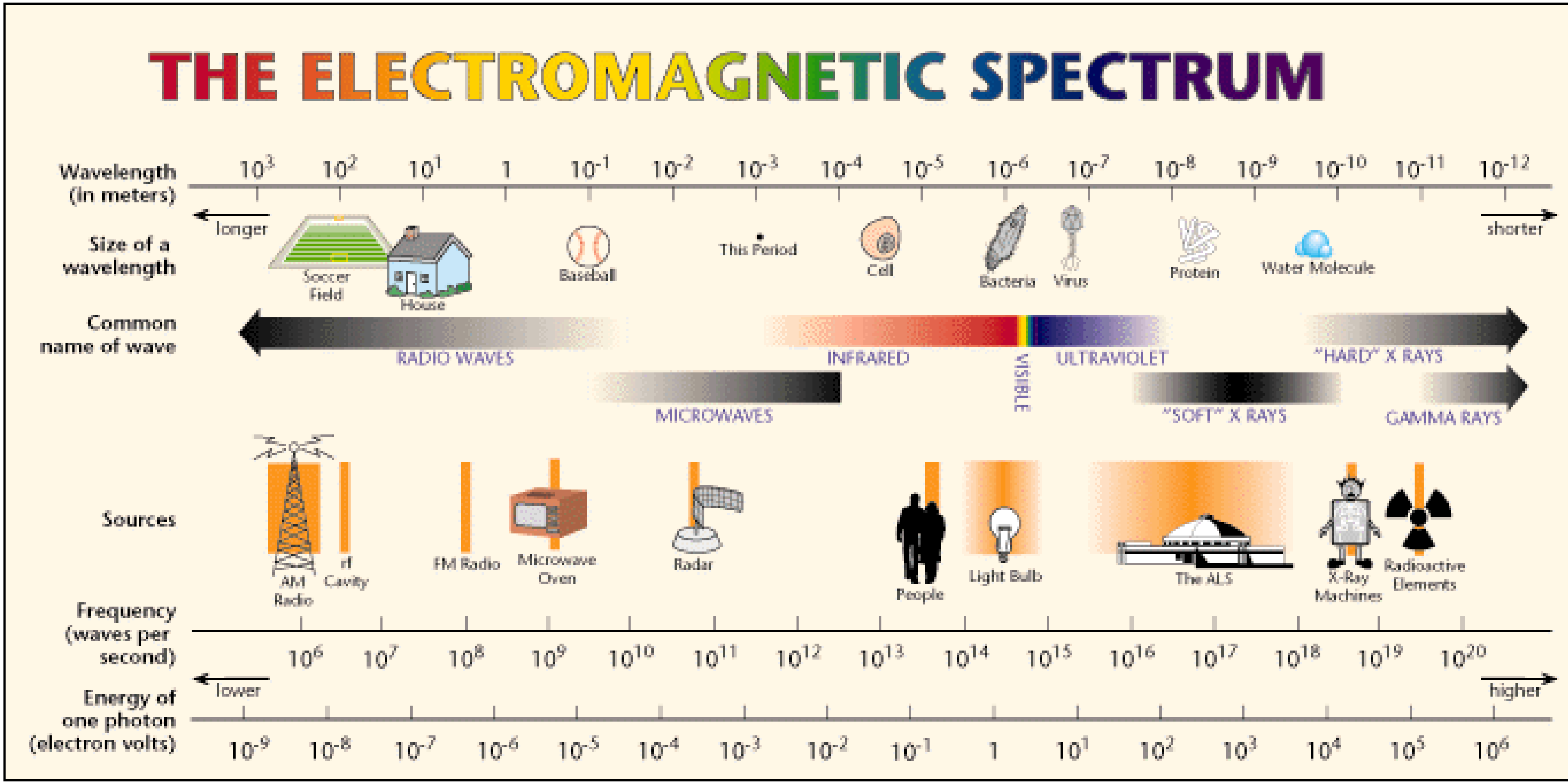
- **Contrast**: describes how clearly we can differentiate various parts of the object in the image.
- **Spatial resolution:** describes how accurate the spatial mapping is



- **Signal to noise ratio (SNP):**
  - The signal is what you are measuring that is the result of the presence of your analyte
  - Noise is extraneous information that can interfere with or alter the signal. it can not be completely eliminated, but hopefully reduced!



In each successive gamma-camera picture of a thyroid phantom, the number of counts is increased by a factor of 2. The number of counts ranges from 1536 to 800,000. The Polaroid camera aperture was reduced to avoid overexposure as the number of counts was increased.



THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10} 10^{-11} 10^{-12}
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18} 10^{19} 10^{20}
lower
higher
Energy of one photon (electron volts)
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10^1 10^2 10^3 10^4 10^5 10^6

❑ Radiography

- X-ray photons are electromagnetic radiation, as are light photons. However, light photons have an energy of 2 to 4 eV and x-ray photons have an energy of 20 to 150 keV, about 10^4 times more energy than light photons. This higher energy makes x-ray photons more penetrating than light photons.

➢ Generation of X-Rays

Watch # I1

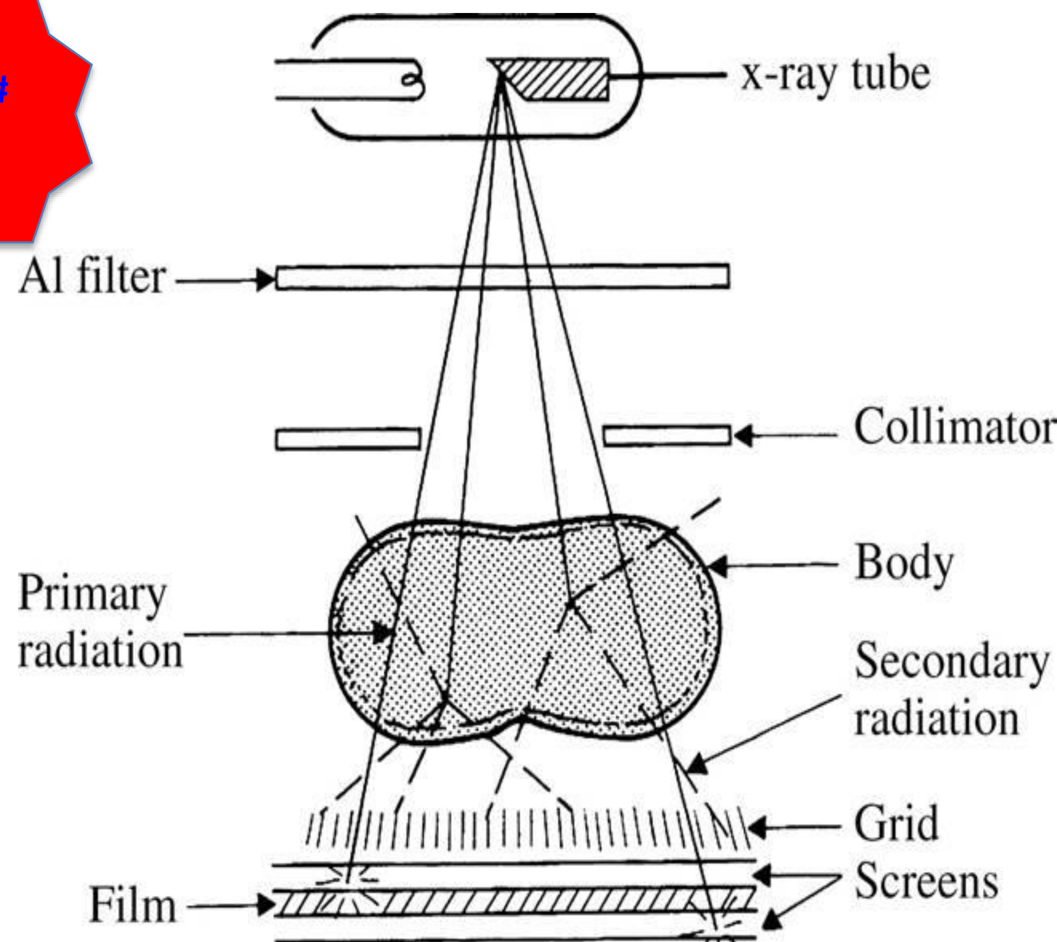
x-ray tube is a temperature-limited diode

$$J_1 = AT^2 e^{-u/kT}$$

$$J_2 = BV^{3/2}$$

filament power equals radiative heat dissipation

$$\sigma T^4 = I^2 R$$



The x-ray tube generates x rays that are restricted by the aperture in the collimator. The Al filter removes low-energy x rays that would not penetrate the body. Scattered secondary radiation is trapped by the grid, whereas primary radiation strikes the screen phosphor. The resulting light exposes the film.

- The beam electrons strike the anode and produce x rays through two mechanisms:

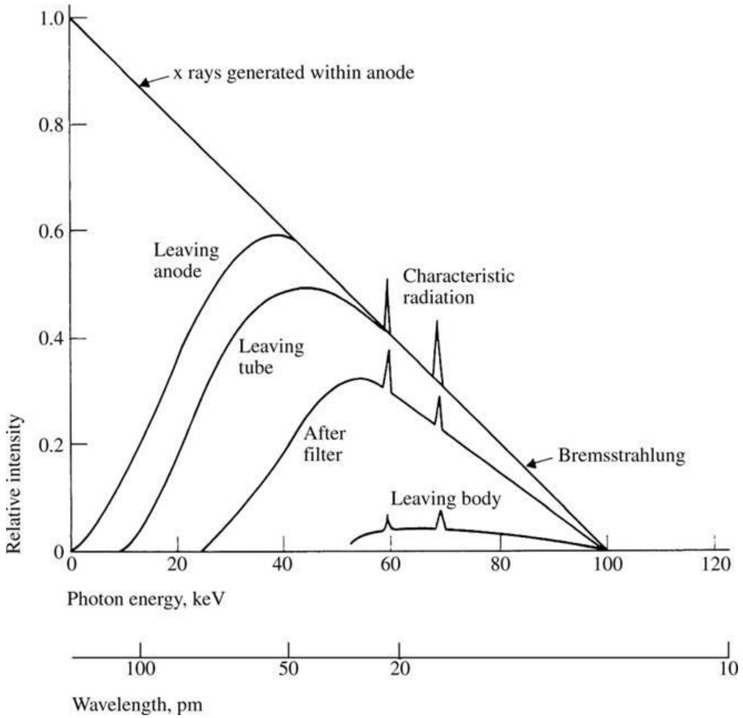
- ***Bremsstrahlung*** produced by the deceleration of the arriving electrons by the positively charged nuclei of the anode atoms

- **characteristic radiation** produced when the anode's innermost electrons, knocked out of orbit by the arriving electrons, are replaced by outer shell electrons.

Watch # I1.1

➢ *Attenuation Of X Rays*

- operating an x-ray tube at a fixed anode voltage V produces x-ray photons that have a distribution of energies.



$$I = I_0 e^{-\mu x}$$

I is the final beam intensity, I_0 is the initial beam intensity, μ, is the attenuation coefficient, and x is the thickness of the attenuator or layer of tissue

- The lowest-energy x rays are absorbed in the anode metal and the tube glass envelope.

- An Al filter further reduces the low-energy x rays that do not pass through the body and would just increase the patient dose. Only the highest-energy x rays are capable of penetrating the body and contributing to the film darkening required for a picture.

- Note that the average energy increases with the amount of filtration.

Detection of X-rays

- As the radiation passes through the patient, a portion is scattered as secondary radiation, most is absorbed, and 1 to 4% of the primary radiation is transmitted to the detector.

- A grid of fine lead strips, analogous to a miniature Venetian blind, is often placed in front of the detector. Most of the primary radiation passes between the strips and most of the secondary radiation is intercepted.

- After passing through the grid, the radiation is detected. Film may be used as the detector, but because of the low Z of the film and the thin emulsion, the film is relatively radiolucent.

- To improve the probability of detecting the x-ray photons, intensifying screens consisting of plastic sheets loaded or coated with high-Z scintillation powders (for example, $CaWO_4$) are placed against each surface of a double-emulsion film .

- The use of screen-film techniques increases the sensitivity and reduces the exposure by a factor of 20 to 100, depending on the screens used.

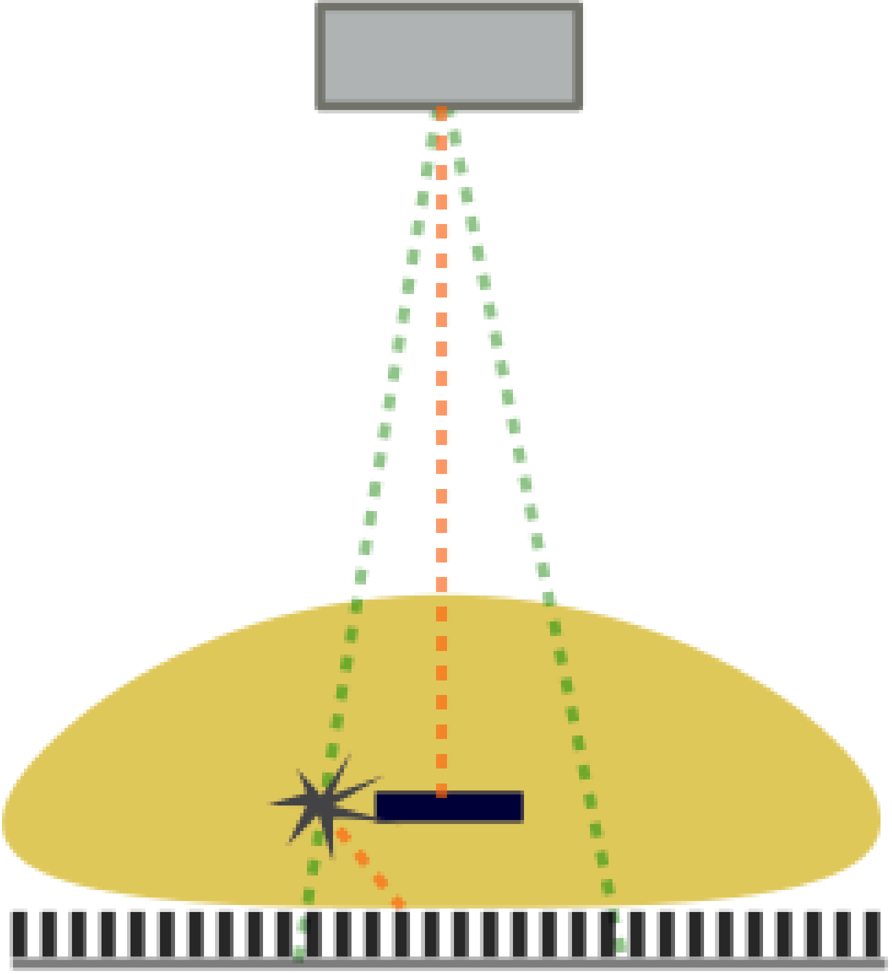
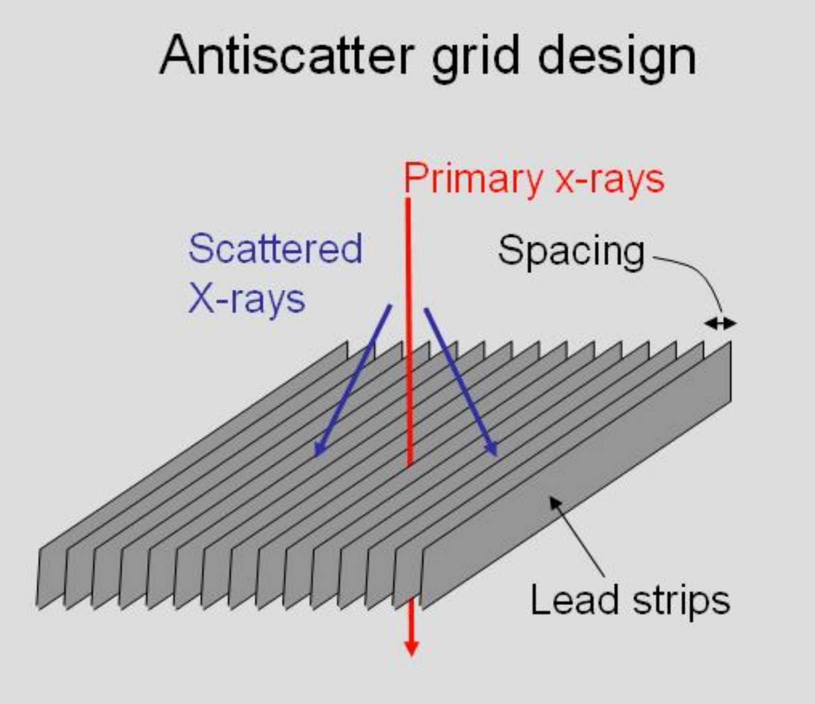


Illustration of the effects of a grid. The primary beams (green) are allowed to hit the detector. However, the scattered beam (orange) hits the septa of the grid and cannot reach the detector since it's at such an oblique angle.



- From consideration of the radiation-noise limit, there is a minimal value for the number of x-ray quanta required to produce an image at a given resolution.

- the radiation exposure required to produce an image can be estimated by using

$$\text{cGy/image} = \frac{2 \times 10^{-7}}{(\text{QDE})(\text{RL})d^2(C - 0.05)^2}$$

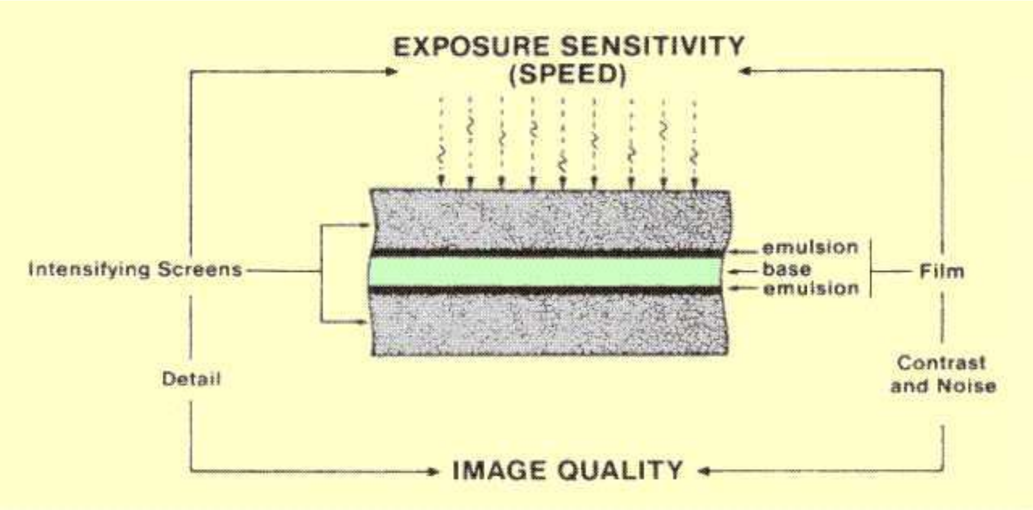
where the quantum detection efficiency (QDE) is the fraction of x-ray photons detected and the radiolucency (RL) is the average fraction of incident x-ray photons that exit the object or patient and contribute to the image.

- Operation at values of x-ray exposure below that estimated by means of this formula results in noisy images. Operation above that value produces quieter images, but at the cost of unnecessary exposure of the patient to radiation.

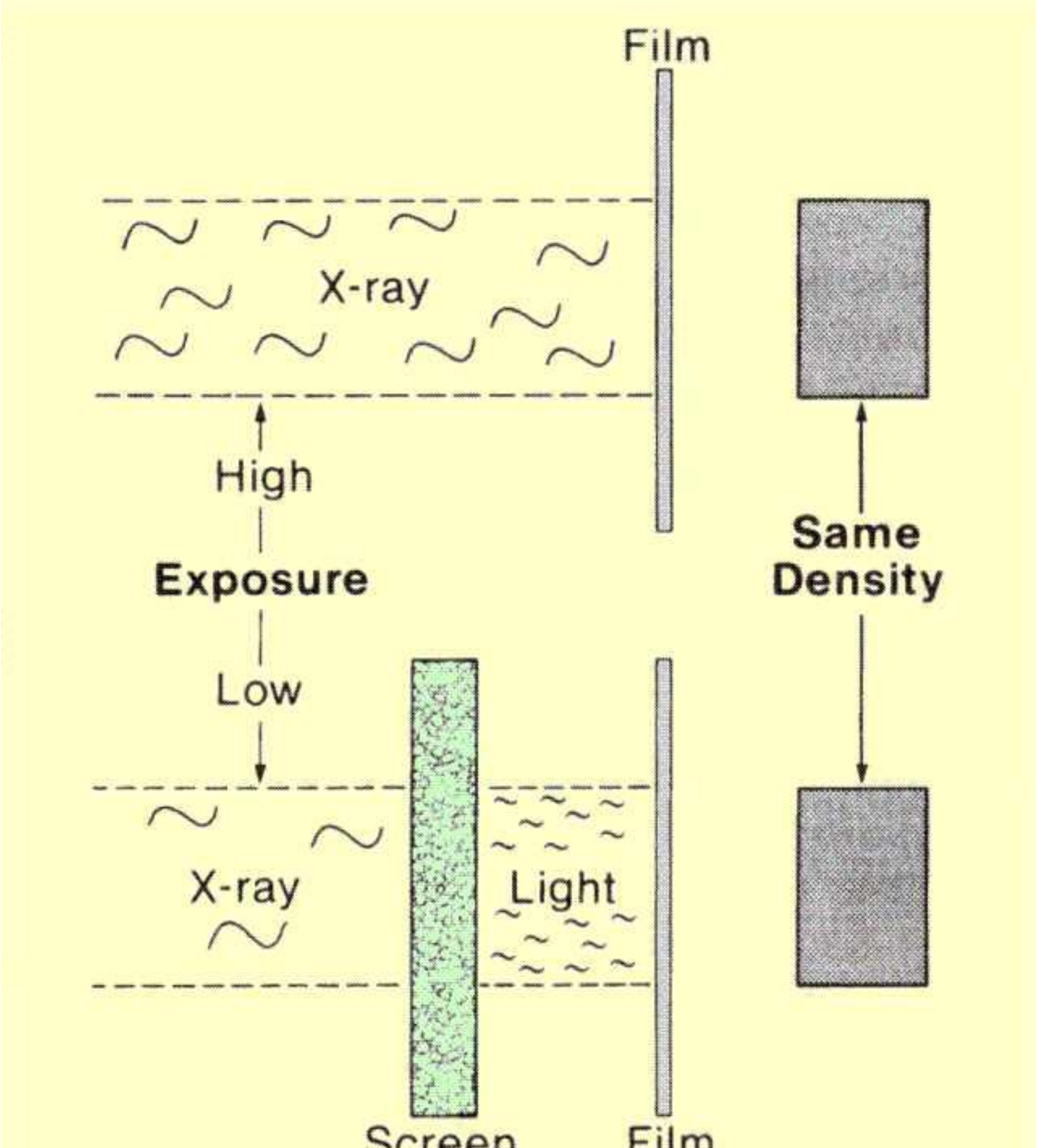
- **In choosing an x-ray film-screen combination, we should choose a screen that will give the necessary resolution and a film that will provide adequate film density when sufficient radiation has been received.**

- **If the film chosen is too sensitive**, the film reaches maximal density before enough photons have been detected to meet the statistical requirements, it appears noisy.

- A better procedure is to use film of lower sensitivity, which permits an increase in the x radiation reaching the film.

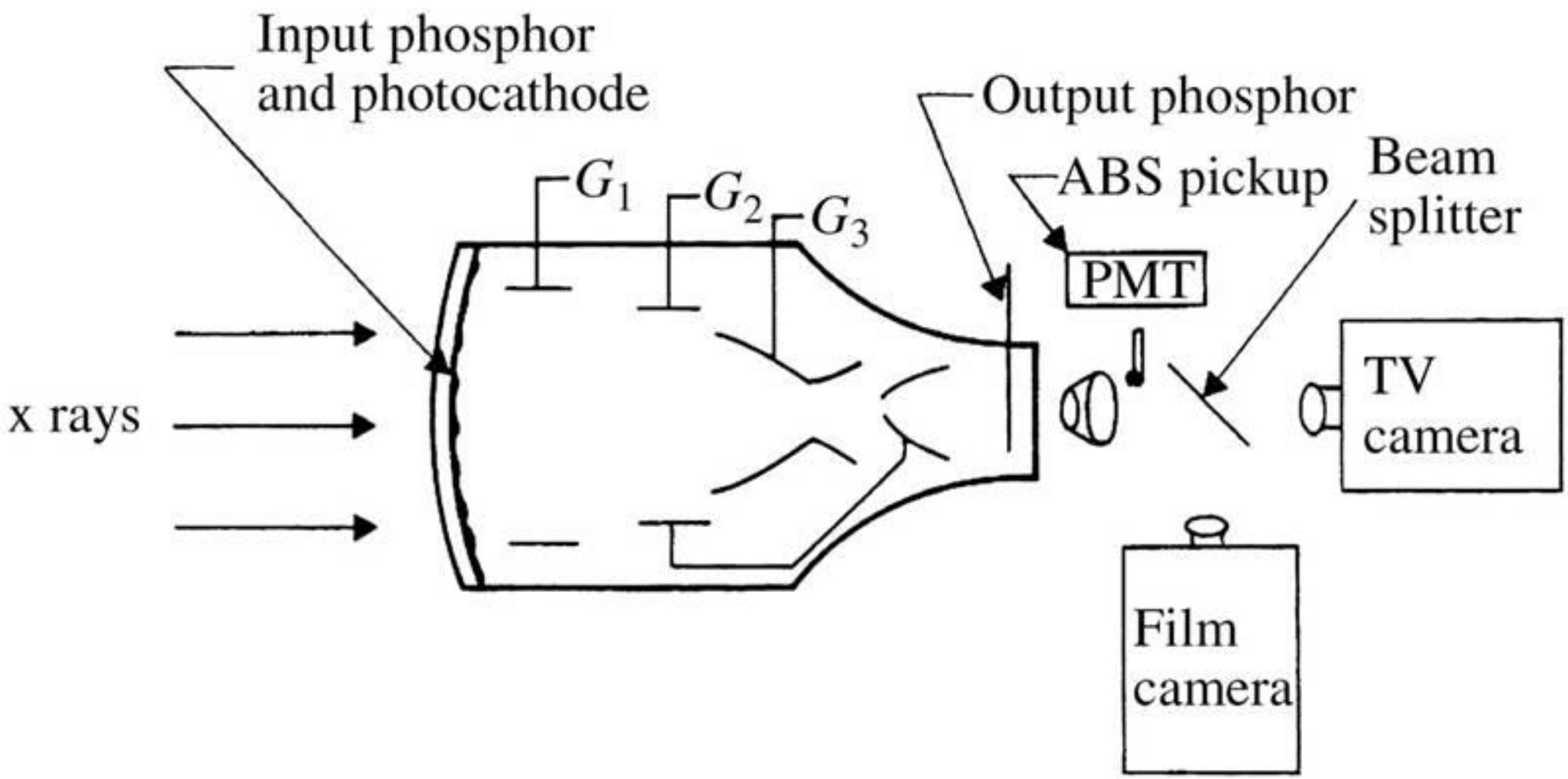


In screen/film radiography, the receptor consists of the film mounted in contact with either one or two intensifying screens, as shown. Intensifying screens are thin sheets, or layers, of fluorescent materials. The x-ray energy is absorbed by the intensifying screen material, and a portion of it is converted into light. The light, in turn, exposes the film. Intensifying screens are used because film is much more sensitive to light than to x-radiation; approximately 100 times as much x-radiation would be required to expose a film without using intensifying screens.


Film
X-ray
High
Exposure
Low
X-ray
Light
Screen
Film
Same
Density

➢ Image Intensifiers

- X-ray image intensifiers are used in fluoroscopic systems.
- The x-ray image intensifier combines the functions of x-ray detection and signal amplification in a single glass envelope.



In the image intensifier, x rays strike the input phosphor screen, thus generating light. Light stimulates the photocathode to emit electrons, which are accelerated through 25 kV to strike the output phosphor screen. Brightness gain is due to both geometric gain and electronic gain.

- X rays strike the input screen— usually a layer of cesium iodide, CsI,— which fluoresces in proportion to the x-ray intensity. The input phosphor is in close proximity to a photocathode, so the light stimulates the emission of electrons.

- These electrons are accelerated through the 25 kV electric field and focused by shaping the electric field. They strike the output phosphor, which produces an image that is smaller but brighter than that produced at the input phosphor

- A lens mounted on the image intensifier serves to collimate or focus the output image to infinity. The objective lens for each camera collects the light of the collimating lens and refocuses it on the film plane.

Watch # I2.1

➢ Computed Radiography

- Computed radiography (CR) uses very similar equipment to conventional radiography except that in **place of a film to create the image, an imaging plate (IP) made of photostimulable phosphor is used.**

- instead of taking an exposed film into a darkroom for developing in chemical tanks or an automatic film processor, the imaging plate is run through a special laser scanner, or CR reader, that reads and digitizes the image.

- The digital image can then be viewed and enhanced using software that has functions very similar to other conventional digital image-processing software, such as contrast, brightness, filtration and zoom.

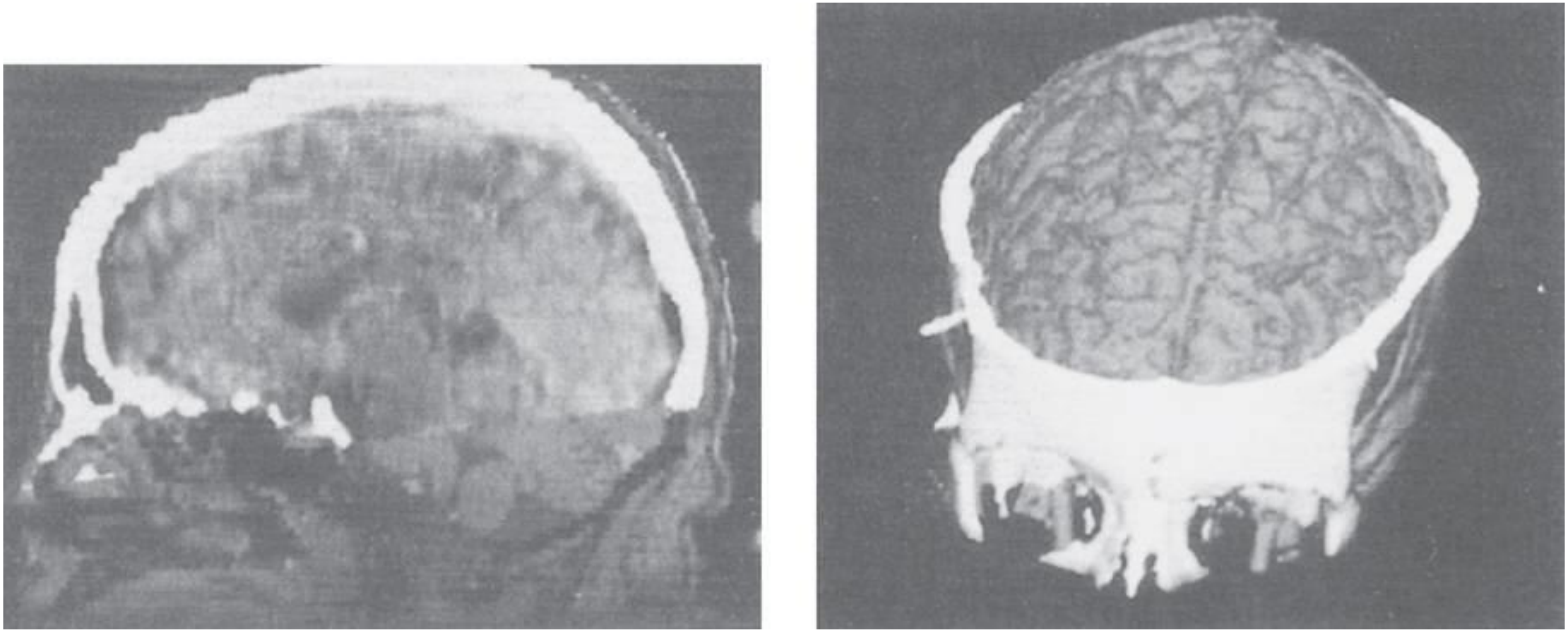
Watch # I3

Table-top Computed Radiography Cassette Scanner. The screen is removed from the cassette, scanned, erased and returned to the cassette for the next exposure. The image information is sent to a computer for display and analysis. Photo courtesy of iCRco.

- The computer can be used for writing the diagnostic report and images and reports sorted and controlled in a database management system

- Computer techniques are used to convert the dimensions of one image to conform to those of another.

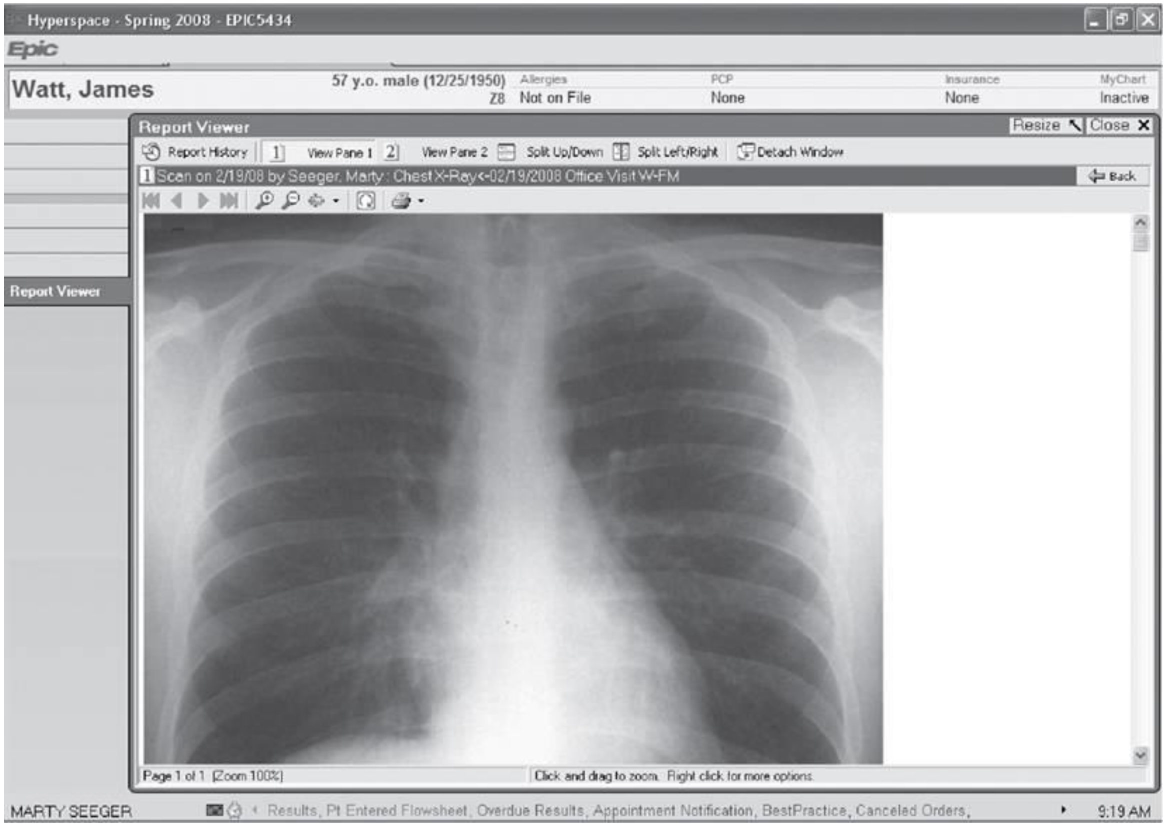
- The technique of generating a composite image from more than one source is called image fusion.



Images of the skull taken using CT and images of the brain taken with MRI, fused into composite images. (Courtesy of Rock Mackie, University of Wisconsin.)

- Medical image diagnosis often requires examination of an entire high-resolution image followed by scrutiny of a portion of the image, the region of interest (ROI).
- Images can be transformed from real space to frequency space by means of the fast Fourier transformation, FFT.
- Computed radiography has been incorporated into local area networks (LANs) as part of a filmless medical imaging system.

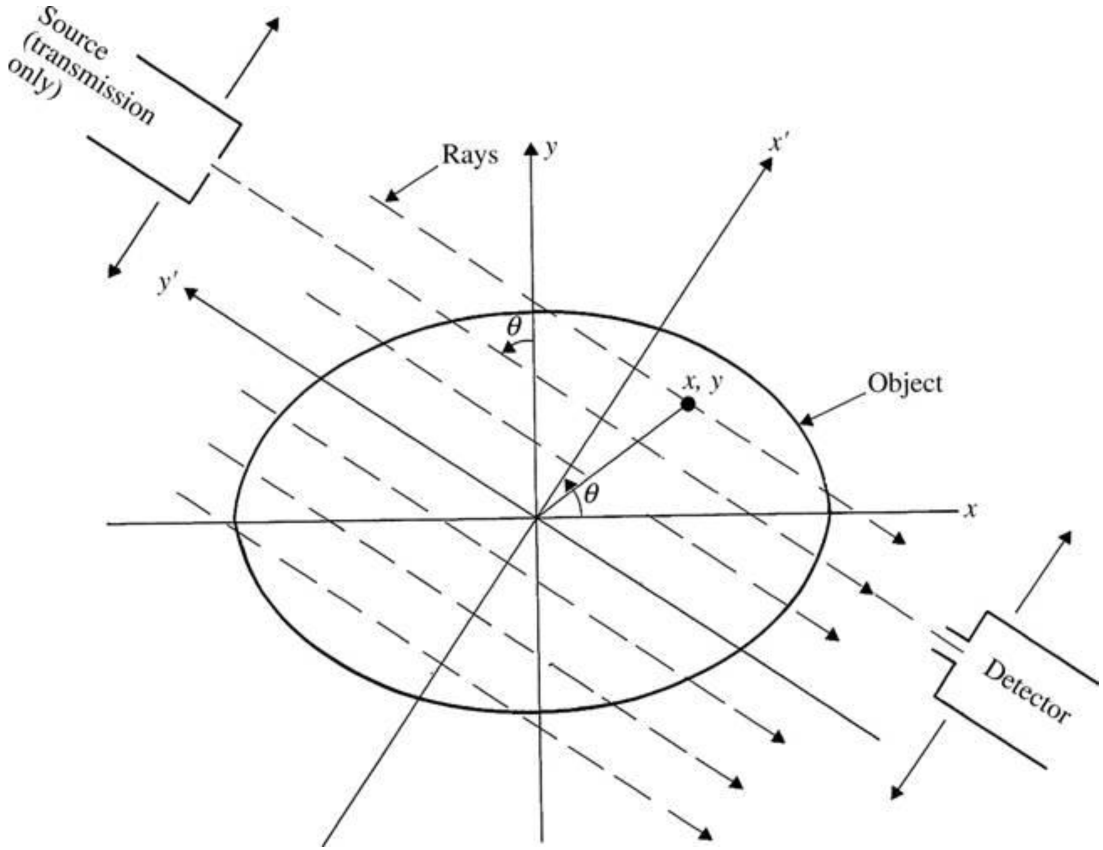
Ex: Computer presentation of an image



Part of a patient report showing a chest X-ray image. Additional pages would give further diagnostic image and reference other images and reports. Copyright © 2008 Epic Systems Corporation.

❑Computed Tomography

- Computed tomography is the name given to the diagnostic imaging procedure in which anatomical information is digitally *reconstructed* from x-ray transmission data obtained by scanning an area from many directions in the same plane to visualize information in that plane



Basic coordinates and geometry for computed tomography. The projection rays shown represent those measured at some angle θ. The source and detector pair are rotated together through a small angle, and a new set of rays measured. The process is repeated through a total angle of 180°. (From R. A. Brooks and G. Di Chiro, "Theory of image reconstruction in computed tomography." *Radiology,* 1975, 117, 561-572.)

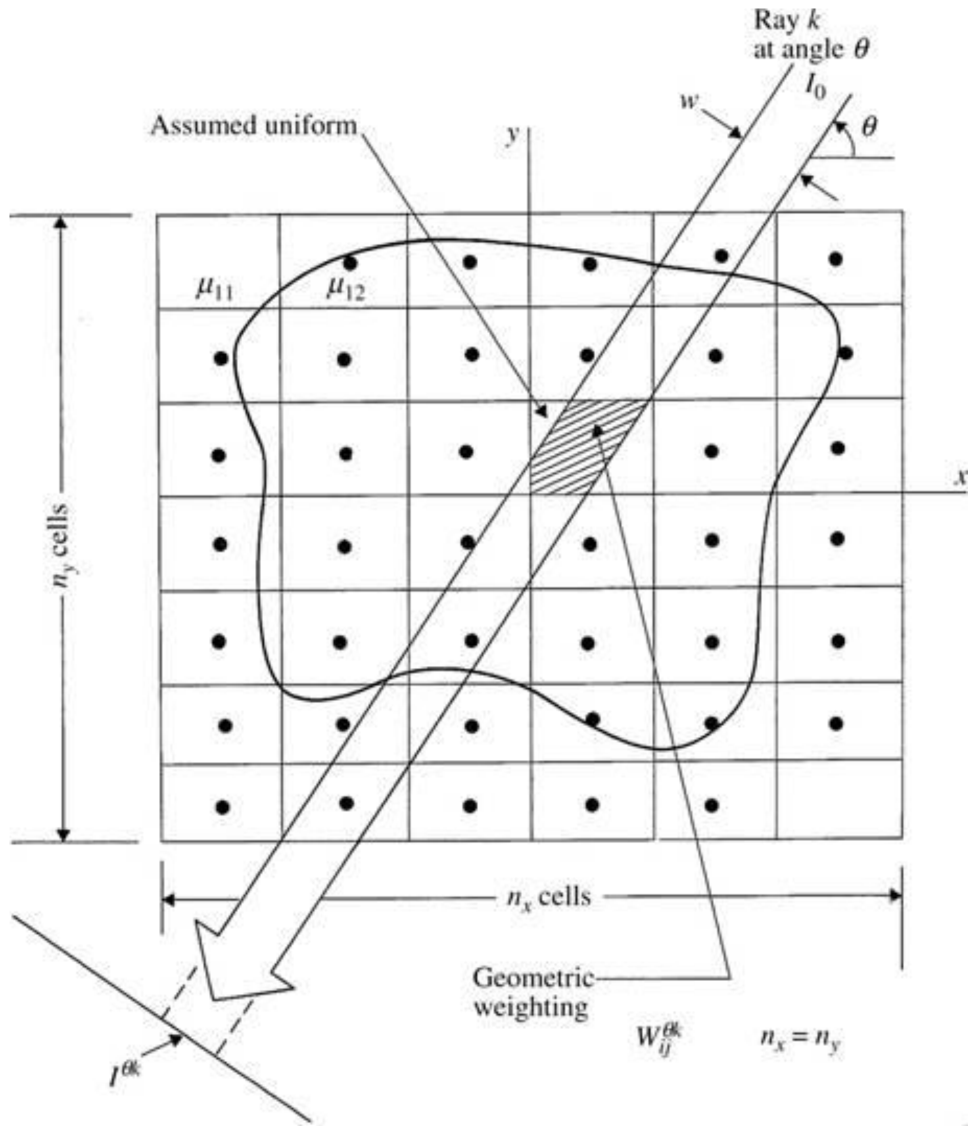
$$I^{\theta k} = I_0 \exp\left(-\sum_{ij} W_{ij}^{\theta k} \mu_{ij}\right)$$

intensity transmitted of position *k* at angle θ

$$P^{\theta k} = \ln\left(\frac{I_0}{I^{\theta k}}\right) = \sum_{ij} W_{ij}^{\theta k} \mu_{ij}$$

the projection data for the position *k* at angle θ

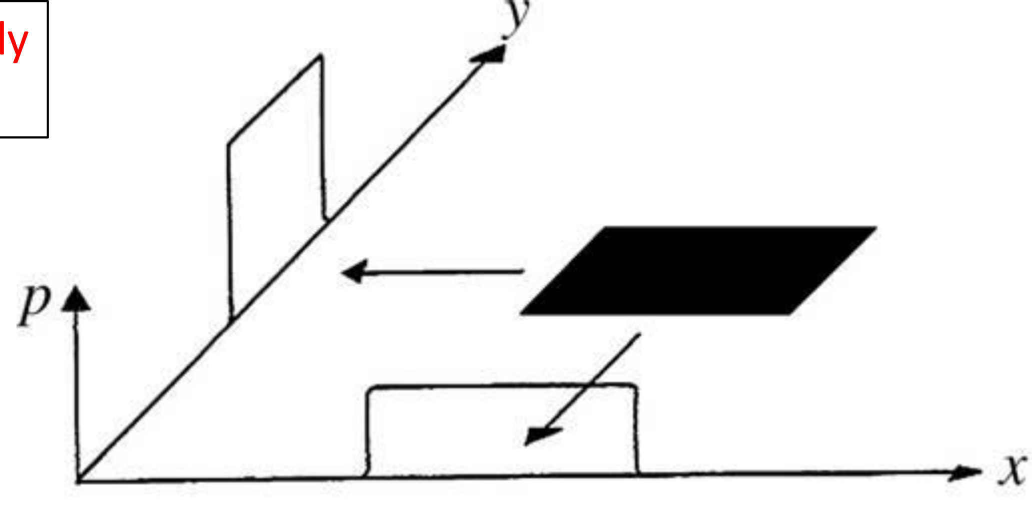
Watch # I4



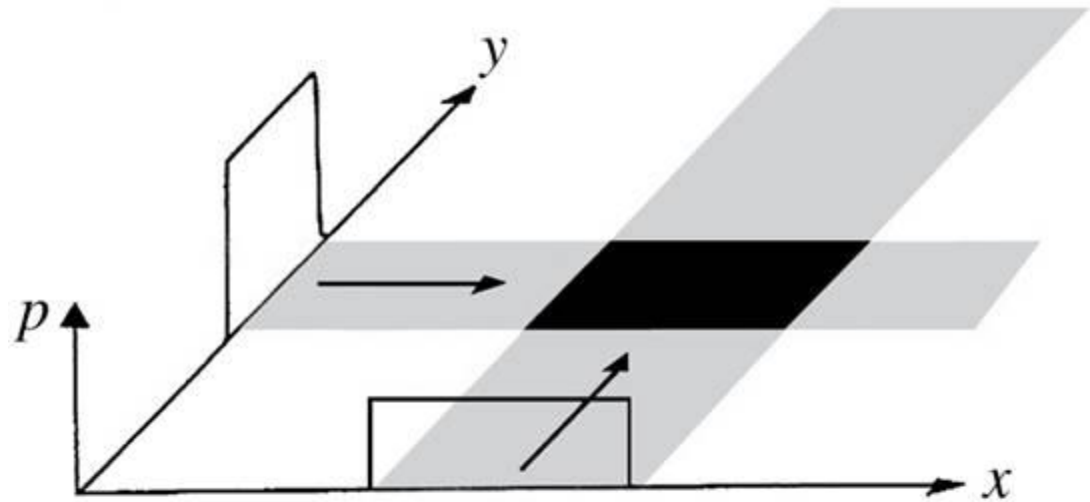
The basic parameters of computerized image reconstruction from projections. Shown are the picture element cells μ_{ij}, a typical projection ray $I^{\theta k}$, and their geometrical overlap $W_{uk}^{\theta k}$. (From Ernest *L.* Hall, *Computer Picture Processing and Recognition*. New York: Academic, 1978.)

the image is reconstructed directly from the projection data

Back projection (a) Projections of this object in the two directions normal to the *x* and *y* axes are measured, (b) These projection data are projected back into the image plane. The area of intersection receives their summed intensities. It is apparent that the back-projected distribution is already a crude representation of the imaged object. (From R. A. Brooks and G. Di Chiro, "Theory of image reconstruction in computed tomography," *Radiology*, 117, 1975, 561–572.)



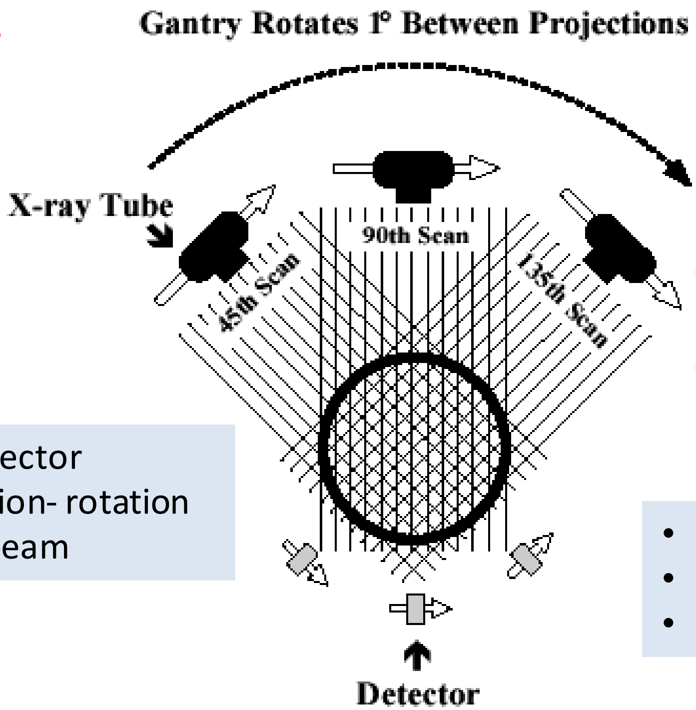
(a)



(b)

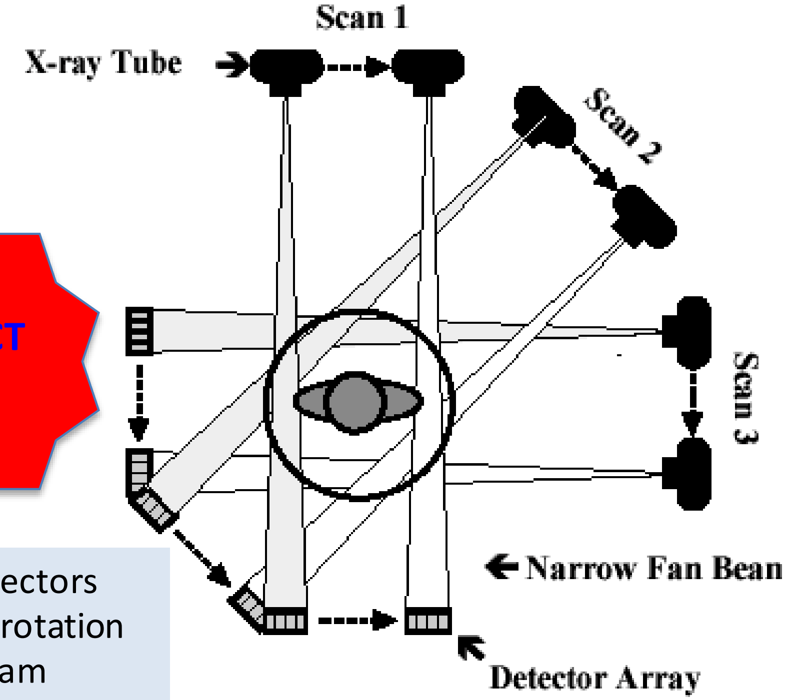
Evolution of CT machines

1st gen.



- One detector
- translation- rotation
- Pencil-beam

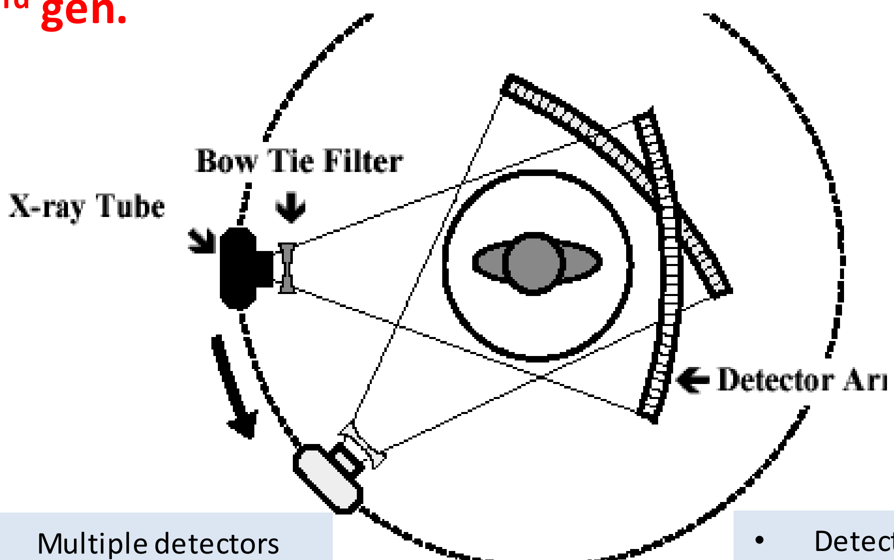
2nd gen.



Watch CT videos

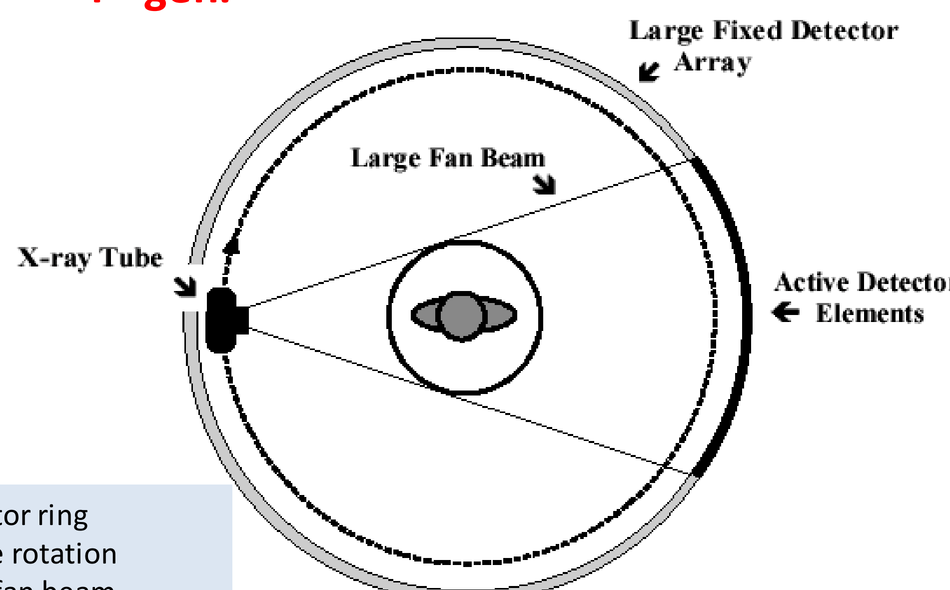
- Multiple detectors
- translation- rotation
- Small fan beam

3rd gen.



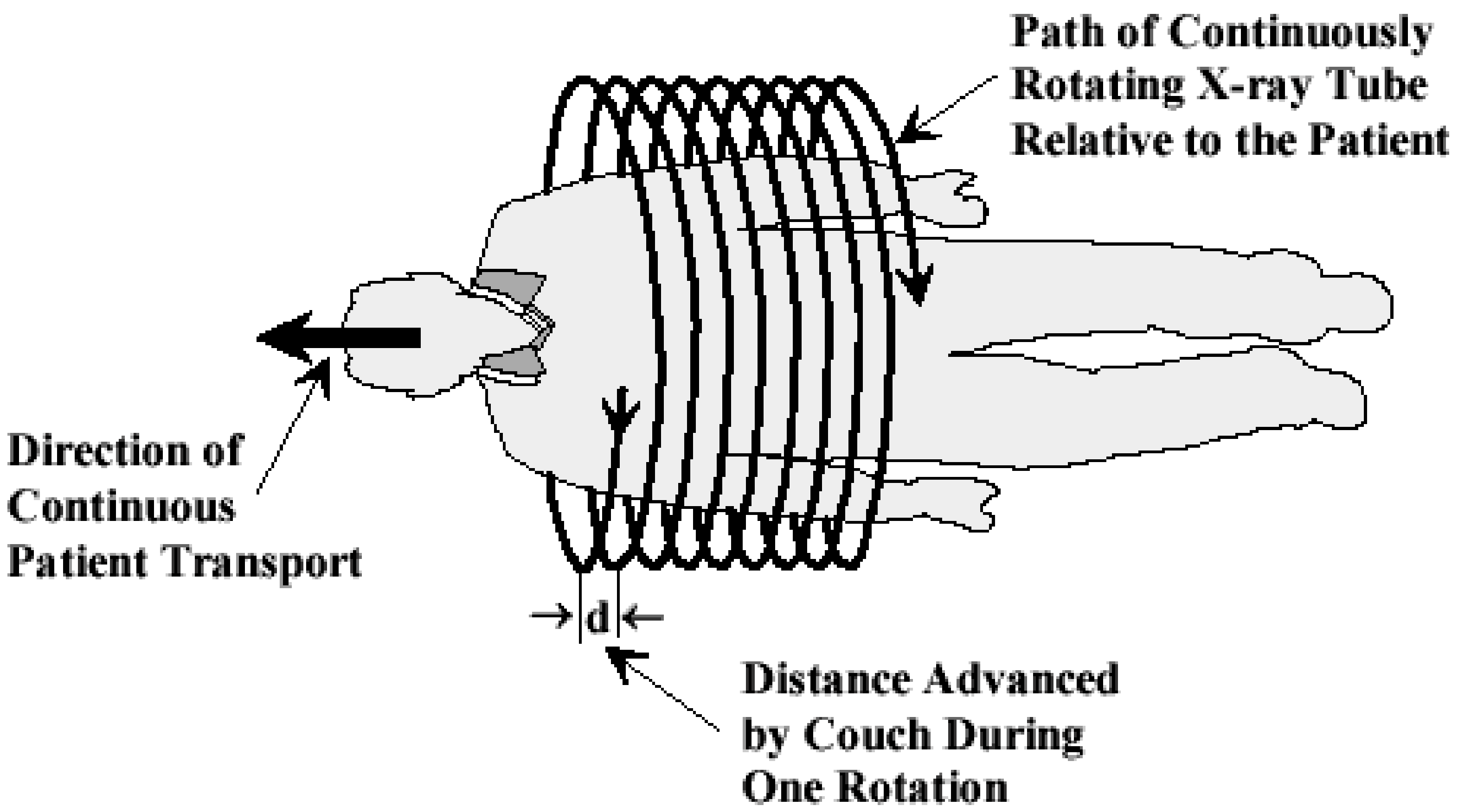
- Multiple detectors
- Rotation- rotation
- Large fan beam

4th gen.



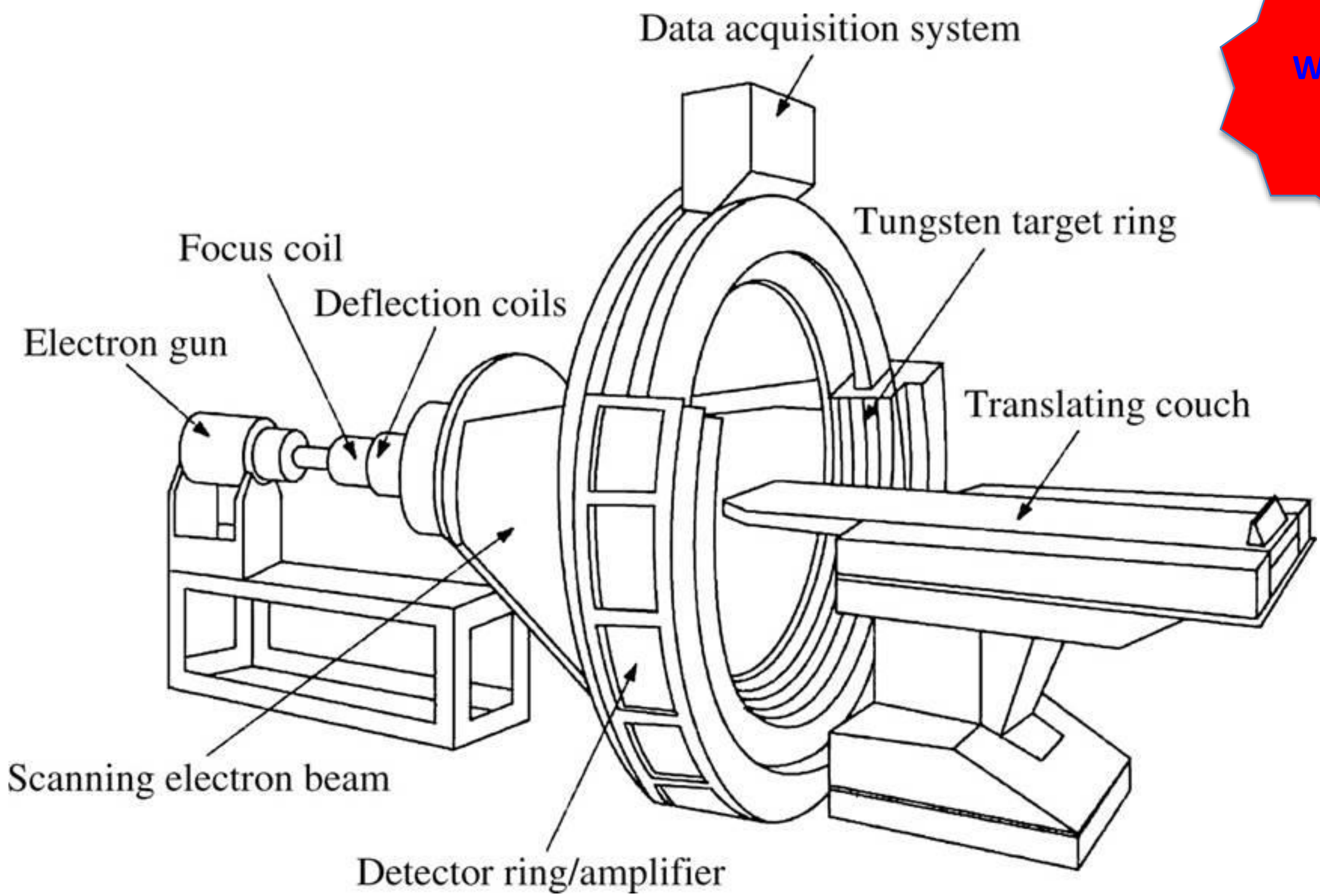
- Detector ring
- Source rotation
- Large fan beam

Illustration of helical scanning.



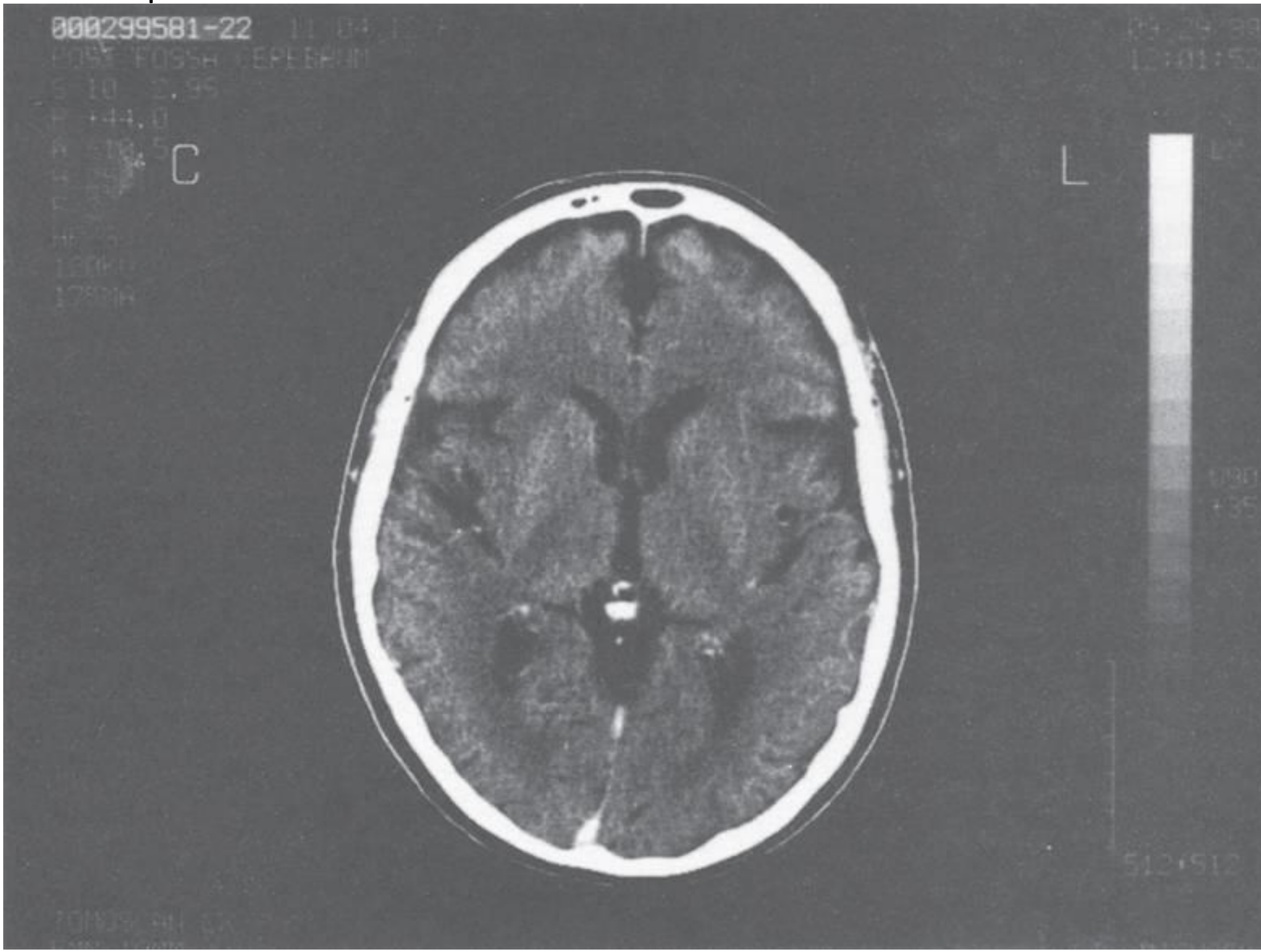
- One novel machine, which avoids the practical problem of accelerating the mass of the x-ray tube and power supplies by building the machine in the form of a ‘‘demountable’’ x-ray tube. Here, the electron beam strikes a circular anode almost 2 m diameter, the patient is within the circle, and the ring of detectors is the same as the fourth-generation machines. Such machines take CT angiographic images faster than 30 images/s.

Watch # I6.1



IMATRON electron beam CT system. (Courtesy of Doug Boyd, IMATRON Corp.)

Figure 12.15 shows that the resolution of the third- and fourth-generation machines can be as high as 512x512 pixels.



A 512 x 512 pixel CT Image of the brain. Note that the increased number of pixels yields improved images. (Photo Courtesy of Philips Medical Systems.)

Control console and gantry assembly of a CT system (Photo courtesy of Philips Medical Systems.)

❑Magnetic Resonance Imaging

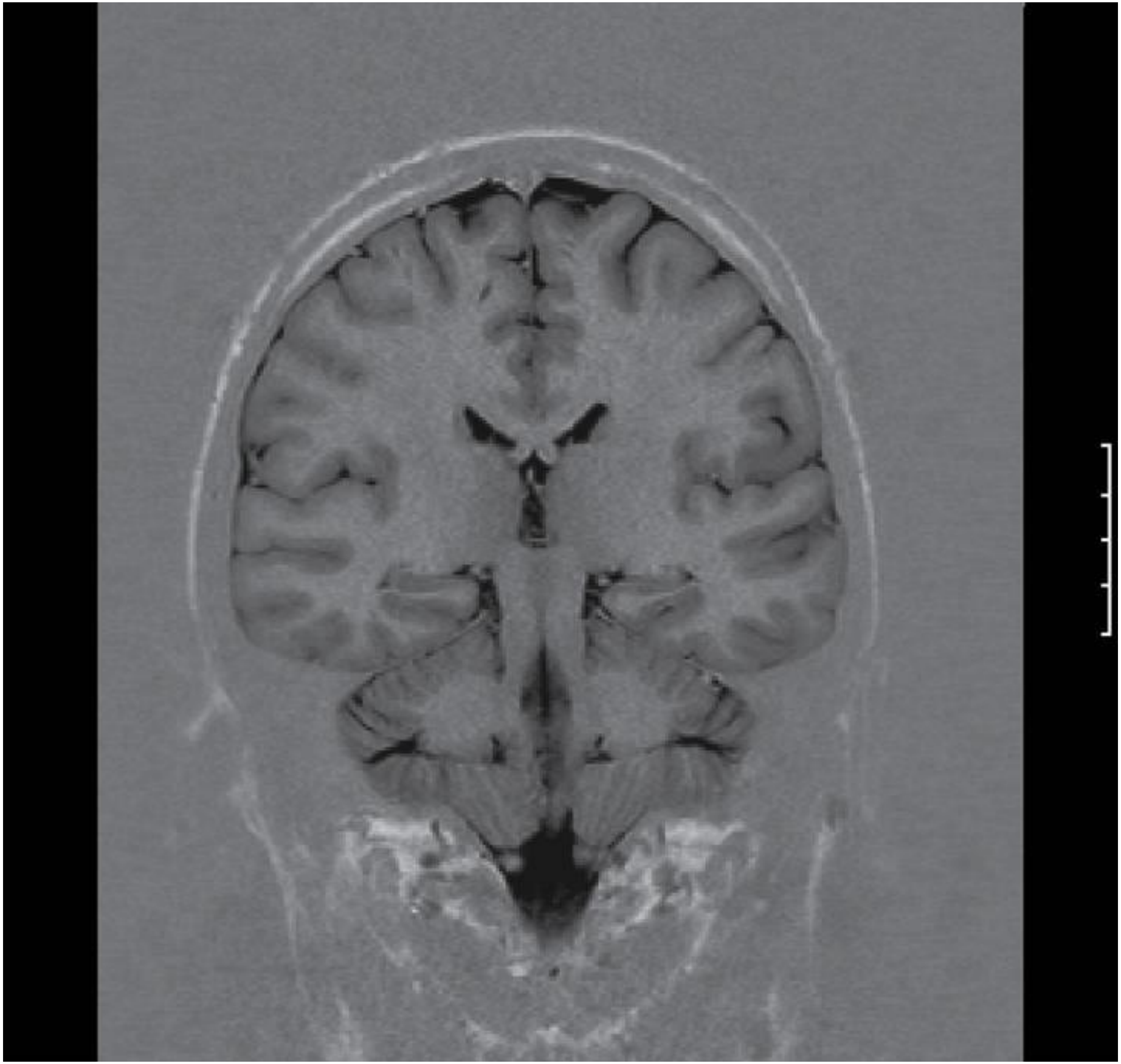
- Spinning charged particles have a magnetic moment and, when placed in an external magnetic field, tend to align with the field.

- The usual state would be for the field of the charged particles to align itself N to S, where N refers to the north pole of the particle's field and S refers to the south pole of the external field.

- However, it is possible for the particles to be oriented N to N and have the property that a slight perturbation causes the particle to flip back to the lower- energy state, N to S, and thereby return energy to the system.

- The N-to-N state is a high-energy state; it corresponds to an ionized state

Watch #
I7.1



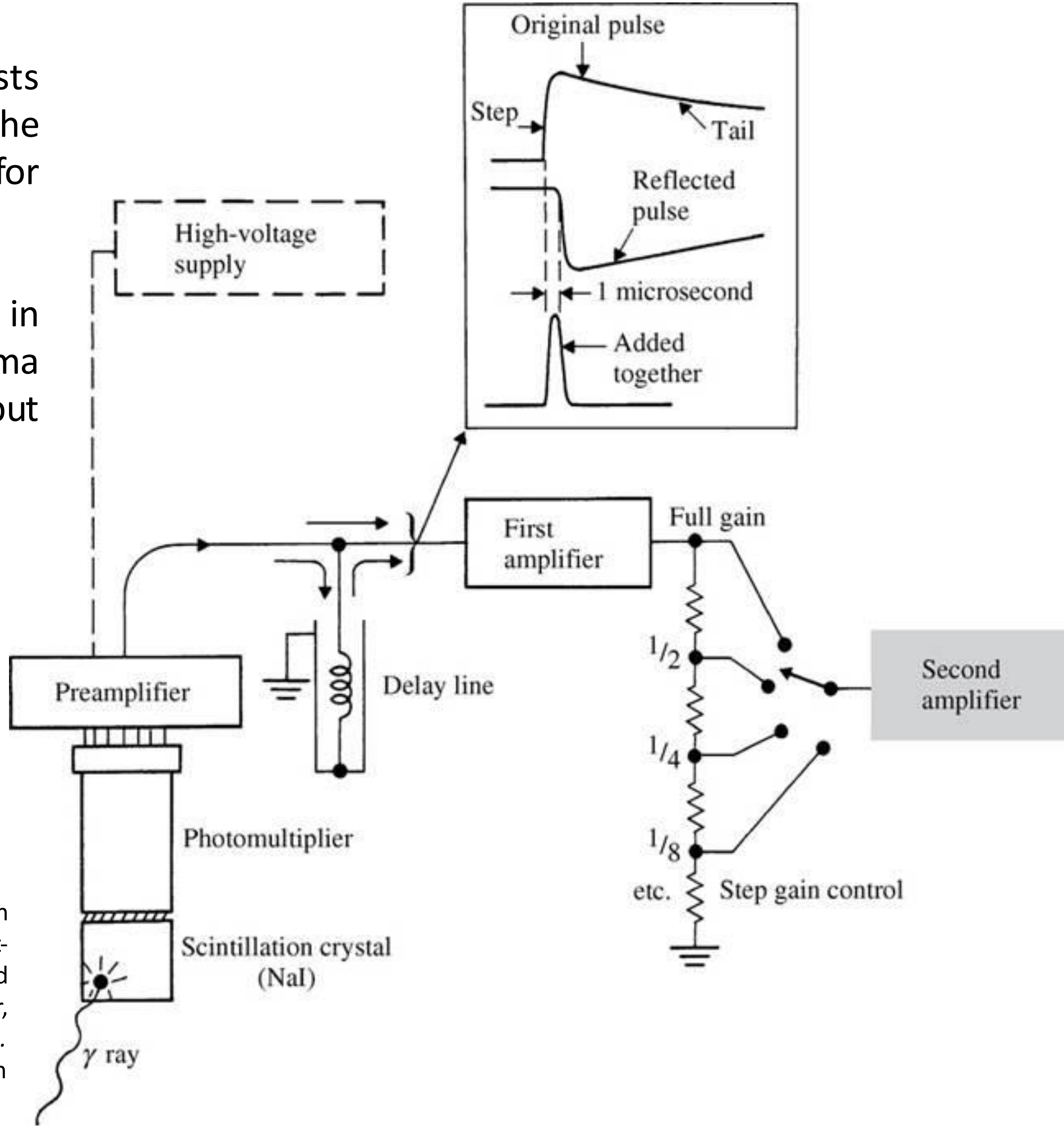
MRI image of the head (1). Sets of images may be acquired for 1 mm section thickness at 2 mm apart for diagnosis of the entire volume of the brain. Photo courtesy of Siemens Medical.

MRI image of the brain. Compare to **CT Image**. The MRI image shows differences due to hydrogen concentration rather than tissue density making the bony part of the skull transparent and having a different contrast pattern than the CT image. Image courtesy of Siemens Medical Systems.

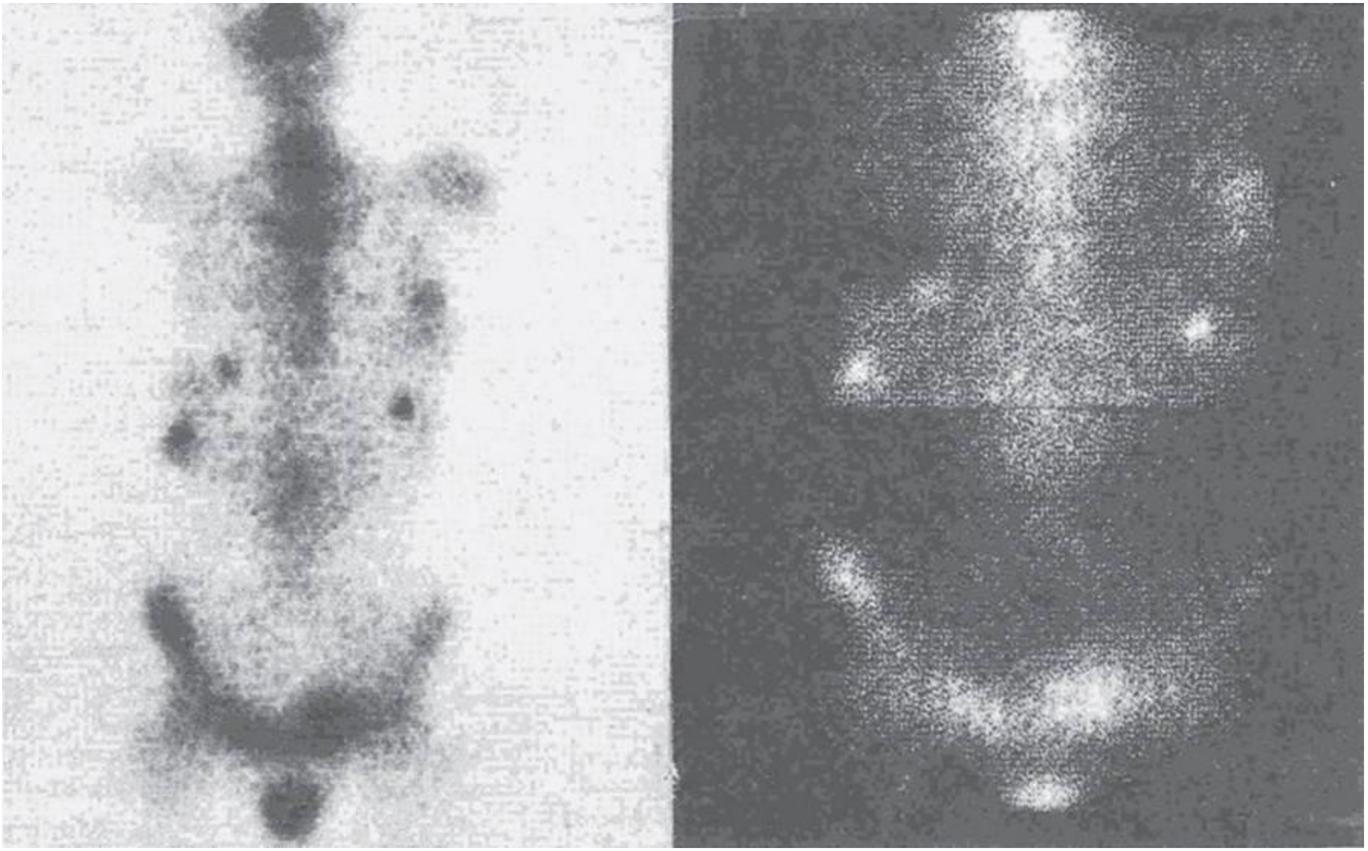
❑Nuclear Medicine

- Nuclear medicine enlists radioactive material for the diagnosis of disease and for assessment of the patient.

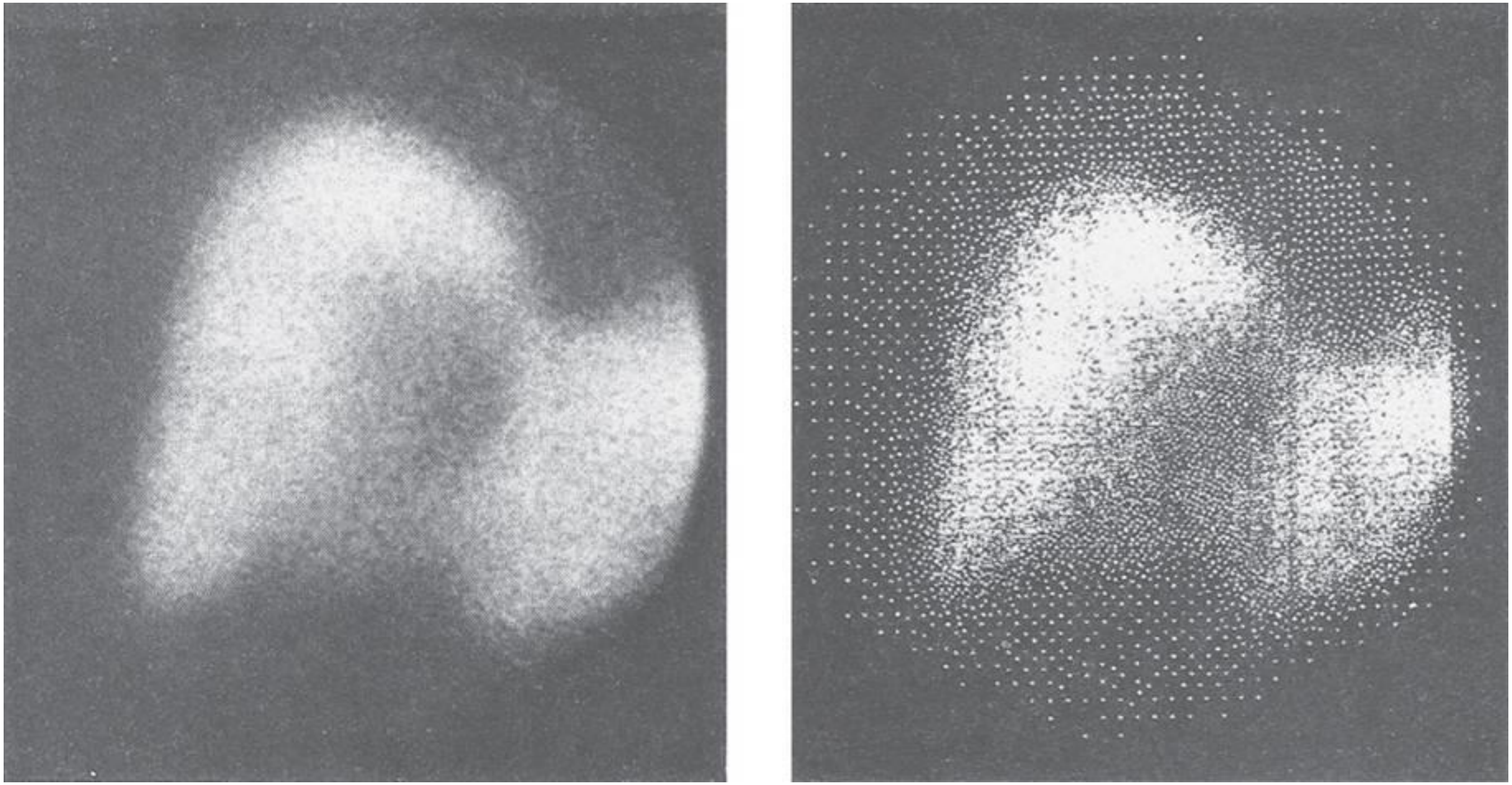
- it differs from radiography in that the source of gamma rays is not external but rather within the patient.



Basic implementation of a NaI scintillation detector, showing the scintillator, light-sensitive photomultiplier tube, and support electronics. (From H. N. Wagner, Jr., ed., *Principles of Nuclear Medicine.* Philadelphia: Saunders, 1968. Used with permission of W. B. Saunders Co.)



Images of a patient's skeleton obtained by a rectilinear scanner, in which a technetium-labeled phosphate compound reveals regions of abnormally high metabolism. The conventional analog image is on the left, the digitized version on the right.



Gamma-camera images of an anterior view of the right lobe of a patient's liver. A colloid labeled with radioactive technetium was swept from the blood stream by normal liver tissue. Left: conventional analog image. Right: digitized version of the same data.

❑ Single-Photon Emission Computed Tomography

- Single-photon emission computed tomography (SPECT) uses a large-area scintillation assembly similar to that of an Anger camera (gamma camera) and rotates it around the patient.

- Many of the isotopes used in nuclear medicine produce a single photon or gamma ray in the useful range of energies.

- The collimator is often designed to collect radiation from parallel rays (the collimator is usually focused at infinity), and the collection of signals is used in an image-reconstruction process analogous to methods used in computed tomography.

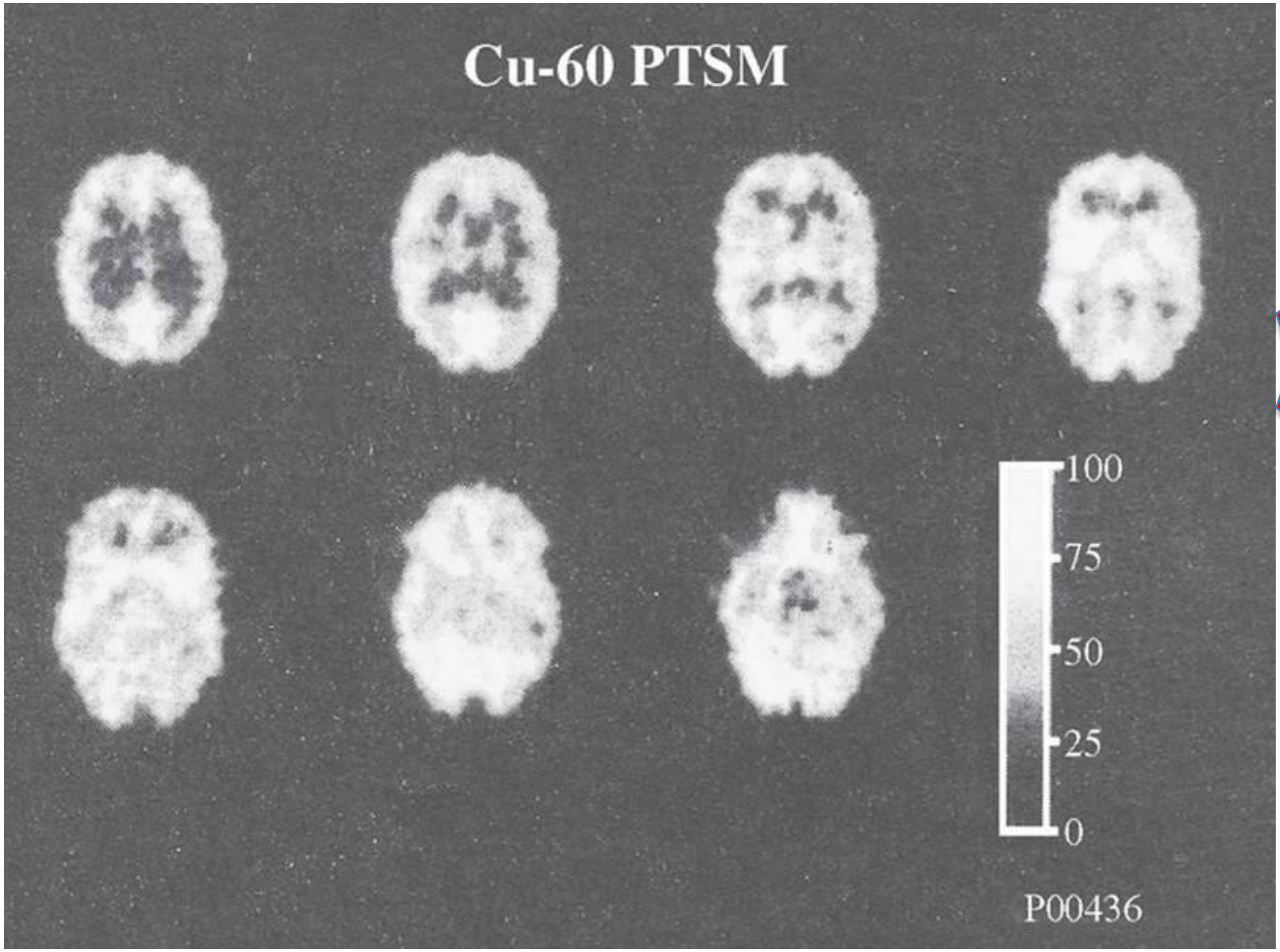
- Several planes or slices of activity are reconstructed at the same time.

❑ Positron Emission Tomography

- Certain isotopes produce positrons that react with electrons to emit two photons at 511 keV in opposite directions. Positron emission tomography (PET) takes advantage of this property to determine the source of the radiation.
- In the simplest PET camera two modified sophisticated cameras called Anger cameras are placed on opposite sides of the patient.
- This increases the collection angle and reduces the collection times which are the limitations of SPECT.
- In PET, radiopharmaceuticals are labeled with positron emitting isotopes.

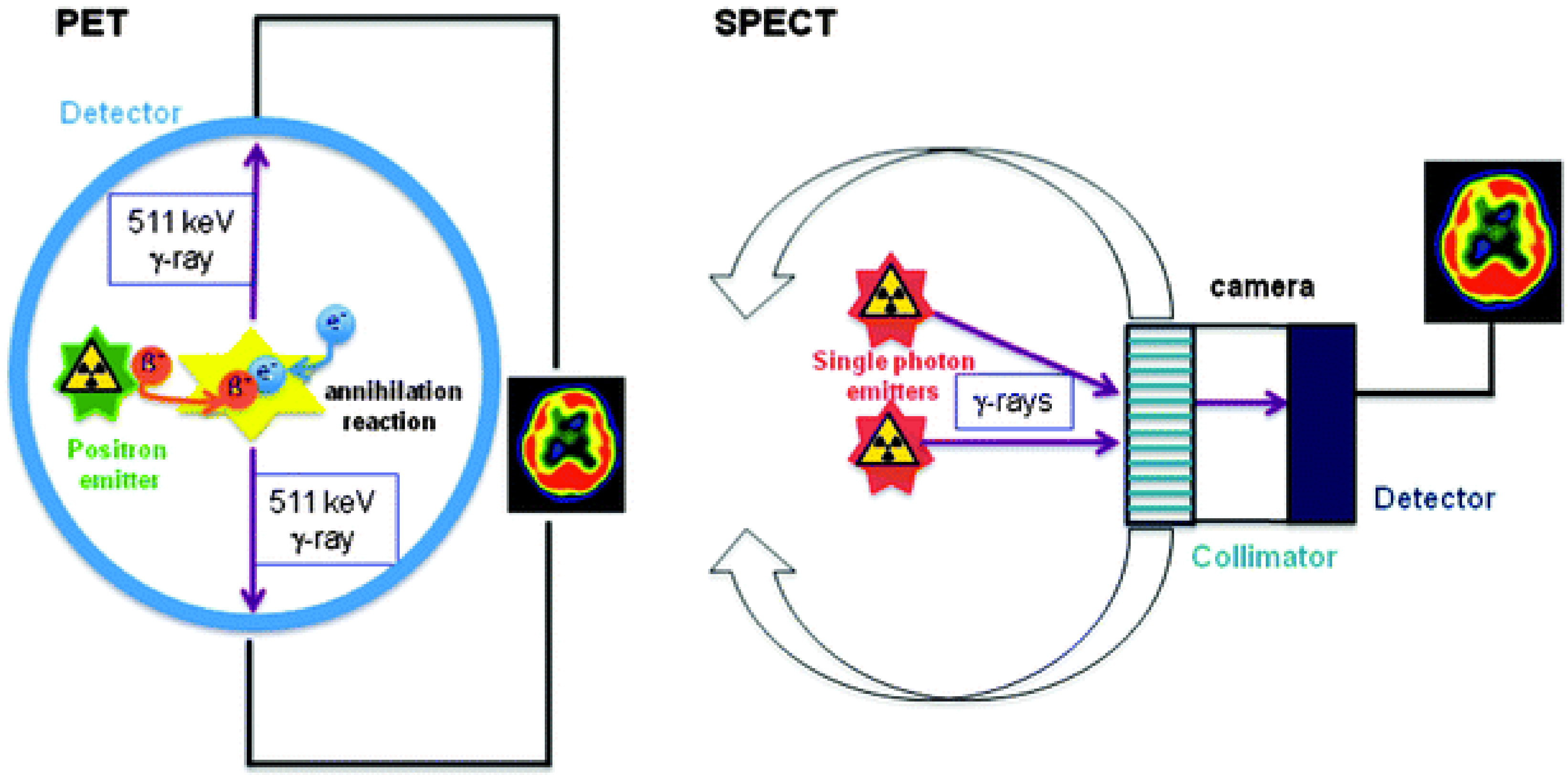
Table 12.2 Characteristics of Five Isotopes for PET

Isotope	Maximal Kinetic Energy	Half-life	Broadening
^{10}F	640 keV	110 min	1.1 mm
^{11}C	960 keV	20.4 min	1.9 mm
^{13}N	1.2 MeV	10.0 min	3.0 mm
^{60}Ga	1.9 MeV	62.3 min	5.9 mm
^{82}Rb	3.4 MeV	1.3 min	13.2 mm



Watch # I11.1

PET image: The trapping of 60Cu-PTSM (a thiosemicarbazone) reflects regional blood flow, modulated by a nonunity extraction into the tissue. (Photo courtesy of Dr. R. J. Nickles, University of Wisconsin.)



- SPECT imaging is inferior to PET because of attainable resolution and sensitivity.
- Different radionuclide is used for SPECT imaging that emits a single photon rather than positron emission as in PET.
- The use of collimator results in a tremendous decrease in the detection efficiency as compared to PET.

❑ Ultrasonography

- Ultrasound transducers use the piezoelectric properties of ceramics such as barium titanate or similar materials. When stressed, these materials produce a voltage across their electrodes. Similarly, when a voltage pulse is applied, the ceramic deforms.

➢ Modes Ultrasound

- A-mode- amplitude mode.
- B-mode- brightness mode.
- M-mode- motion mode.

A-mode

- A-mode (Amplitude-mode) ultrasound is used to judge the depth of an organ, or otherwise assess an organ's dimensions.

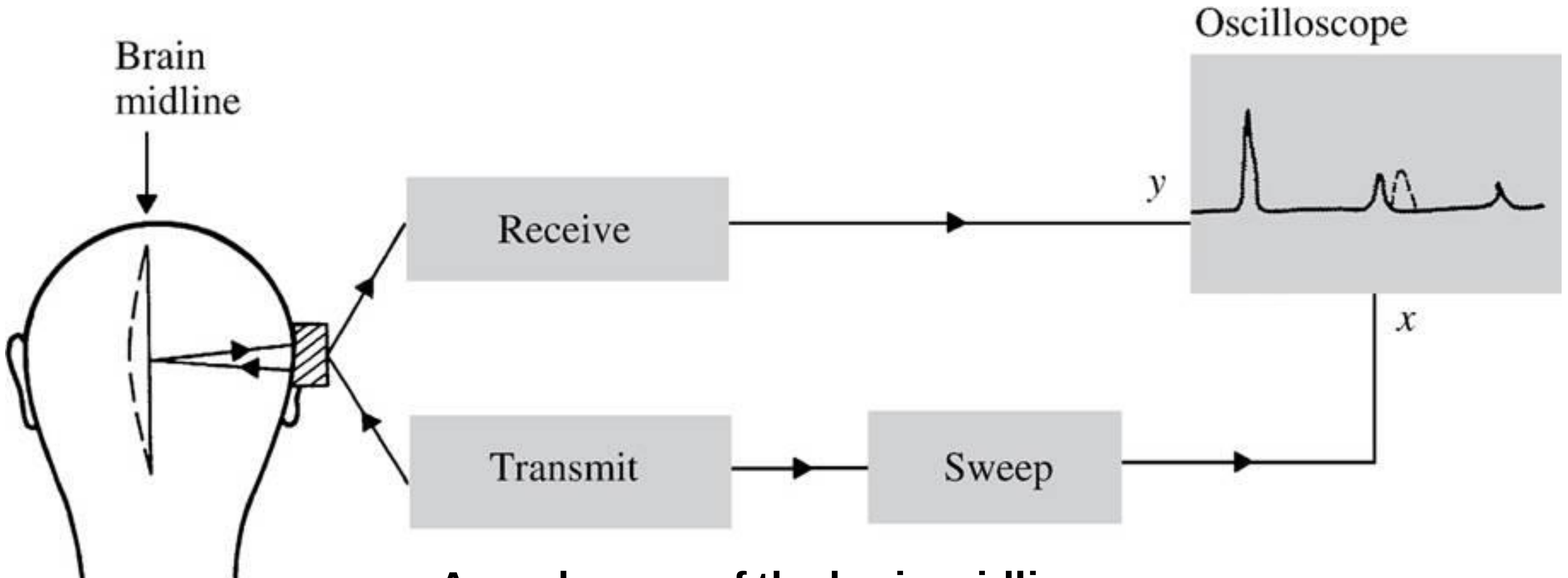
- Display of echo amplitude (Y-axis) versus distance (X-axis) into the tissue, which is related to elapsed time and the speed at which ultrasound propagates in the tissue.

- The A-mode scan had also been used for early pregnancy assessment (detection of fetal heart beat), and placental localization.

- Also used to test the symmetry between left and right hemispheres of the brain: R-L then L-R.

- For example:

    - The transducer is placed against the skull and the display gives the echo time of the brain midline (proportional to depth).
    - The transducer is then moved to the other side of the skull and the procedure repeated.
    - The images of normal patients are symmetric so that the brain midline should appear in the same position in the two images.
    - A tumor or large blood clot could move the cerebral hemispheres to shift the midline.



A-mode scan of the brain midline

A-mode scan gives information about distances of different boundaries inside the body, they cant give a picture that we can interpret

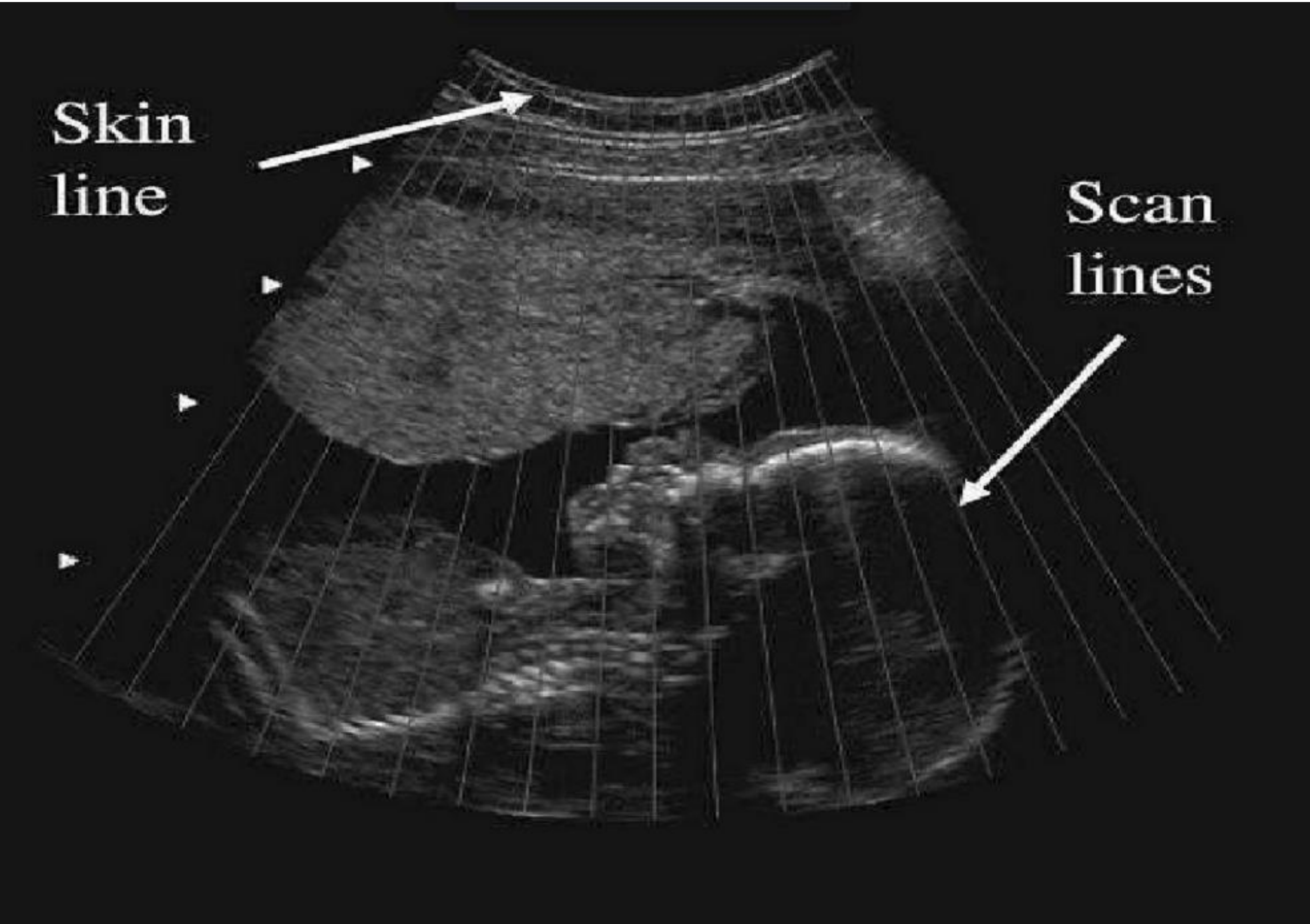
➢ B-Mode

- B-mode ultrasound (Brightness-mode) is the display of a 2D-map of B-mode data, currently the most common form of ultrasound imaging.
  - This form of display (solid areas appear white and fluid areas appear black) is also called gray scale.
- The B-mode scan is the basis of 2D scanning. The transducer is moved about to view the body from a variety of angles.
- The probe can be moved in a line **(linear scan),** or rotated from a particular position (**sector scan).**

Watch #
I14.1

Real Time B-mode

- Used phased array transducer called a real-time scanner.
- Used most often to scan abdomen and to check the fetus in pregnant women.
- System scans 15-60 frames/s.
- Hand-held transducer moved to different positions or held at different angles to get complete picture.
- Transducer can be moved and angles so that get 3-D information.
- Real-time B-scans allow body structures which are moving to be investigated.
- The simplest type of scanner is just a speeded up version of the 2-D B-scan , allowing a rapid series of still pictures to be built up into a video of the movement.


Skin
line
Scan
lines

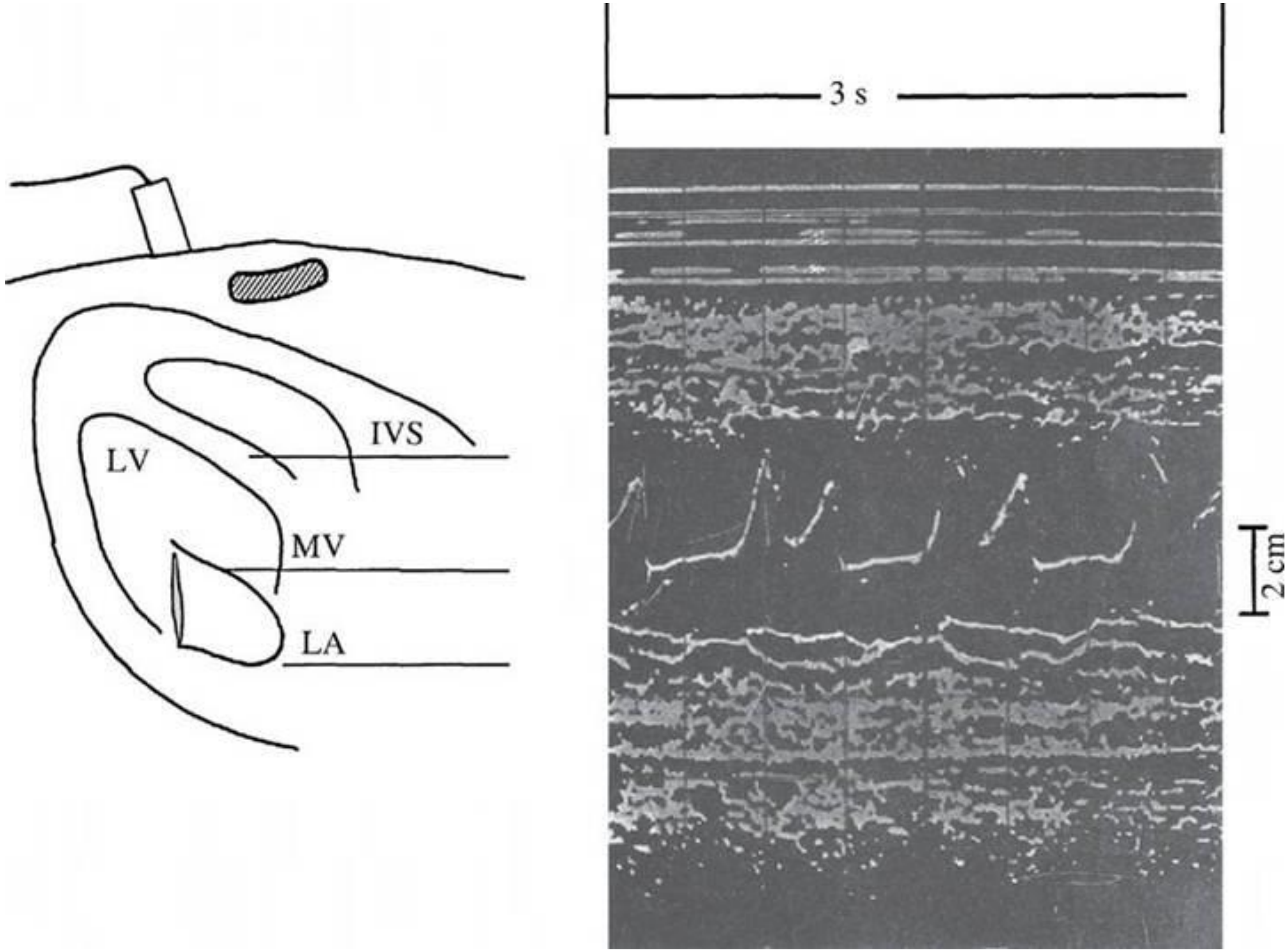
➢ M-mode

- The M-mode (Motion-mode) ultrasound is used for analyzing moving body parts (also called time-motion or TM-mode) commonly in cardiac and fetal cardiac imaging.

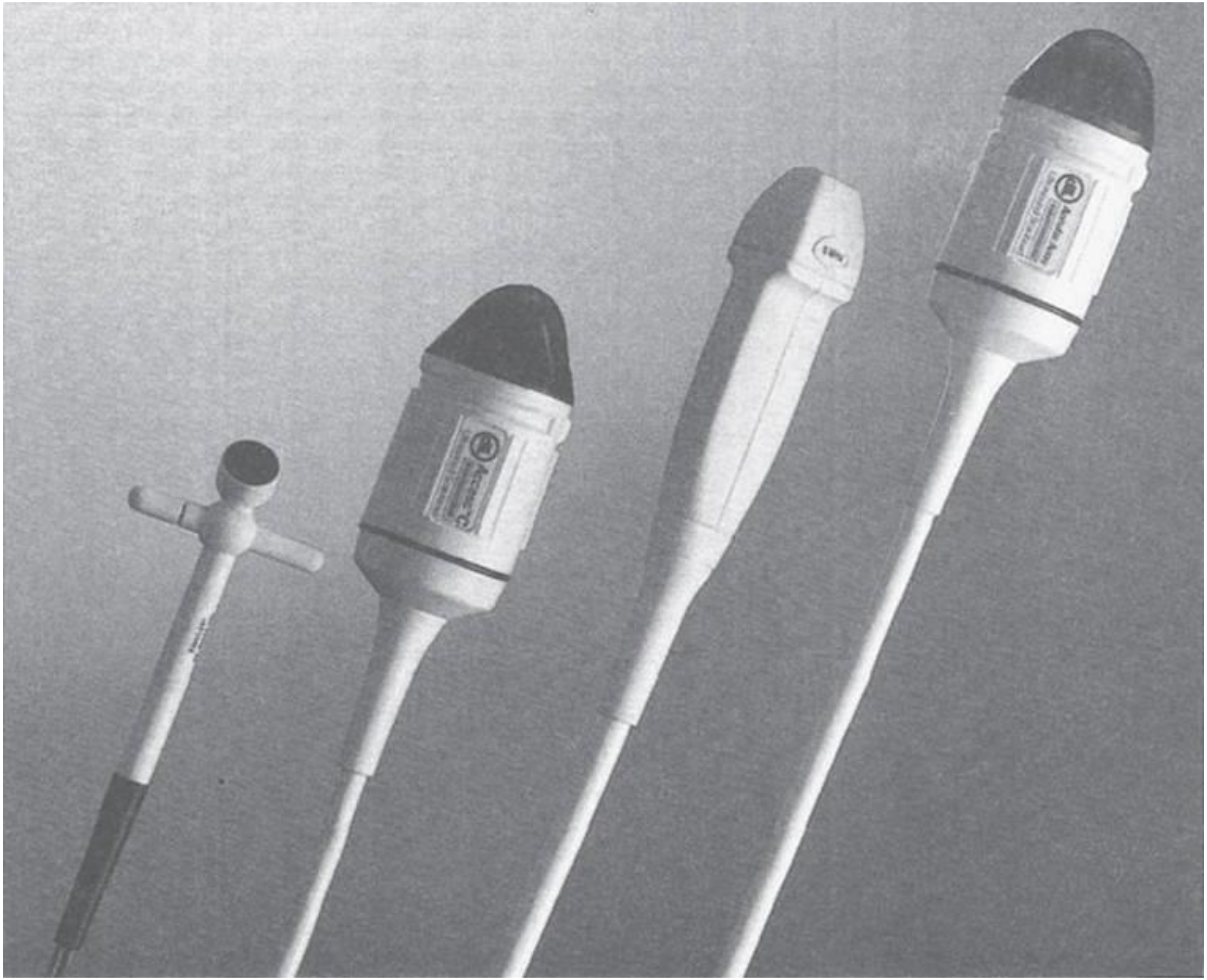
- Used for studying the motion of interface.

- The high sampling frequency (up to 1000 pulses per second) is useful in assessing rates and motion, particularly in cardiac structures such as the various valves and the chamber walls.

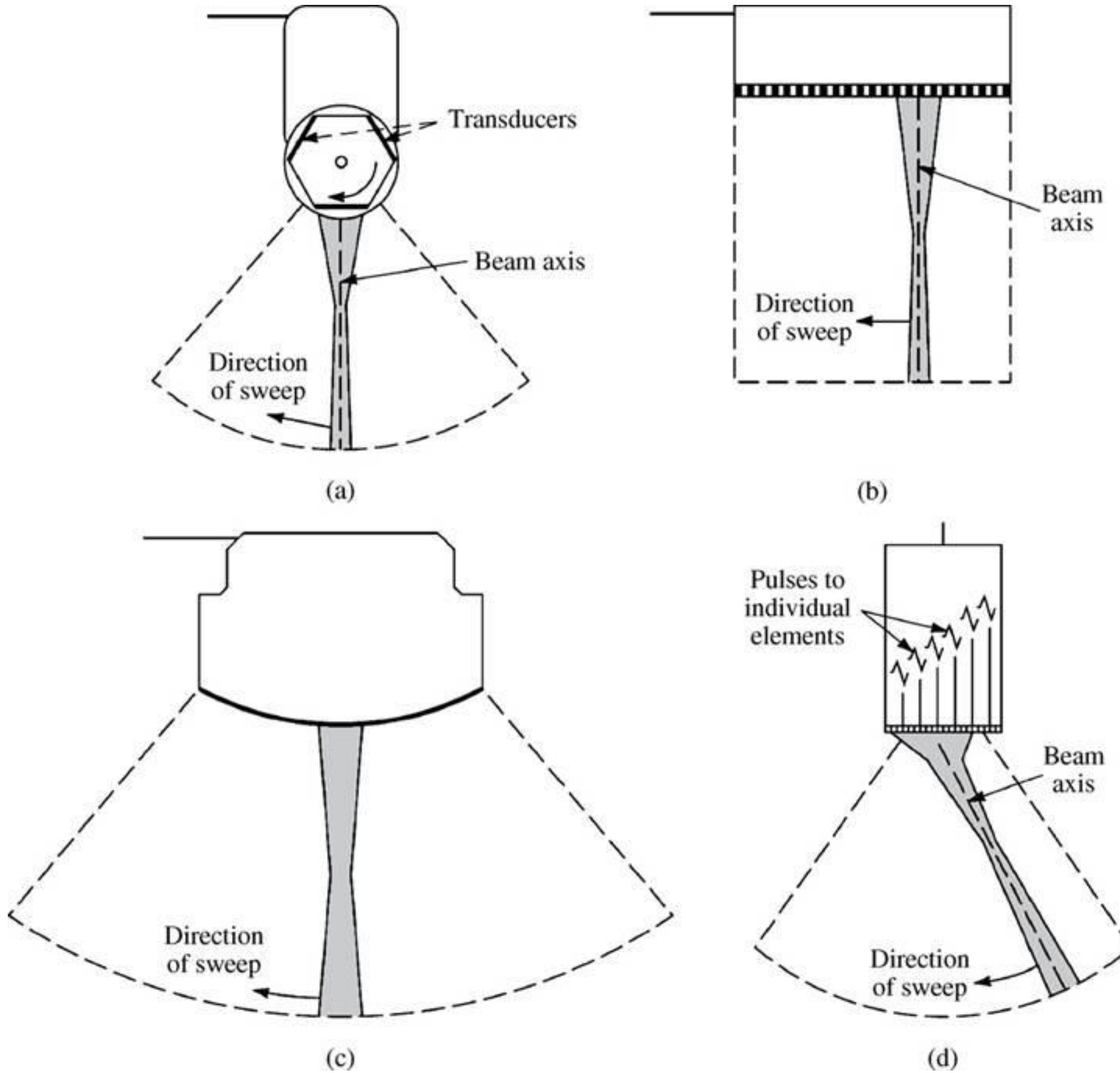
Watch # I13



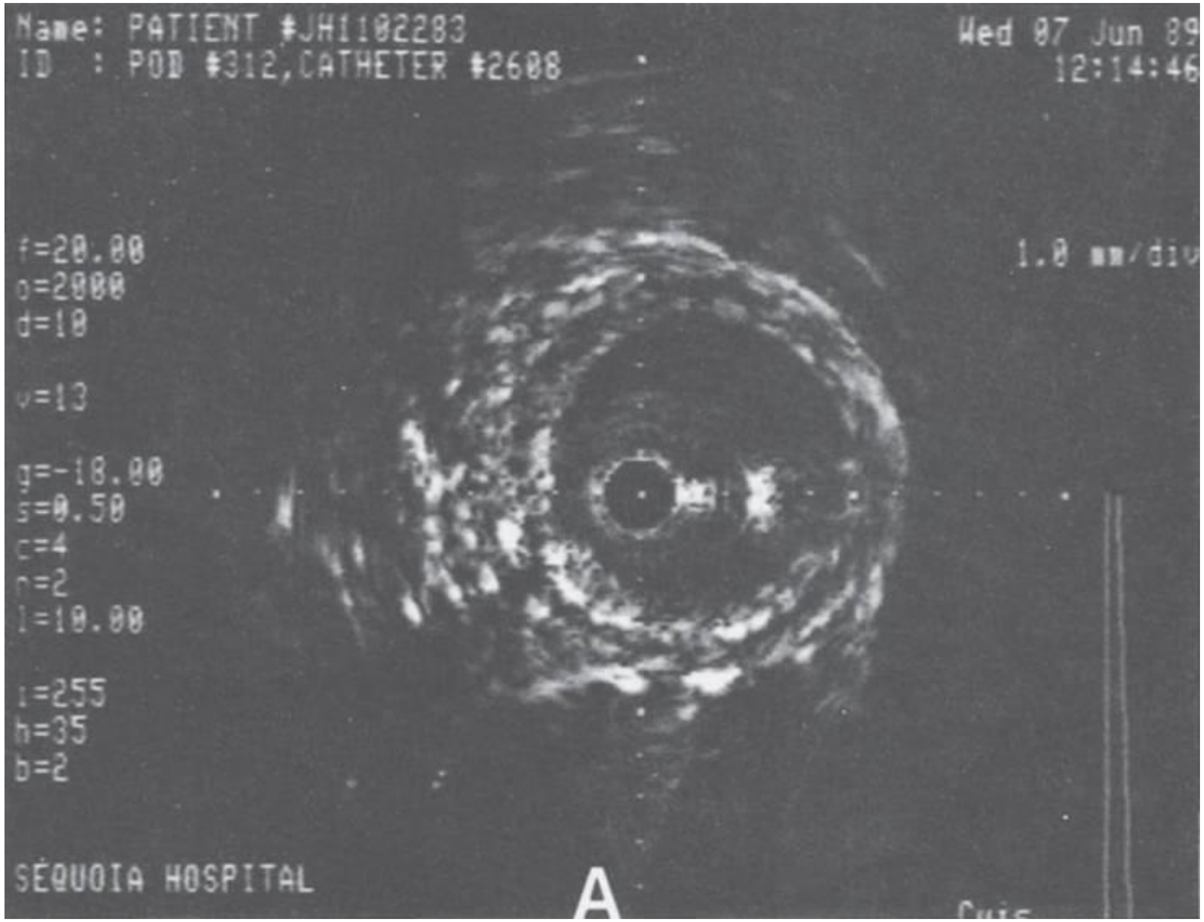
Time-motion ultrasound scan of the mitral valve of the heart: The central trace follows the motions of the mitral valve (MV) over a 3 s period, encompassing three cardiac cycles. The other traces correspond to other relatively static structures, such as the interventricular septum (IVS) and the walls of the left atrium (LA).



Different types of ultrasonic transducers range in frequency from 12 MHz for ophthalmic devices to 4 MHz for transducers equipped with a spinning head. (Photo courtesy of ATL.)



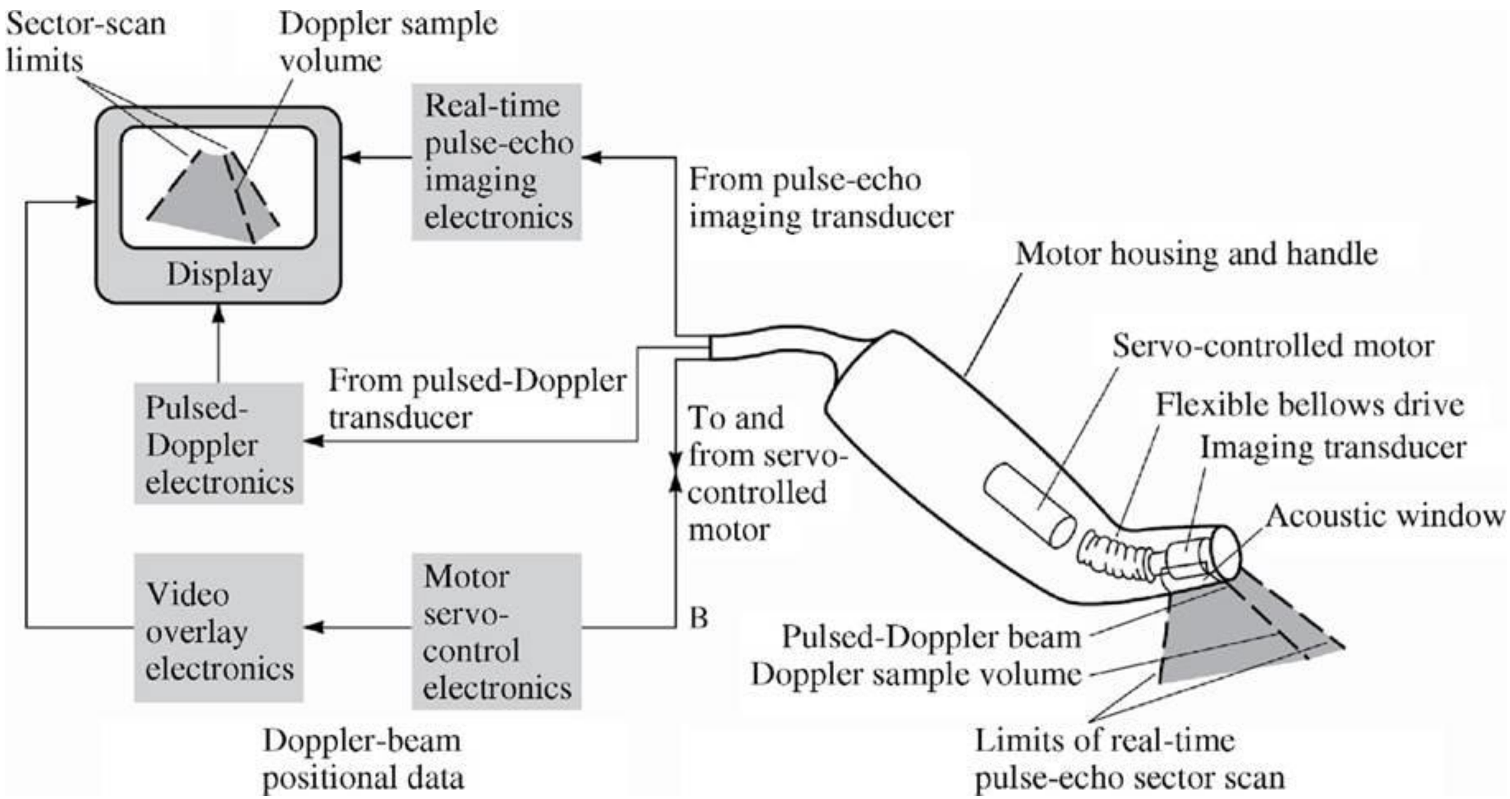
Ultrasound scan heads, (a) Rotating mechanical device, (b) Linear phased array which scans an area of the same width as the scan head, (c) Curved linear array can sweep a sector, (d) Phasing the excitation of the crystals can steer the beam so that a small transducer can sweep a large area.



Intravascular ultrasonic image showing the characteristic three-layer appearance of a normal artery. Mild plaque and calcification can be observed at 7 o'clock. (Photo courtesy of Cardiovascular Imaging Systems, Inc.)

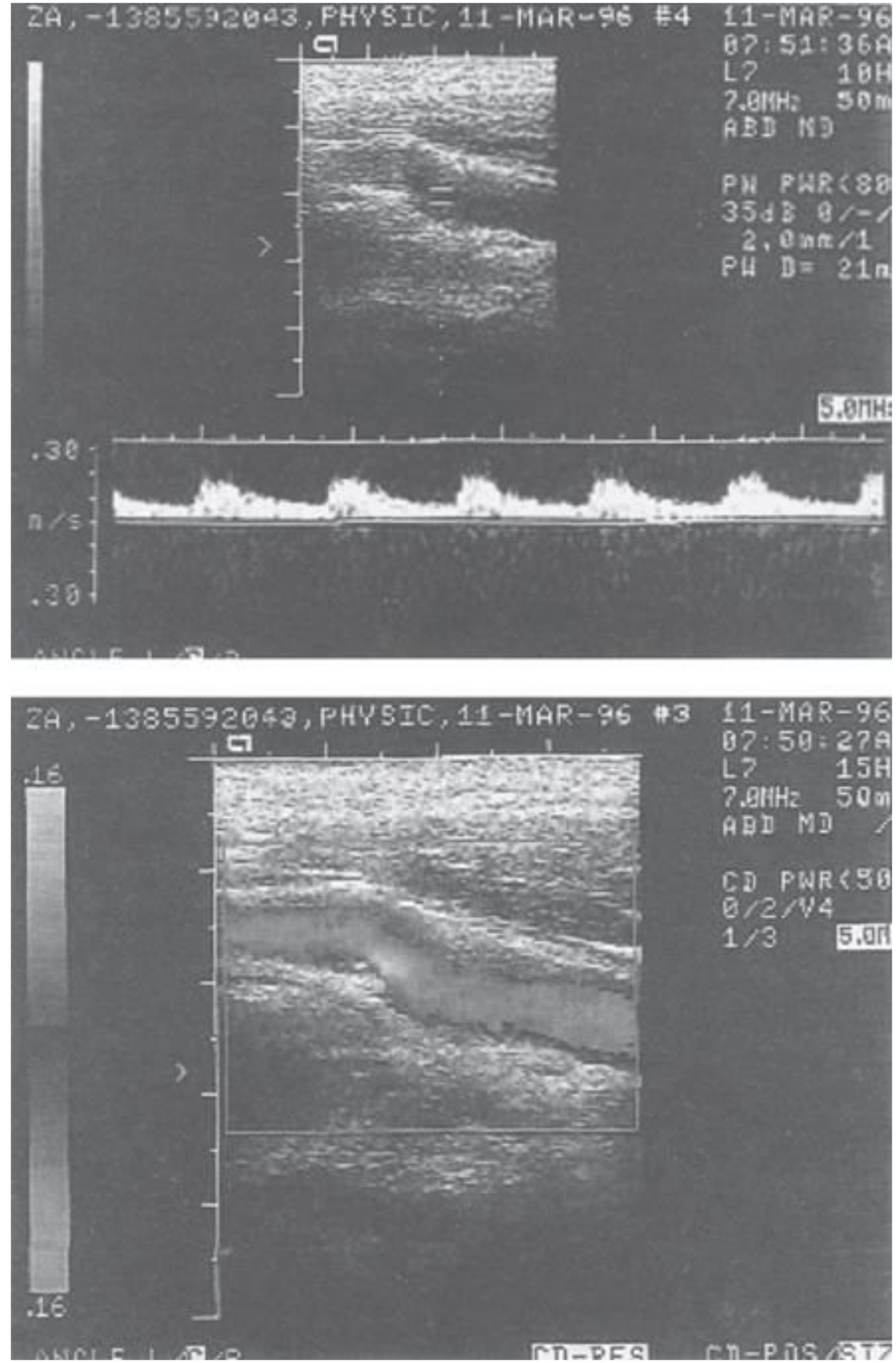
➢ Duplex Scanners

Halberg and Thiele (1986) describe the design of a phased array ultrasonic duplex scanner that combines real-time two-dimensional imaging with the pulsed-Doppler method to measure directional blood velocity noninvasively.



The duplex scanner contains a mechanical real-time sector scanner that generates a fan-shaped two-dimensional pulse-echo image. Signals from a selected range along a selected path are processed by pulsed Doppler electronics to yield blood velocity (from Wells, 1984).

Watch #
I15



(a) Duplex scanner B-mode image and Doppler spectral analysis record for a normal carotid artery, near the bifurcation. The Doppler signals were recorded from the sample volume defined by the Doppler cursor, the two parallel lines located inside the carotid artery, (b) Color flow image of the vessel in (a). Higher velocity components (lighter color, reproduced here in black and white) are seen where the vessel direction courses more directly toward the transducer.

- ## Advantages Of Ultrasound

- Ultrasound scanning is noninvasive (no needles or injections) and is usually painless.
- Ultrasound is widely available, easy-to-use and less expensive than other imaging methods.
- Ultrasound imaging uses non ionizing radiation.
- Ultrasound scanning gives a clear picture of soft tissues that do not show up well on x-ray images.
- Ultrasound causes no health problems and may be repeated as often as is necessary if medically indicated.
- There are no hazards for the patient and operator.

Disadvantages Of Ultrasound

- The major disadvantage is that the resolution of images is often limited.
- Still in many situations where X-rays produce a much higher resolution.
- Bone absorbs ultrasound so that brain images are hard to get.
- Attenuation can reduce the resolution of the image.
- Sonography performs very poorly when there is a gas between the transducer and the organ of interest

Contrast Agents

- The images of low contrast structures, blood vessels and anatomic spaces can be enhanced by the injection of a contrast agent.

Watch # I16

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DR. FARNHAM [NEW]

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Scene: 3

Angiogram of the author taken with iodine-based contrast agent. Image courtesy of Drs. Hinderaker and Farnham.