# Unit 2

## Computed Tomography

- Computed tomography
- system components
- gantry geometry
- system electronics
- patient dose in CT scanners
- Recent developments – Digital radiography Digital subtraction angiography (DSA)
- 3D reconstruction
- Dynamic Spatial Reconstructor (DSR)

# Computed Tomography

http://www.stabroeknews.com/images/2009/08/20090830ctscan.jpg

http://upload.wikimedia.org/wikipedia/commons/archive/d/da
/20060904231838!Head_CT_scan.jpg


http://www.capitalhealth.org/subpage.cfm?ref=36

# Computed Tomography

## - *Introduction*

- *Computed Tomography*, CT for short (also referred to as CAT, for Computed Axial Tomography), utilizes X-ray technology and sophisticated computers to create images of cross-sectional “slices” through the body.
- CT exams and CAT scanning provide a quick overview of pathologies and enable rapid analysis and treatment plans.
- Tomography is a term that refers to the ability to view an anatomic section or slice through the body.
- Anatomic cross sections are most commonly refers to transverse axial tomography.
- The CT scanner was developed by Godfrey Hounsfield in the very late 1960s.
- This x-ray based system created projection information of x-ray beams passed through the object from many points across the object and from many angles (projections).
- CT produces cross-sectional images and also has the ability to differentiate tissue densities, which creates an improvement in contrast resolution.

# Computed Tomography

## - *Introduction*

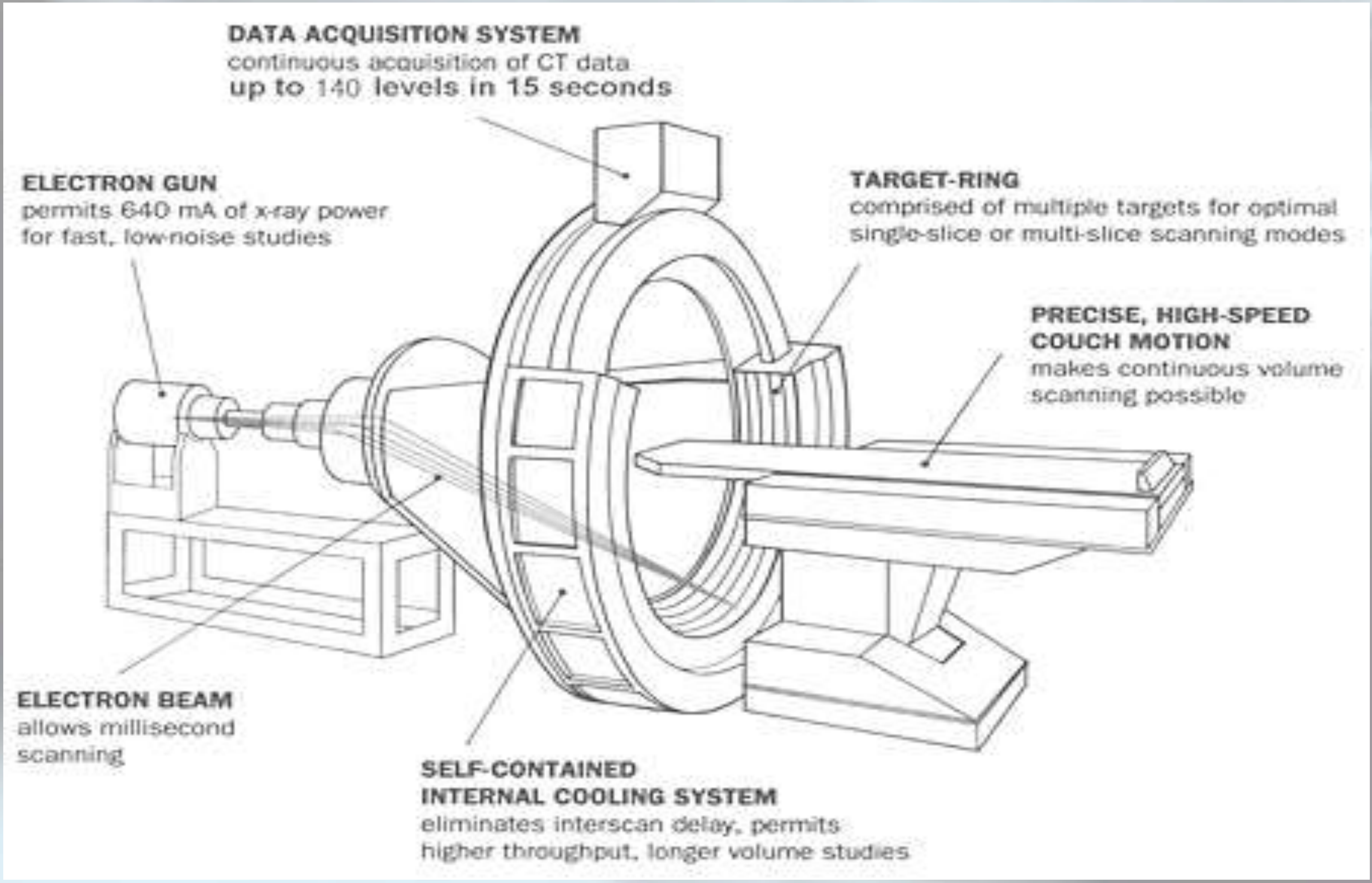
- The x-ray tube in a CT scanner is designed to produce a fan shaped beam of x-rays that is approximately as wide as your body.
- Tissue attenuation is measured over a large region from one position of the x-ray tube
- The x-ray tube on a CT scanner is more heavy duty than tubes used for standard film imaging since the unit rotates.
- Opposite the patient is an array of detectors that measure the intensity of the x-ray beam at points laterally across the patients body.
- Modern CT scanners use solid state detectors that have very high efficiency at the low energy of x-rays produced by CT scanners.
- Solid state detectors are made of a variety of materials that create a semiconductor junction similar to a transistor.
- Ultrafast ceramic detectors use rare earth elements such as silicon, germanium, cadmium, or gadolinium, which create a semiconducting p-n junction.

# Computed Tomography

## - *The basics*

- The x-rays are produced in a part of the ring and the ring is able to rotate around the patient.
- The target ring contains an array of detectors and is internally cooled to reduce electronic noise and to cool the anode.
- The patient is put into the system using a precise high speed couch.

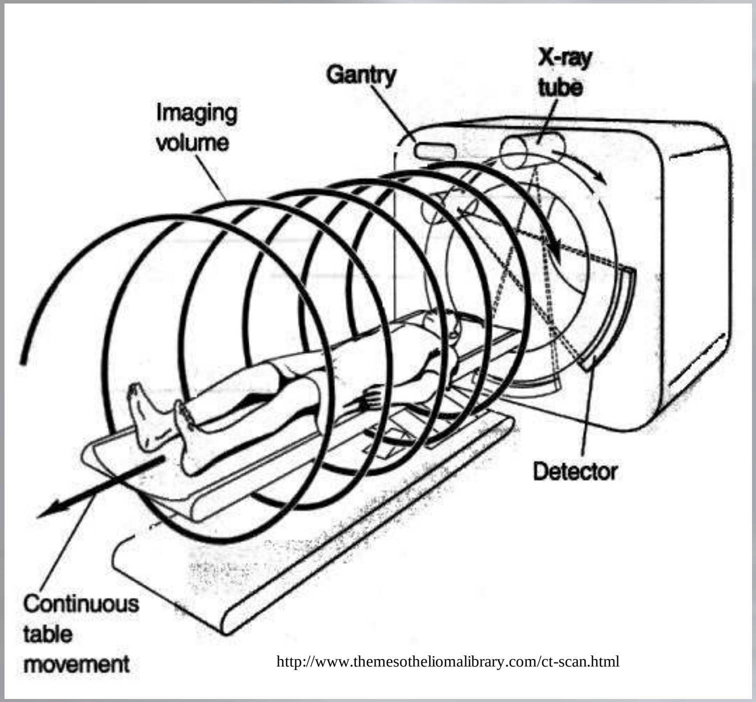

http://www.endocrinesurgery.ucla.edu/images/adm_tst_ct_scan.jpg




http://www.themesotheliomalibrary.com/ct-scan.html

# Computed Tomography

## - *The basics of image formation*




- The x-ray tube and detectors rotate around the patient and the couch moves into the machine.

- This produces a helical sweep pattern around the patient.

- The patient opening is about 70cm in diameter.

- The data acquired by the detectors with each slice is electronically stored and are mathematically manipulated to compute a cross sectional slice of the body.

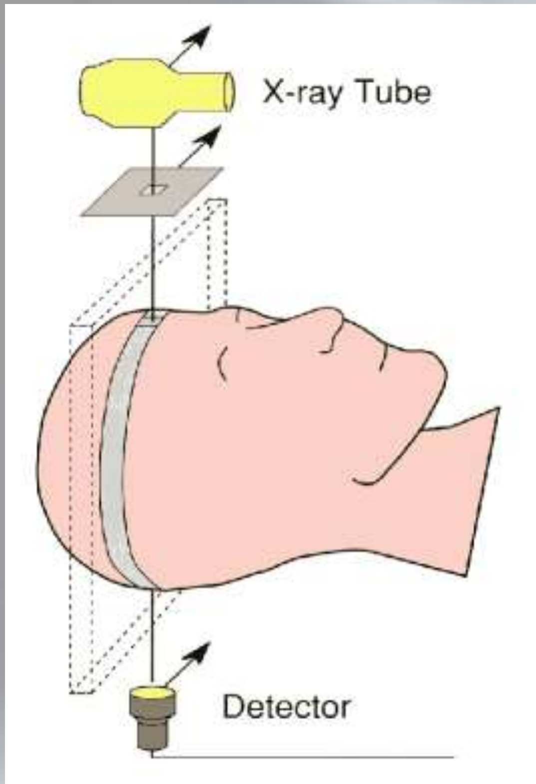
- Three dimensional information can be obtained by comparing slices taken at different points along the body.

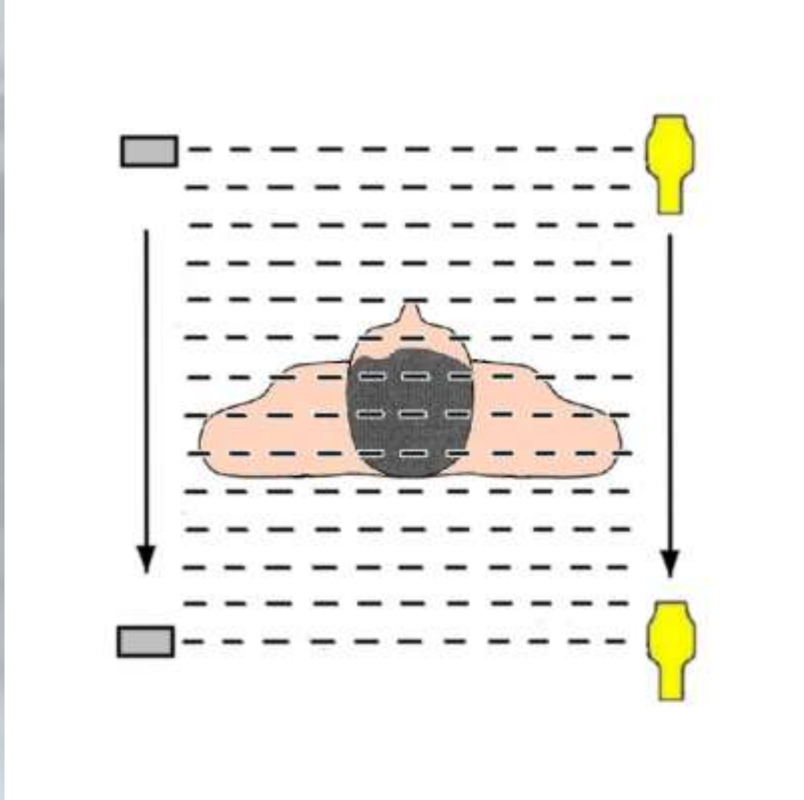
- Or the commuter can create a 3D image by stacking together slices.

- As the detector rotates around many cross sectional images are taken and after one complete orbit the couch moves forward incrementally.

# Computed Tomography

## - *The basics of image formation*



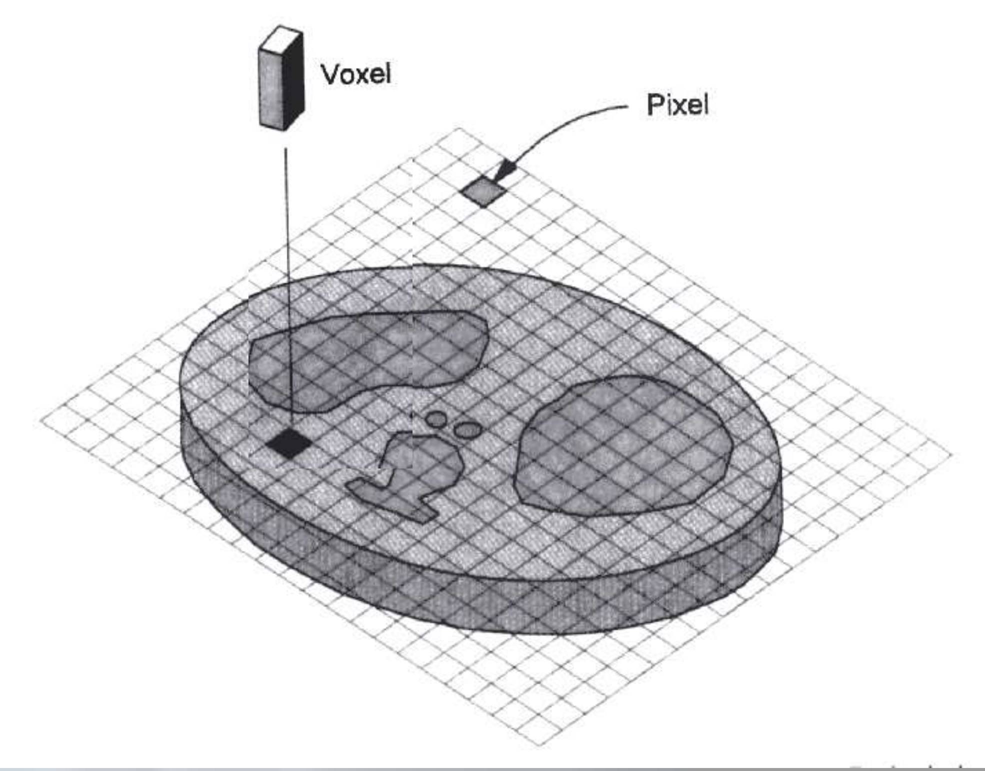
• Here the x-ray tube and detector array makes many sweeps past the patient.

• The x-ray tube and detector array is capable of rotating around the axis of the patient.

# Computed Tomography

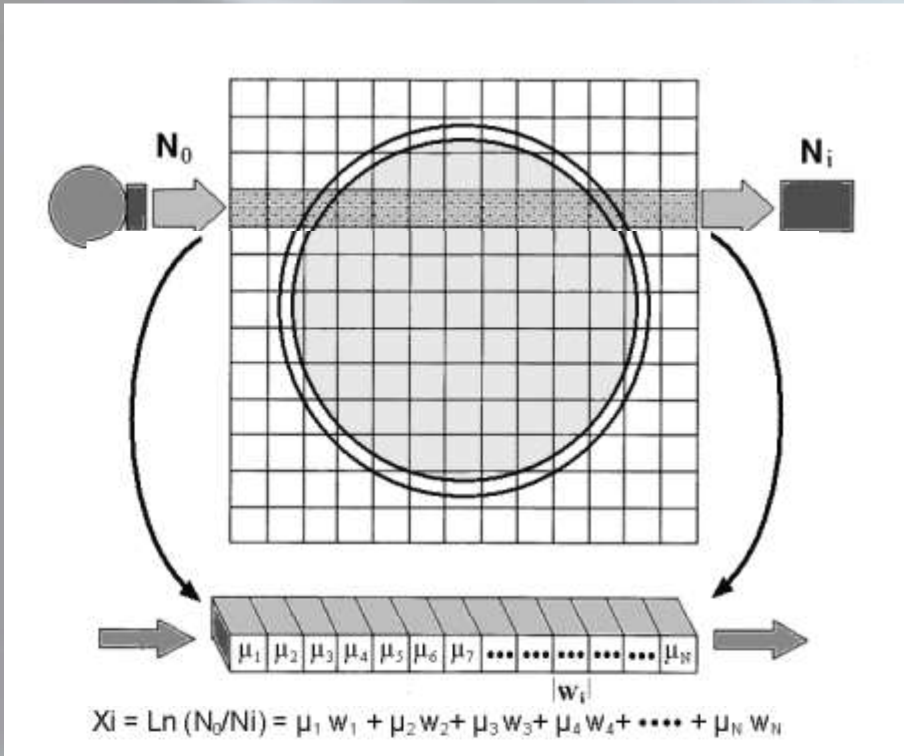
## - *The basics of image formation*

- *Pixel* – picture element – a 2D square shade of gray.
- *Voxel* – volume element – a 3D volume of gray.
- This is a result of a computer averaging of the attenuation coefficients across a small volume of material.  This gives depth information.
- Each voxel is about 1mm on a side and is as thick as 2 – 10mm depending on the depth of the scanning x-ray beam.



# Computed Tomography

## - *The basics of image formation*




The detectors see the forward projected x-rays and measure the intensity given that the x-ray intensity without the body present is known.

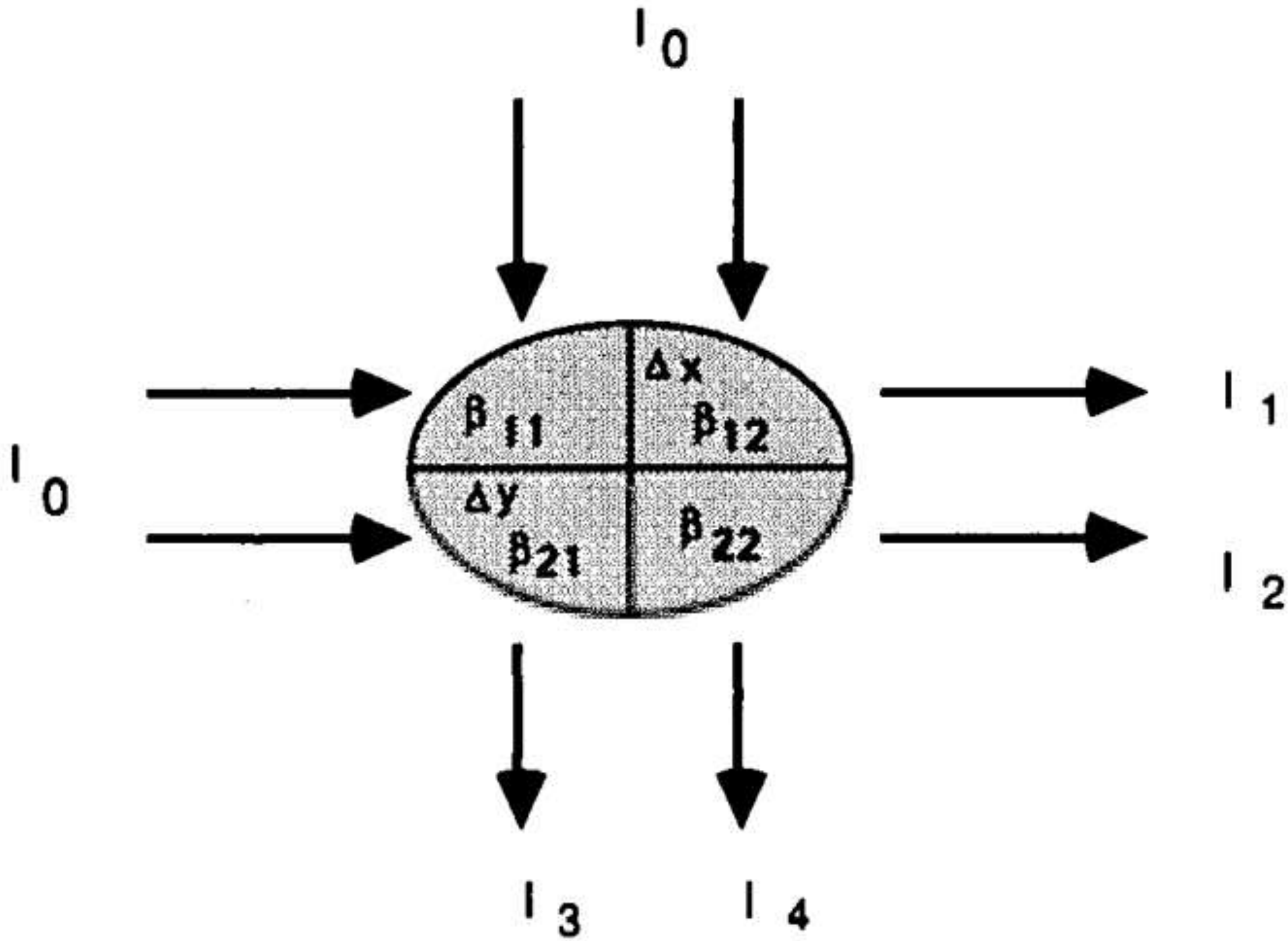
The intensity $N_i$ written as sum of attenuation coefficients along a given x-ray path.

This generates a shade of gray and a number associated with this shade.

Then the detector changes angles and the process repeats.

The images are reconstructed by a method called *back projection*, or tracing backwards along the x-rays forward path to reconstruct the image and calculating the absorption due to a localized region.

This a mathematically tedious process, but is handled easily with computers.




Object divided into four pixels.

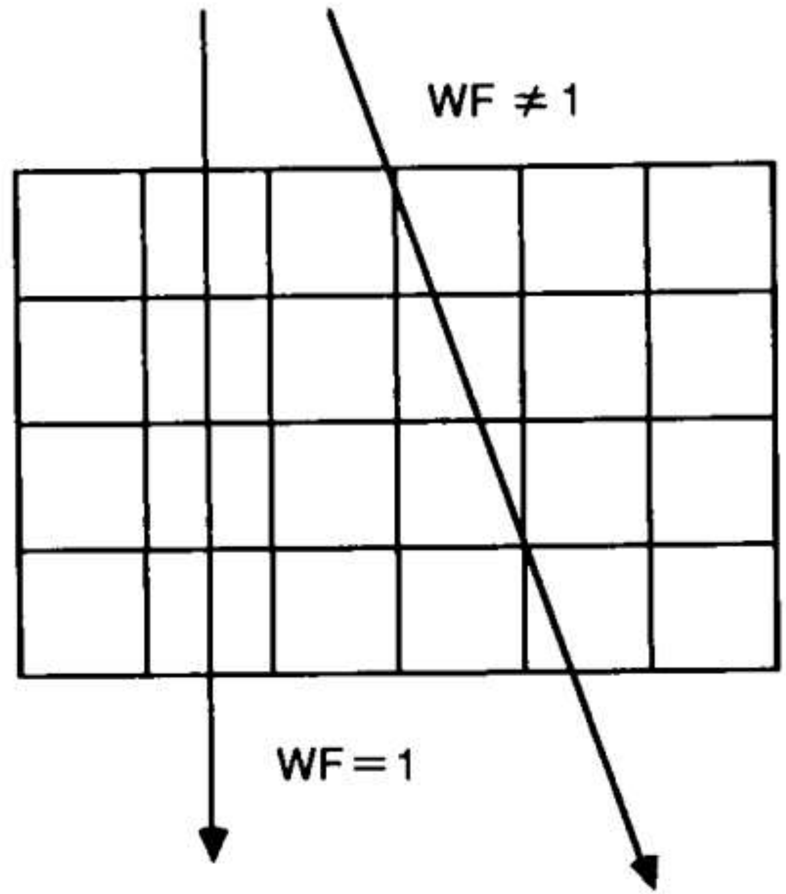
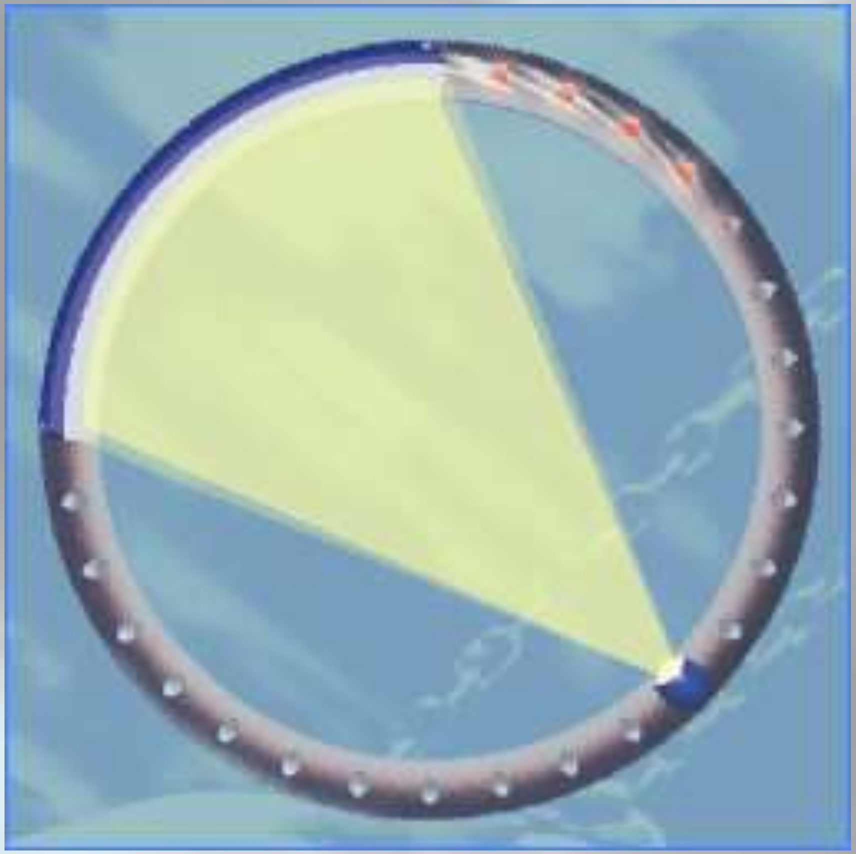
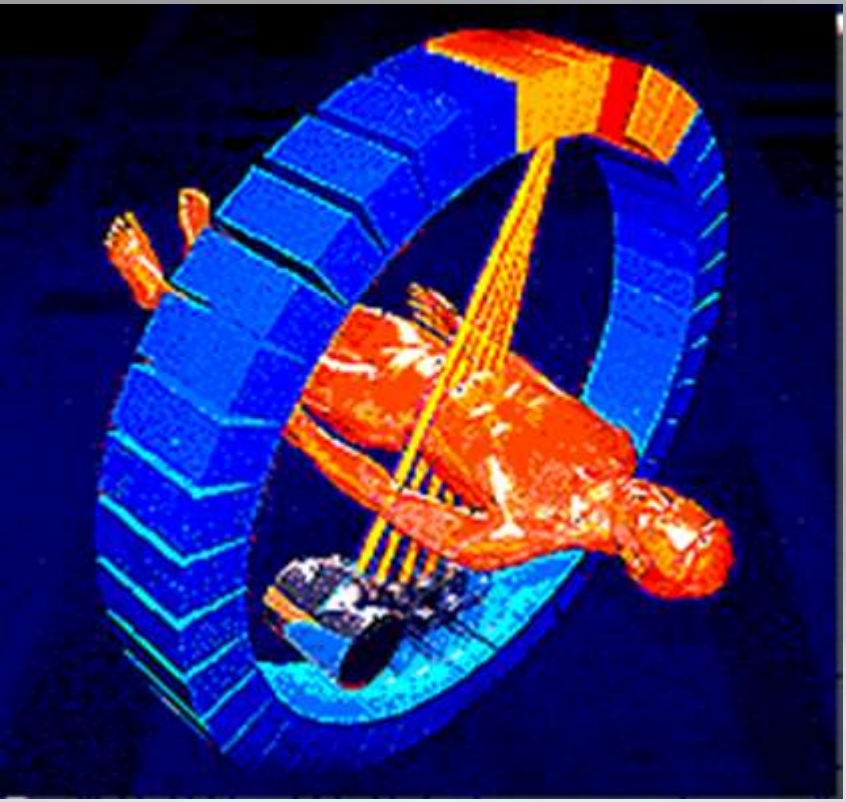


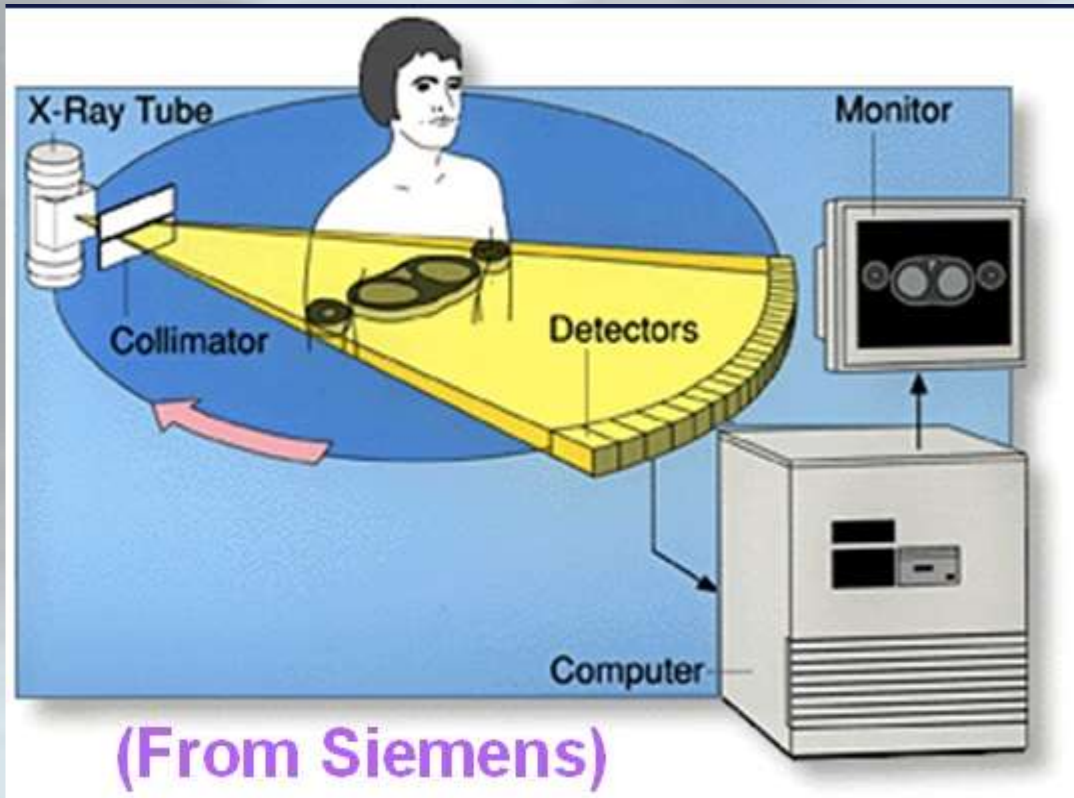

**Figure 41** Weighing factor (WF) has to be applied to account for differences in propagation distance of X-ray beam in each pixel at different angles.

# CT – Source and Detector

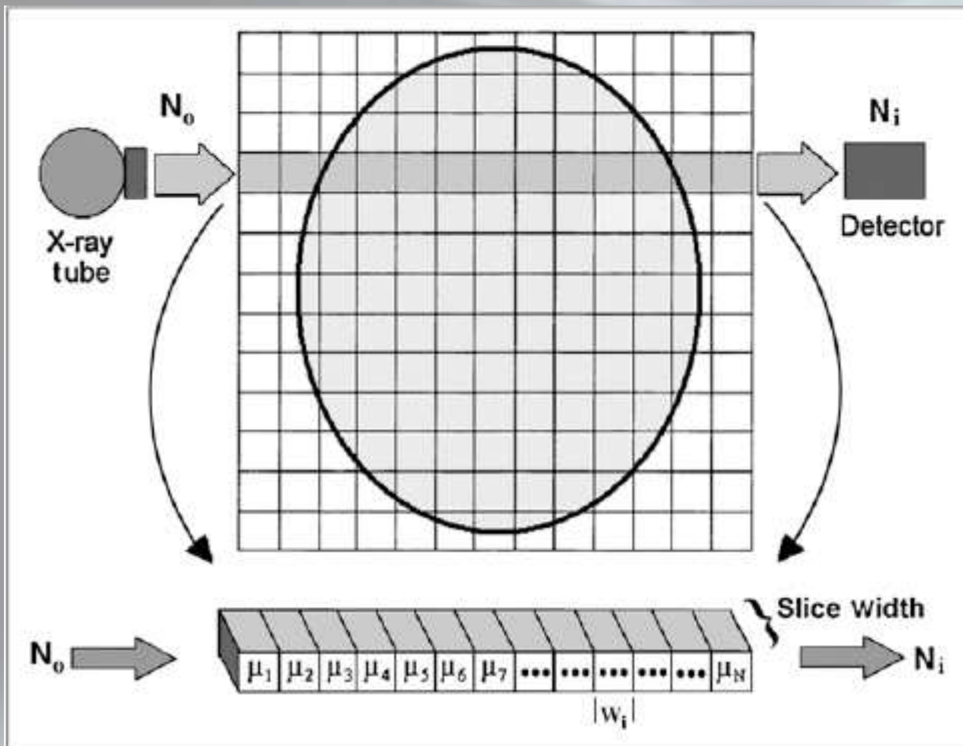


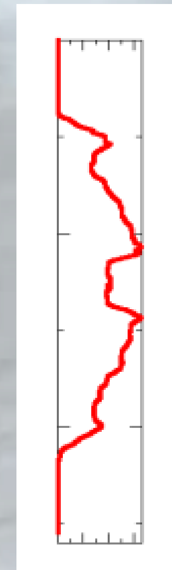
# Projection Data in a Scan

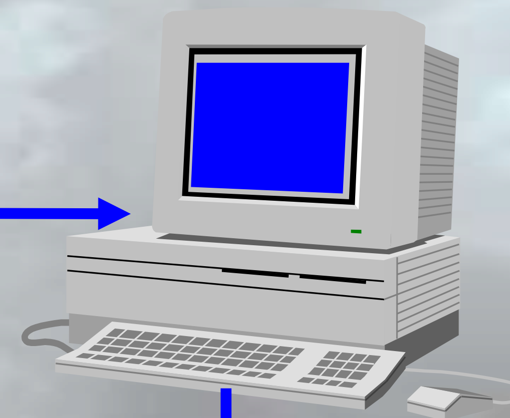




# Attenuation Coefficients in a Projection Beam



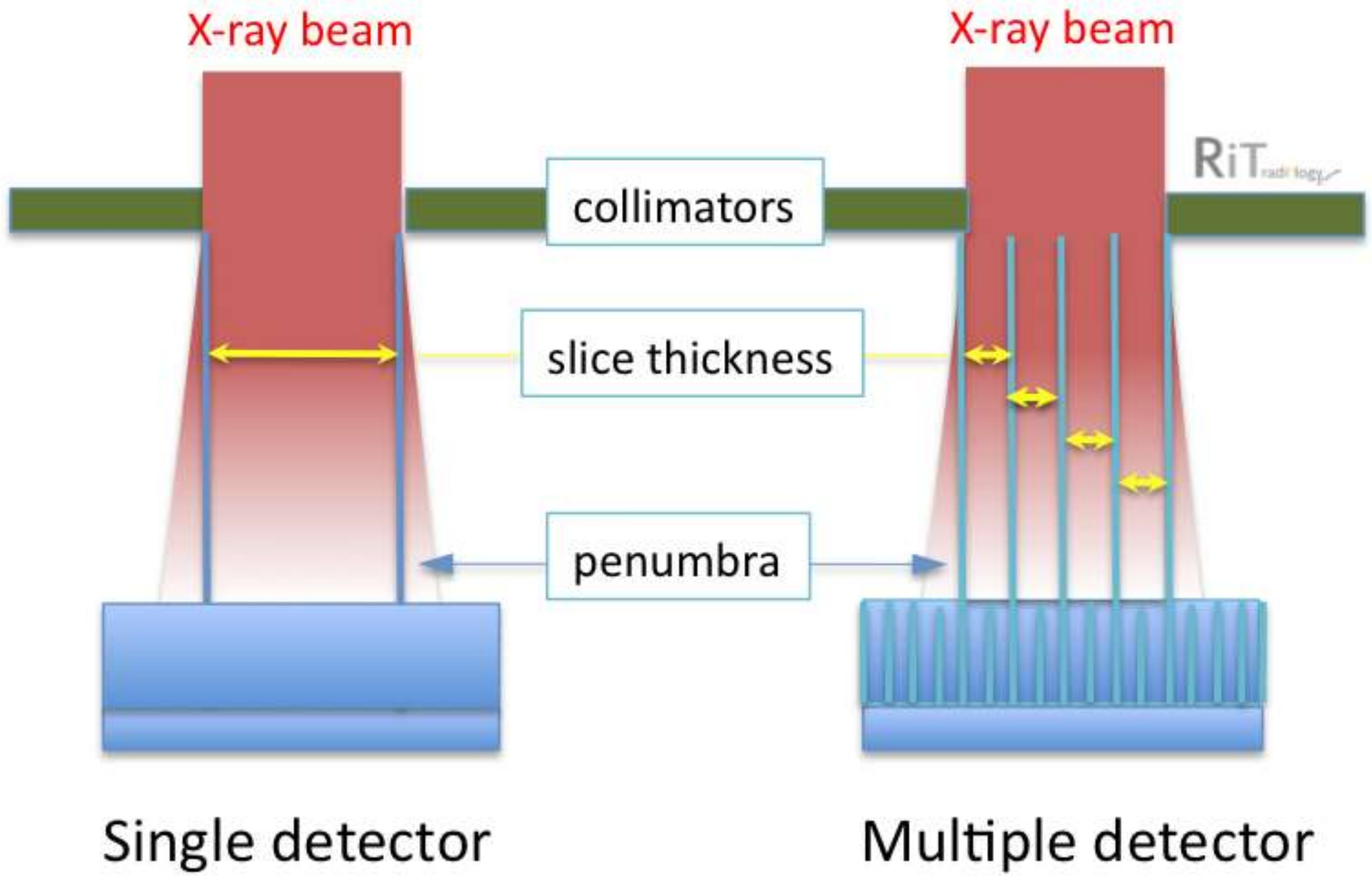


| | | | | |
|---|---|---|---|---|
| 35 | 36 | 34 | 39 | 33 |
| 31 | 34 | 33 | 35 | 32 |
| 31 | 78 | 80 | 85 | 90 |

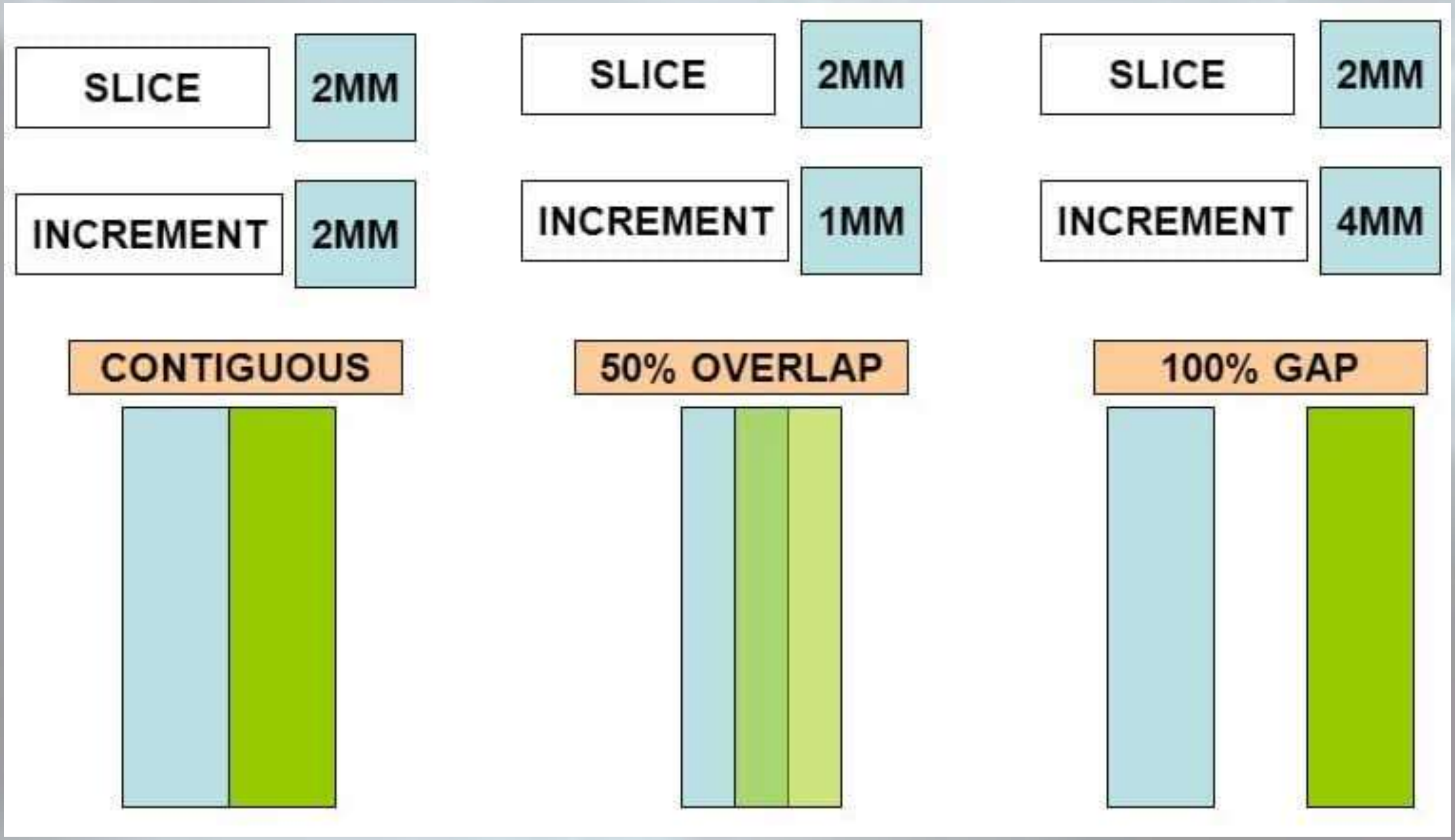
$$N_i = N_o\, e^{-\sum_k \mu_k \Delta x}$$

Or

$$\sum_k \mu_k \Delta x = \ln (N_o / N_i)$$




Adapted from Bushberg, et al. The Essential Physics of Medical Imaging, 2nd Edition, 2001




- Slice thickness and slice increment are central concepts that surround CT/MRI imaging.
- Slice thickness refers to the (often axial) resolution of the scan (2 mm shown in figure)
- Slice Increment refers to the movement of the table/scanner for scanning the next slice (varying from 1 mm to 4 mm shown in figure).

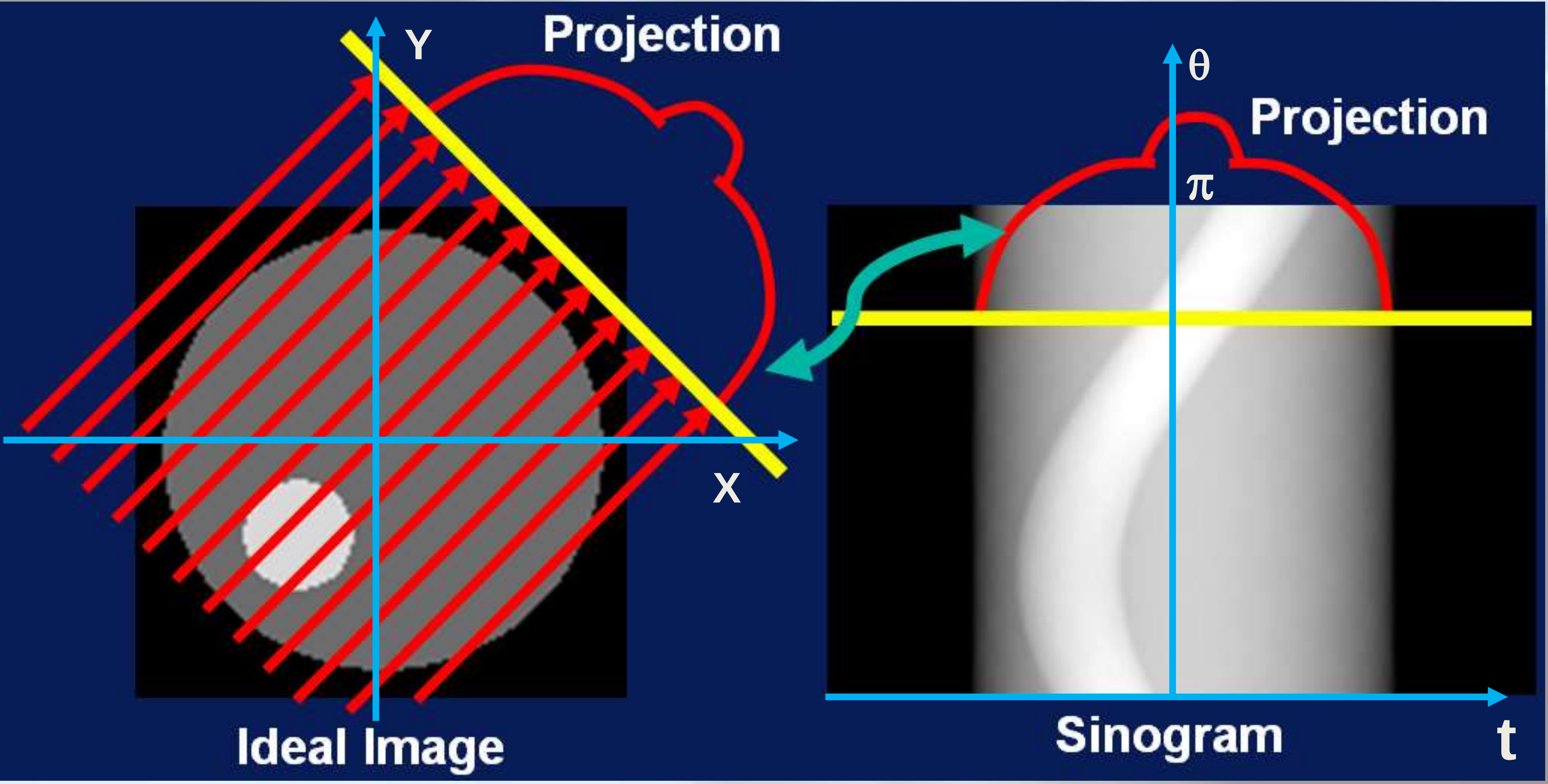
# Slice thickness

- It is acceptable and common to have an overlap in these values.
- The slice thickness is an important factor in understanding the resolution of your images.
- If the scan has a slice increment greater than the slice thickness, there is no information about the skipped section, so anatomical information or objects might not show up on the scan.

# Slice thickness

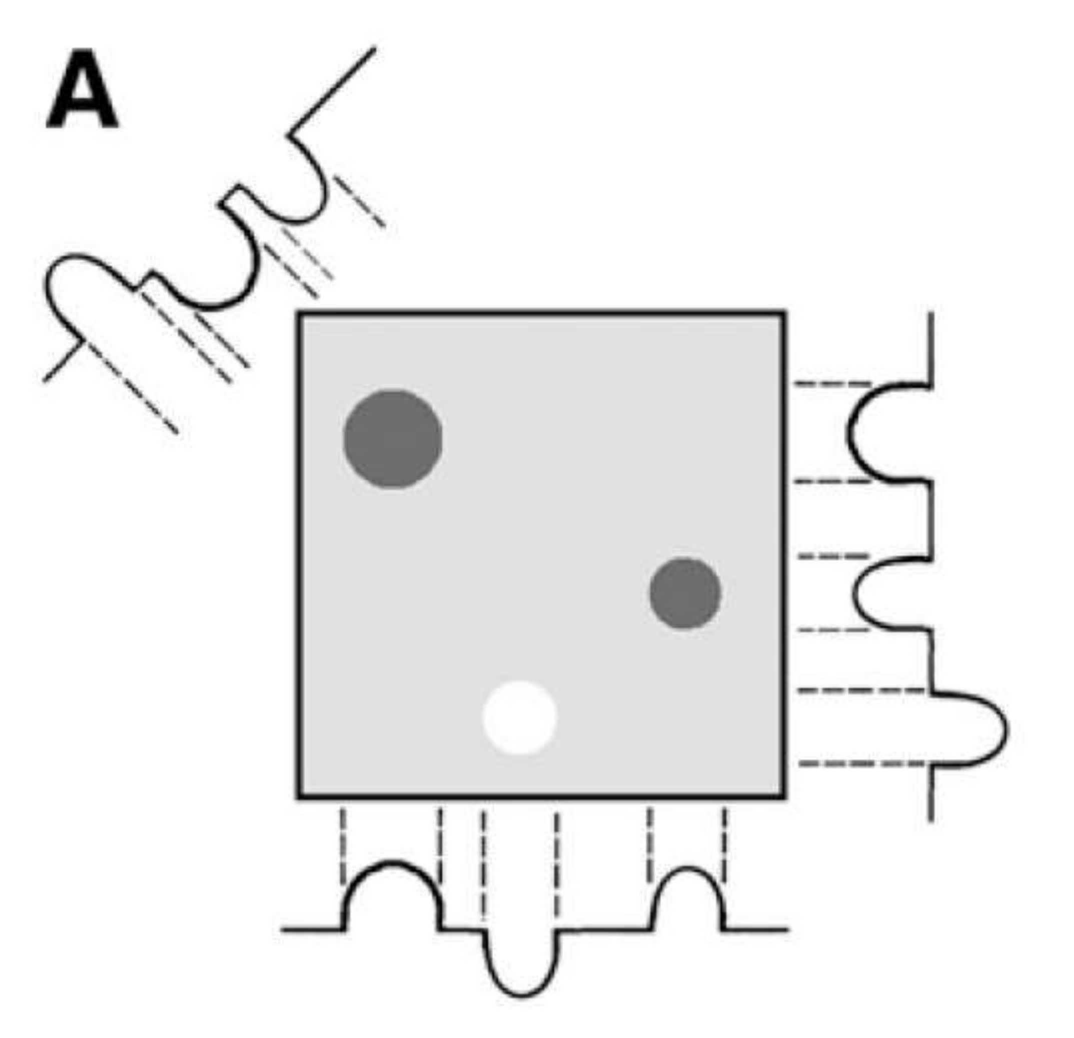
- **CT Scanner machines are differentiated by the number of slices they have, and the slice number correlates to how many images the CT scanning machine can garner per gantry rotation.**
- **For example, a 16 Slice CT Scan machine is capable of acquiring 16 images per gantry rotation.**
  - **64 - Slice CT Scan**
  - **128 – slice CT scan**

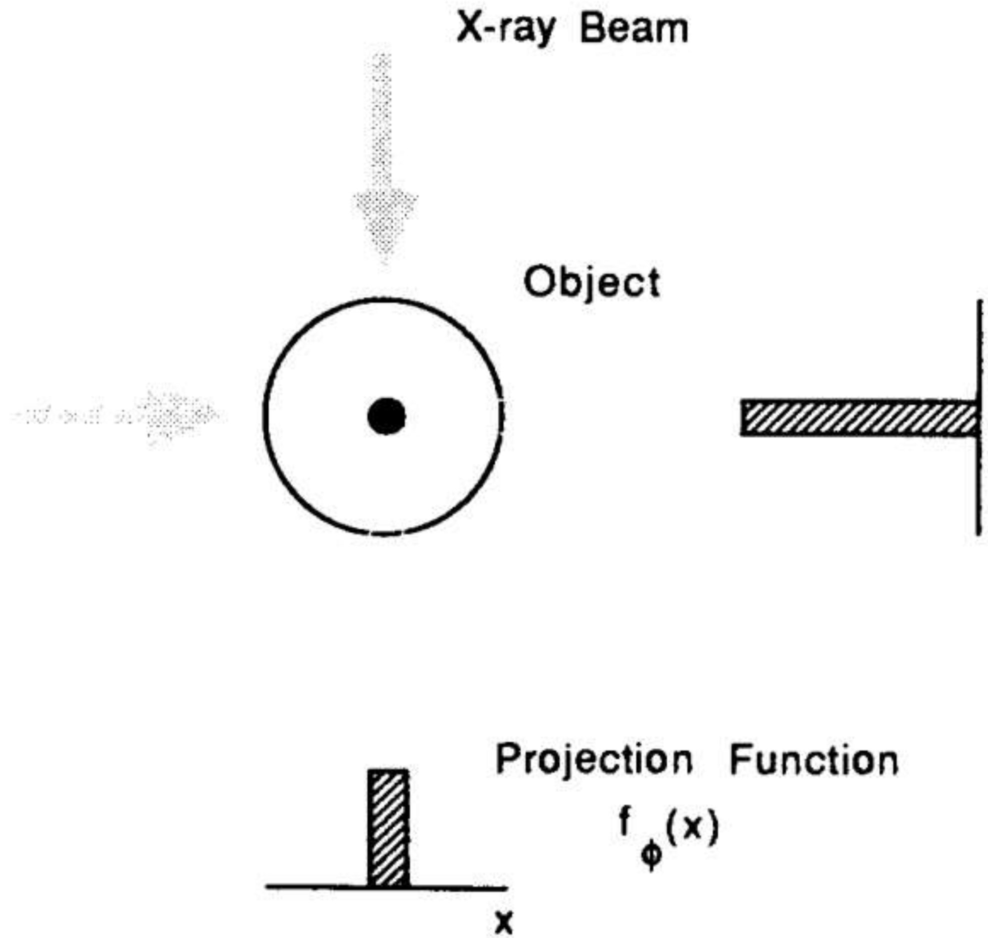
# Sinorgram: Projection from Multiple Directions




https://www.youtube.com/watch?v=q7Rt_OY_7tU
https://www.youtube.com/watch?v=rKh_XIpsuc4

# Another Example of Projection






Projection functions of an object of simple geometry at different angles.

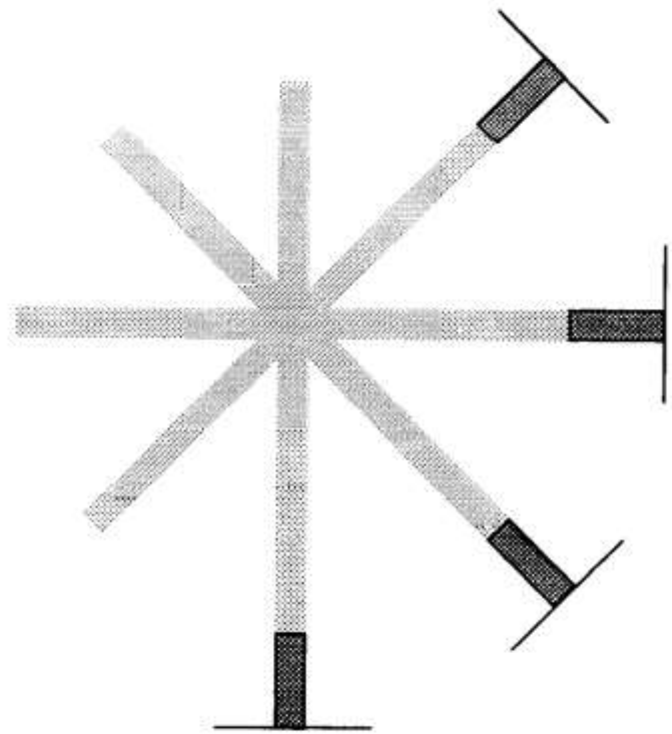
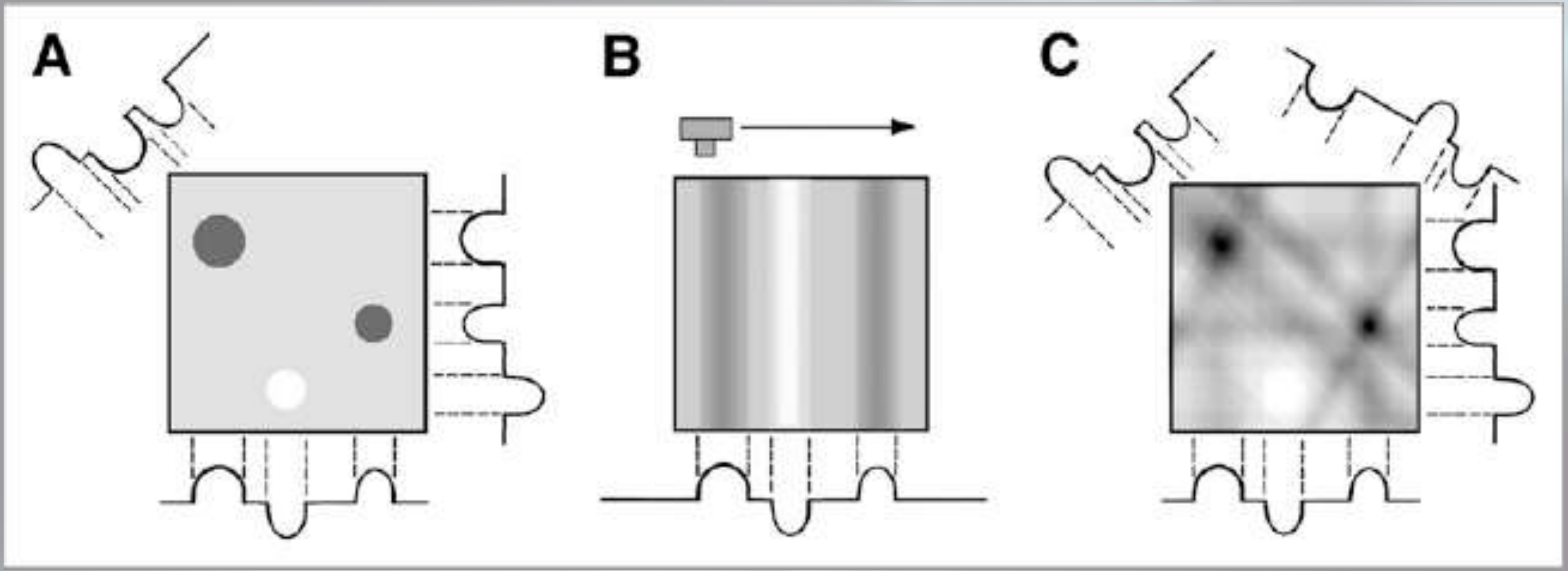


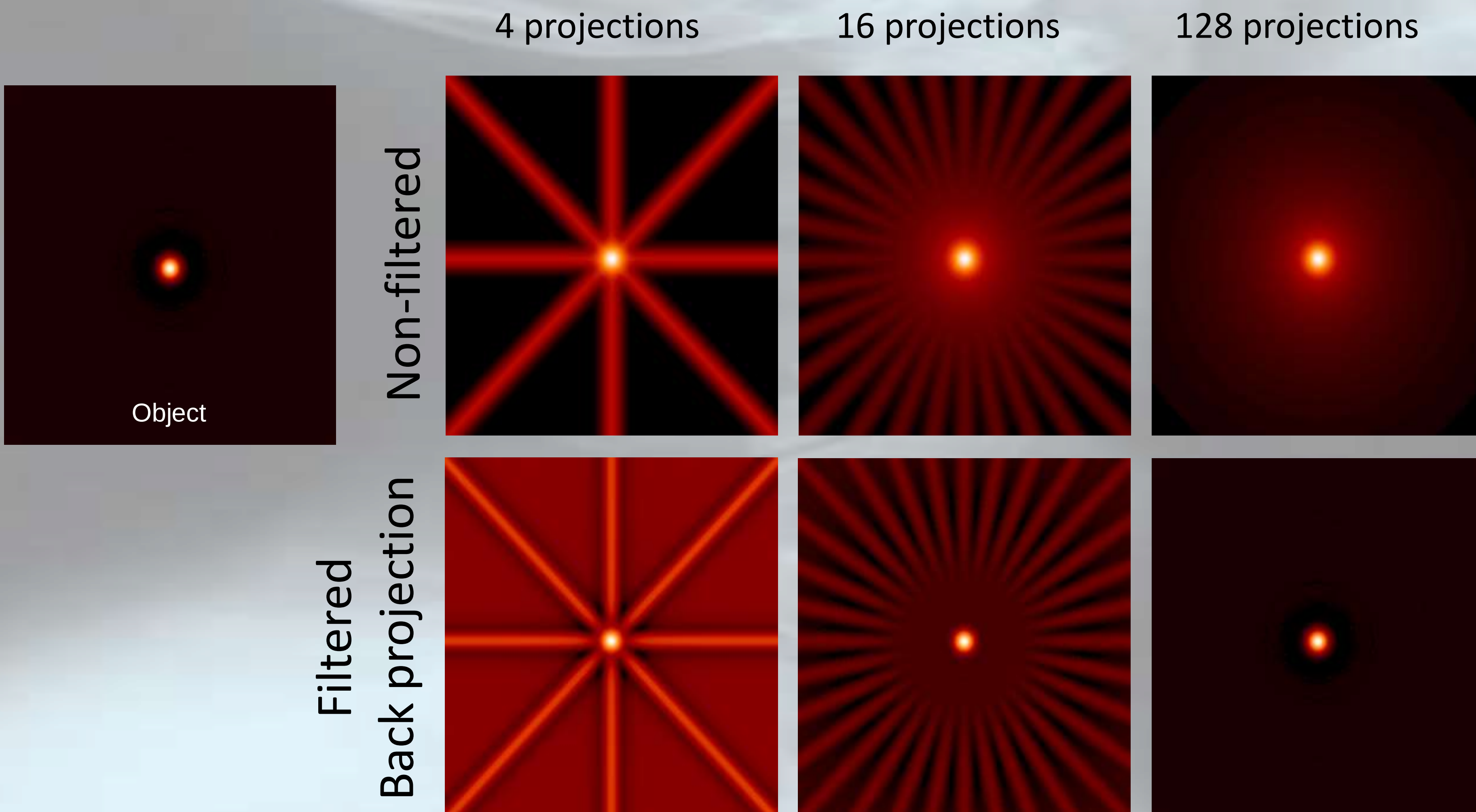
**Figure 39** Image of the object shown in Fig. 38 can be reconstructed by backprojection.

# Back Projection (contd)




This principle of back projection to reconstruct the original image is called **RADON TRANSFORM**

# Affect of Filtering and Number of Projections on Image Quality



# CT Machines

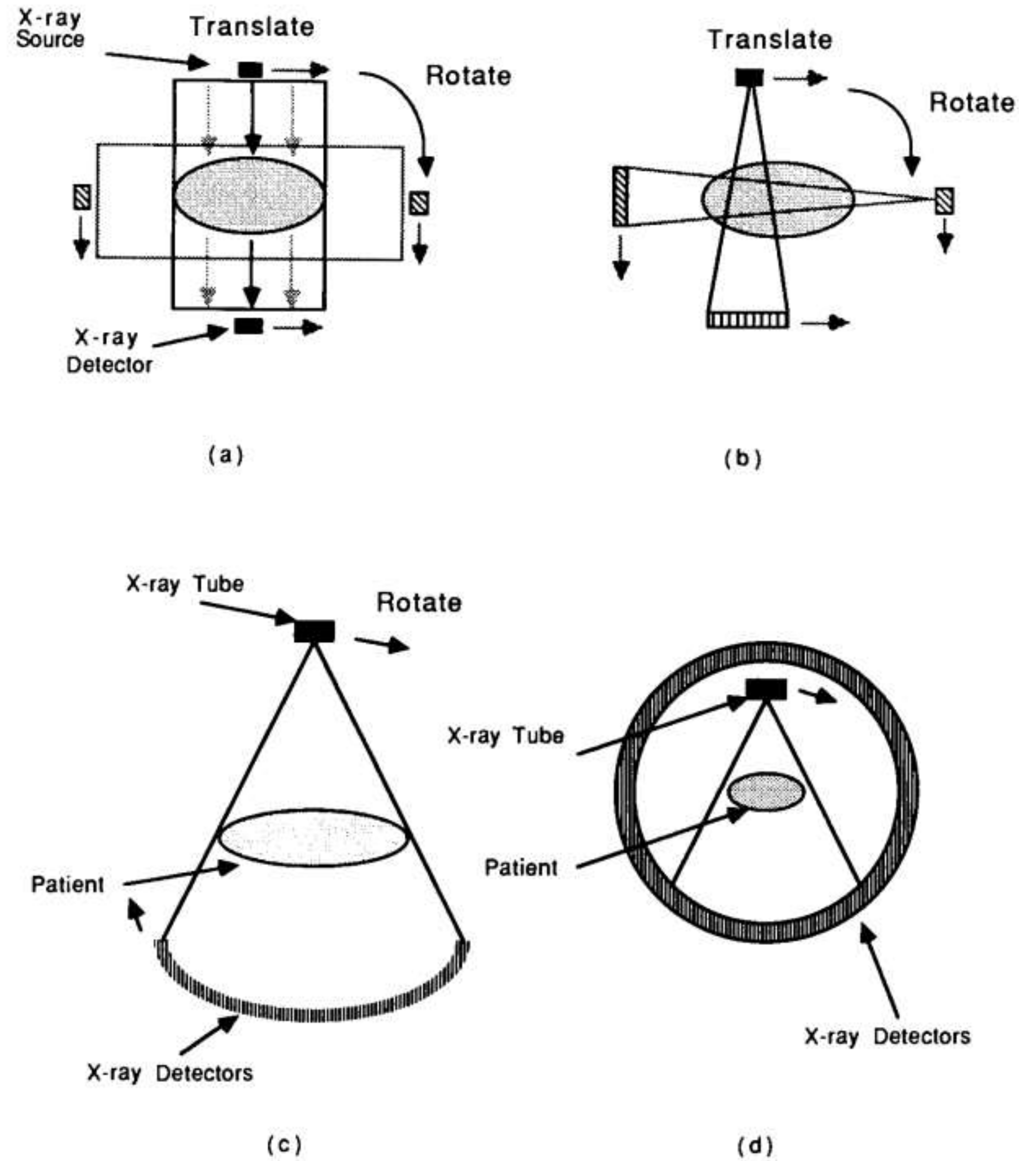


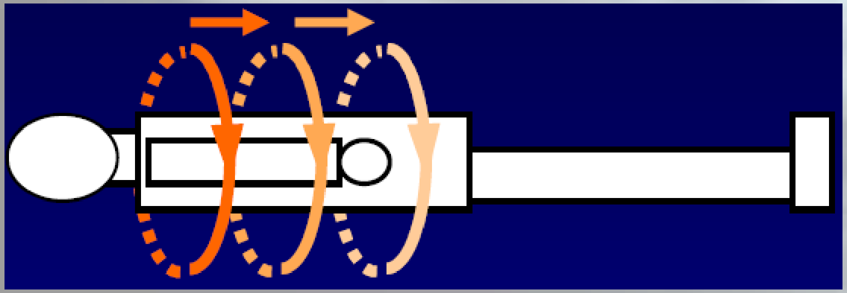

**Figure 42** CT machines: (a) first generation, (b) second generation, (c) third generation, and (d) fourth generation.

# Computer Tomography

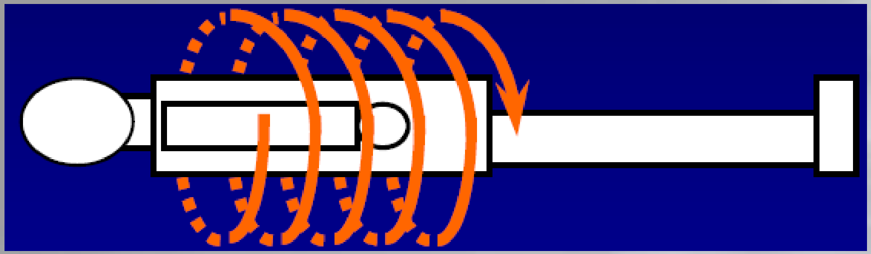
- The word "*tomography*" is derived from the Greek *tomos* (slice) and *graphein* (to write)

| Generation | configuration | detectors | beam | min scan time |
|---|---|---|---|---|
| • First | translate-rotate | 1~2 | pencil thin | 2.5 min |
| • Second | translate-rotate | 3~52 | narrow fan | 10 sec |
| • Third | Rotate-rotate | 256~1000 | wide fan | 0.5 sec |
| • Fourth | Rotate-fixed | 600~4800 | wide fan | 1 sec |
| • Fifth | electron beam | 1284 detectors | wide fan | 33 ms |

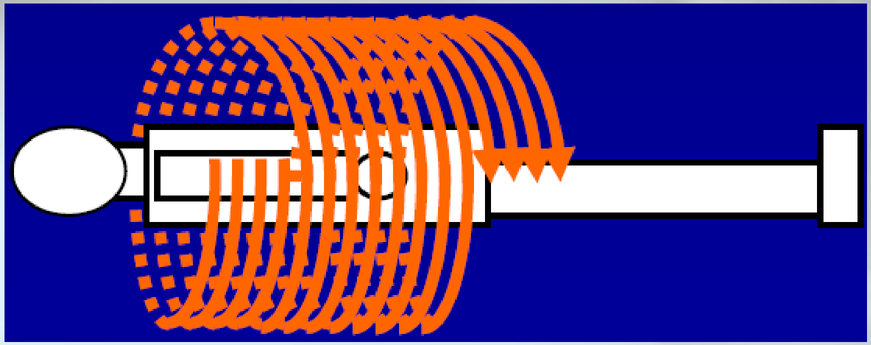
# Evolution in CT



Conventional (Sequential) CT:
Axial Slices



Helical / Spiral CT:
Volume Scanning: Reconstruction of axial slices



Multislice or
Multidetector spiral CT:
Larger volume in less scan-time

# CT Protocolling

- What happens when an exam is requested?
  - A requisiton is completed.
  - The requested exam is protocolled according to history, physical exam and previous exams.
  - The patient information is confirmed.
  - The exam is then performed.
  - Images are ready to be interpreted in …
    - Uncomplicated exam – 5-10 minutes after completion
    - Complicated exams with reconstructions take at least 1 hour but usually 1-2 hours.

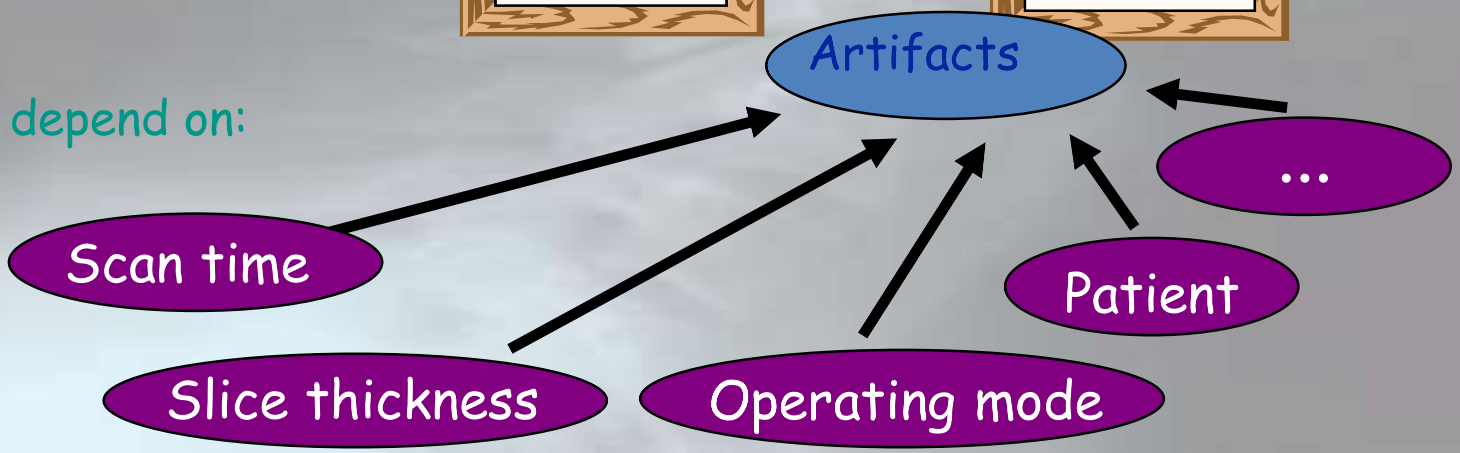
# CT Protocolling

- Plain or contrast enhanced
- Slice positioning
- Slice thickness (image details vs noise)
- Slice orientation
- Slice spacing and overlap (image sharpness, details vs noise)
- Timing of imaging and contrast administration
- Reconstruction algorhithm (resolution vs noise)
- Radiation dosimetry
- mAS (determines strength of x-ray beam)
- kV – determines hardness of x-ray
- Convolution filter (depending on patient body size and organ to be imaged)
- Patient Information
- Is the patient pregnant?
- Radiation safety
- Can the patient cooperate for the exam?

# Artifacts...

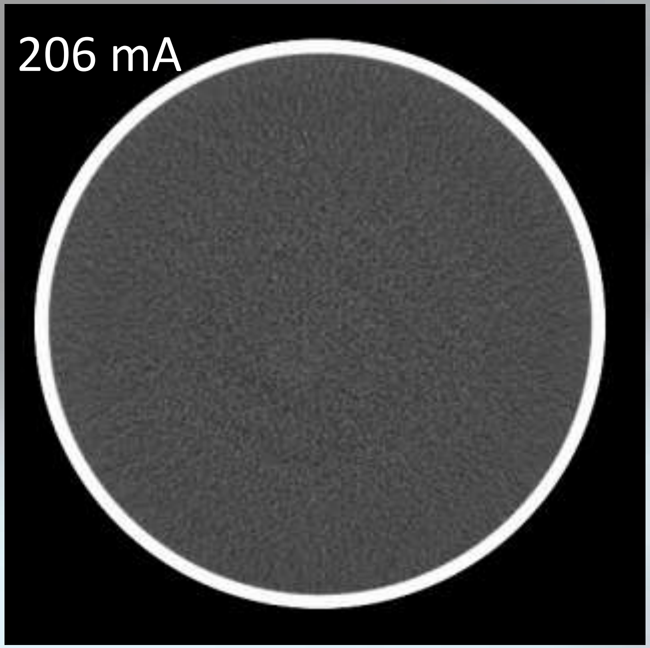
The various structures or patterns that appear in a CT image, but are not found in the original object.

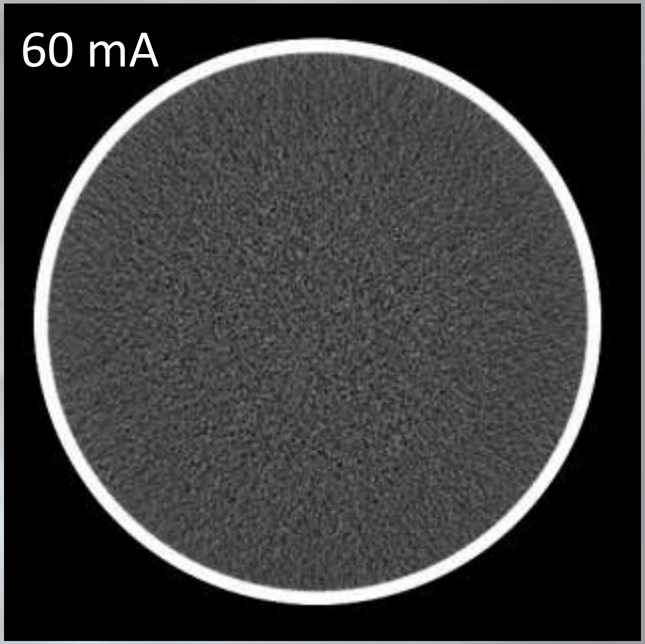
They depend on:



# Noise?

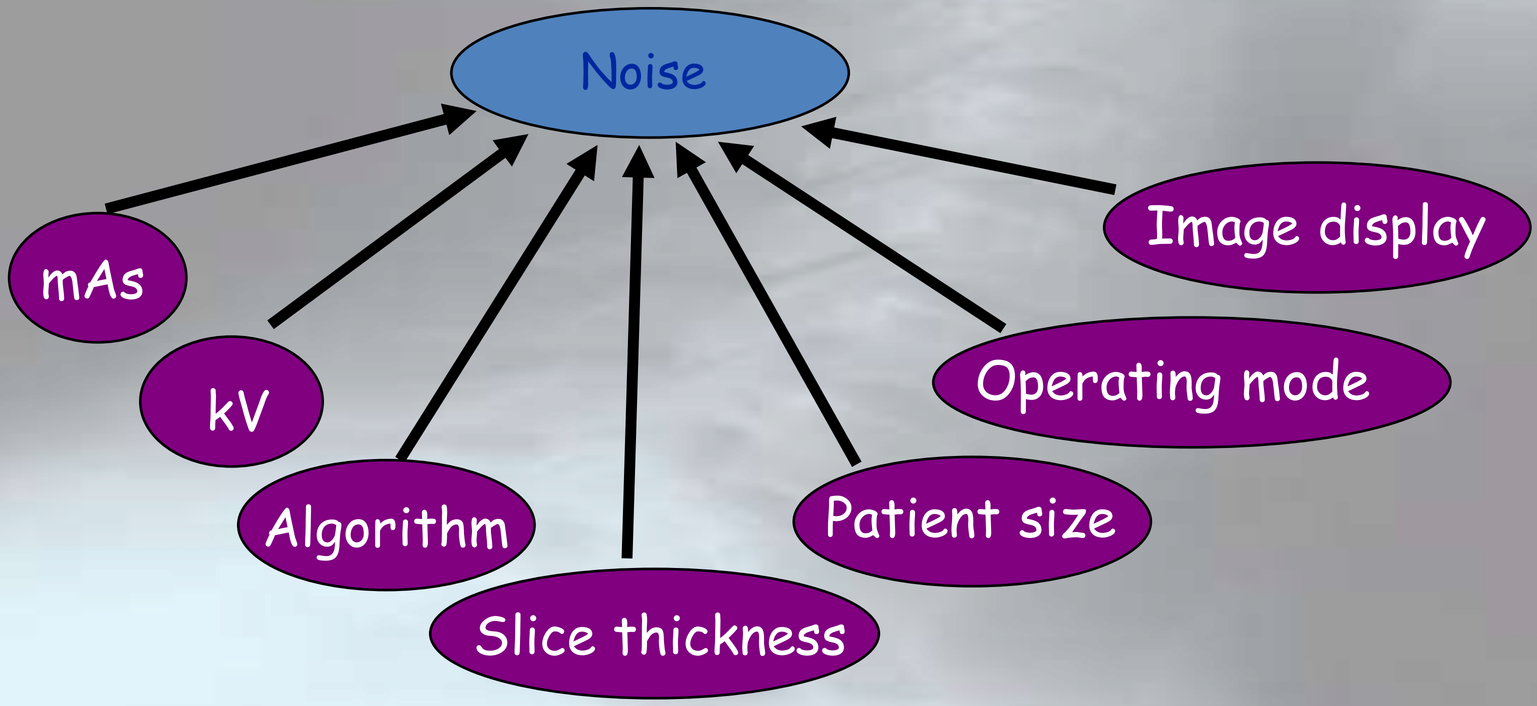
Noise is superimposed on the image and results in a "grainy" impression, as is the case with poor TV reception.



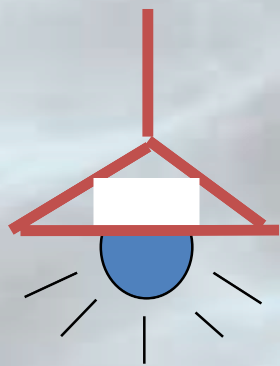



# Noise…

Image “noise” is determined by the number of x-ray quanta that reach the detector and then contribute to the image. It depends on:

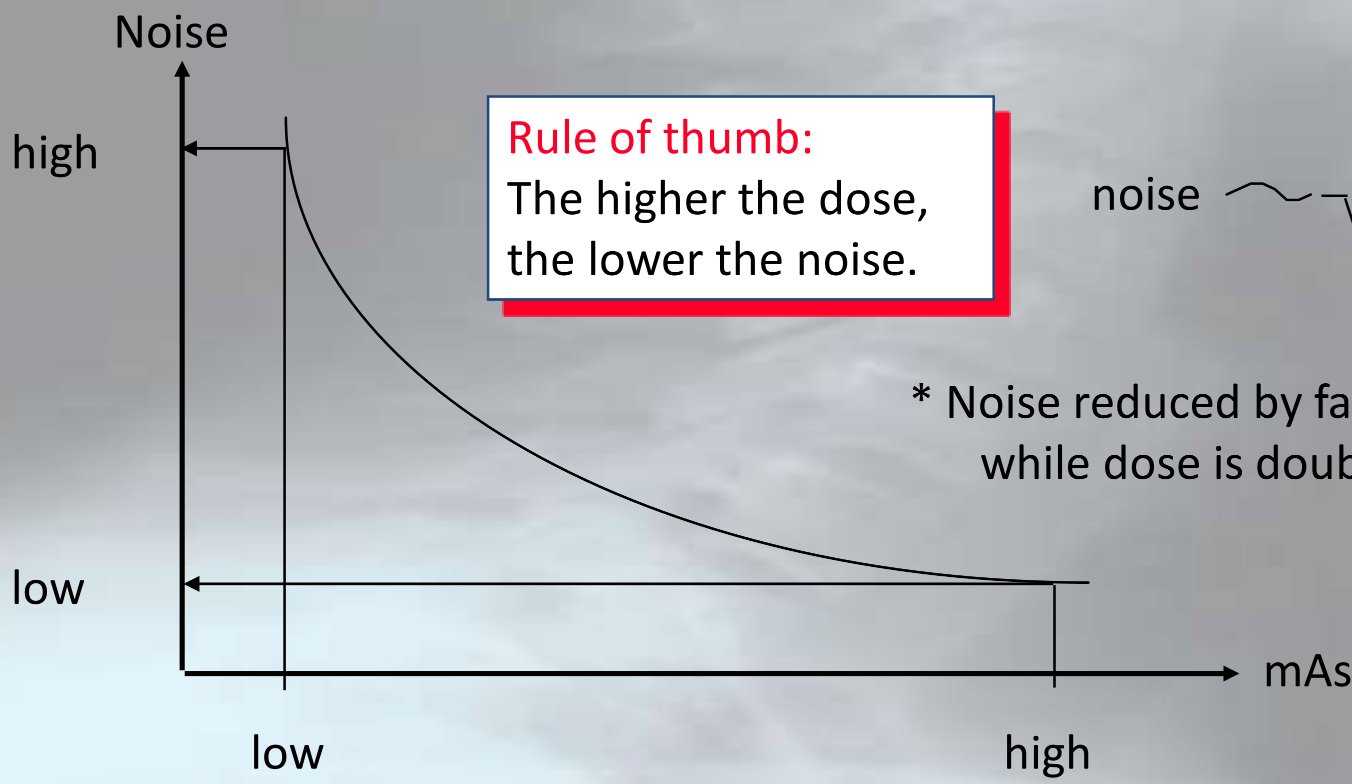


# mAs…



Tube current-time product (milliampere-second, or **mAs**) is the product of the x-ray tube current (in milliamperes) and the **CT scanner** exposure time per rotation (in seconds)

Tube current and scan time, determine dose.




Rule of thumb:
The higher the dose, the lower the noise.

$$\text{noise} \sim \sqrt{\frac{1}{\text{dose}}}$$

* Noise reduced by factor 1.4 while dose is doubled.

# mAs…

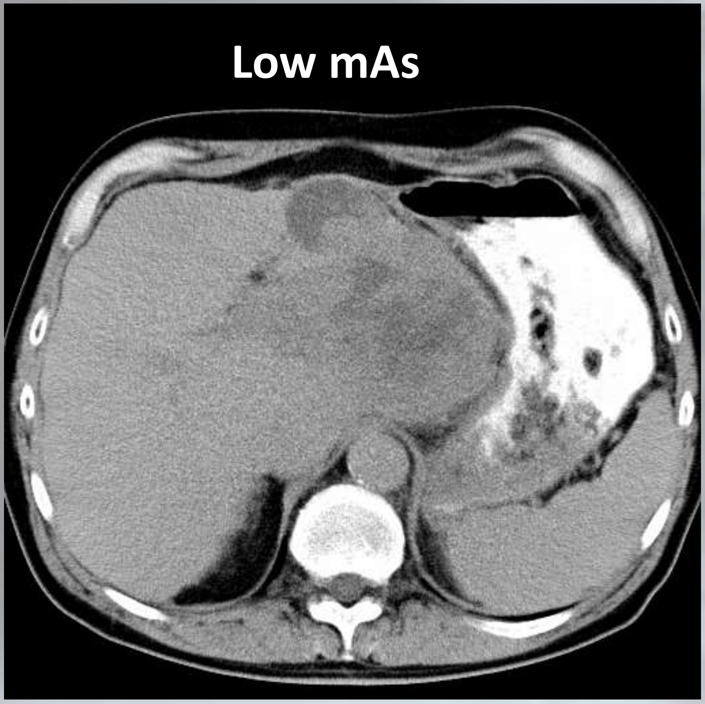



Image 1:
Low mAs value -
high noise level

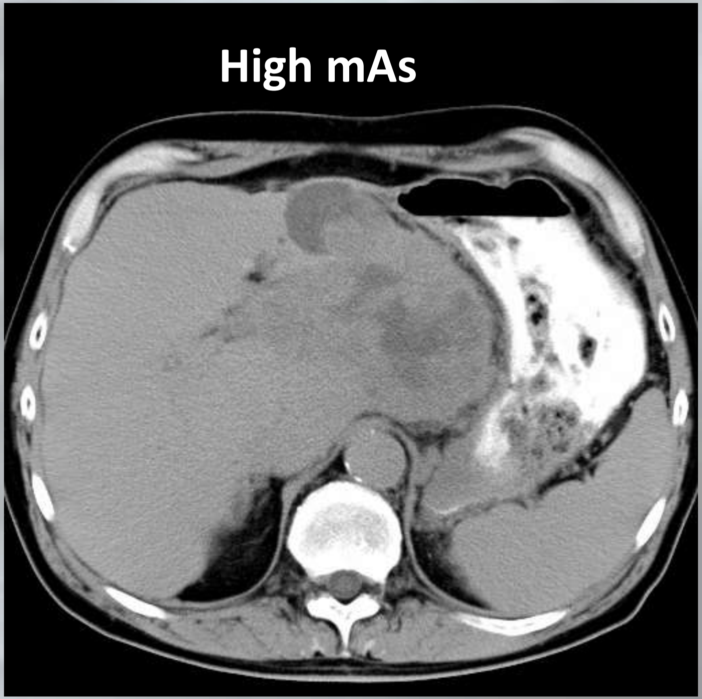
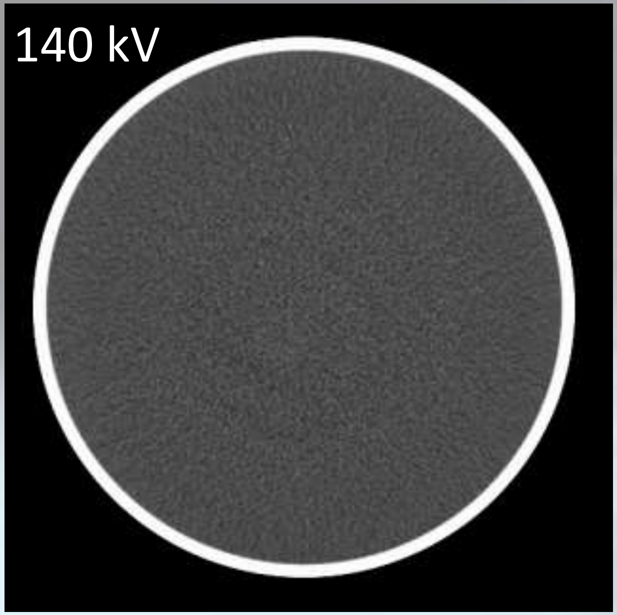
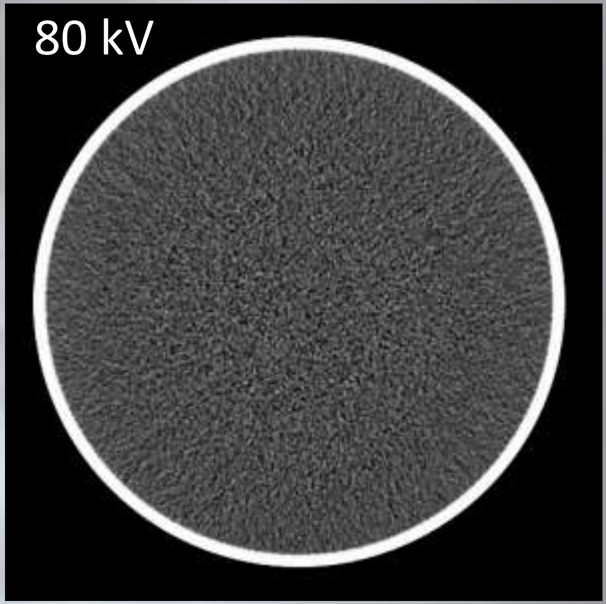



Image 2:
4 times the mAs value-
half the noise level

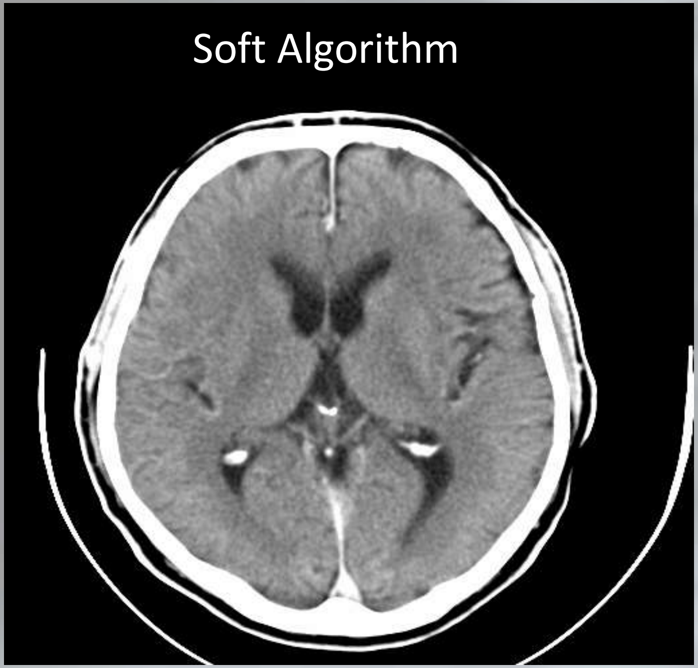
# Tube Voltage - kV

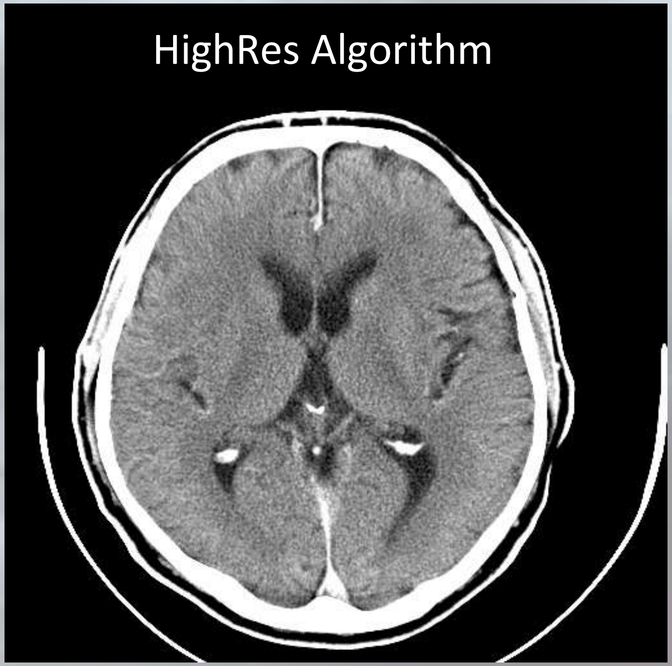
The higher the voltage, the more the radiation spectrum is shifted to a **higher energy level**, resulting in decreased radiation attenuation. This is most noticeable in bone and contrast media.



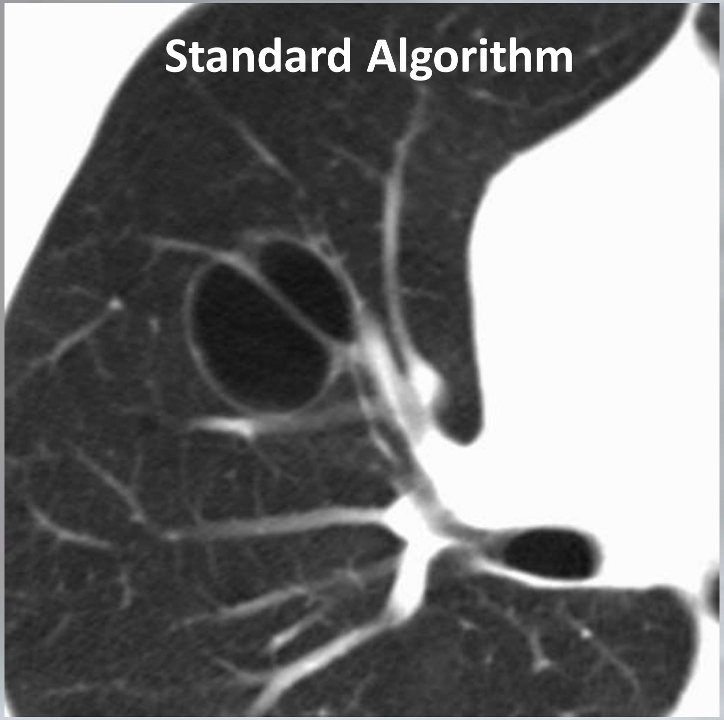
# Algorithms

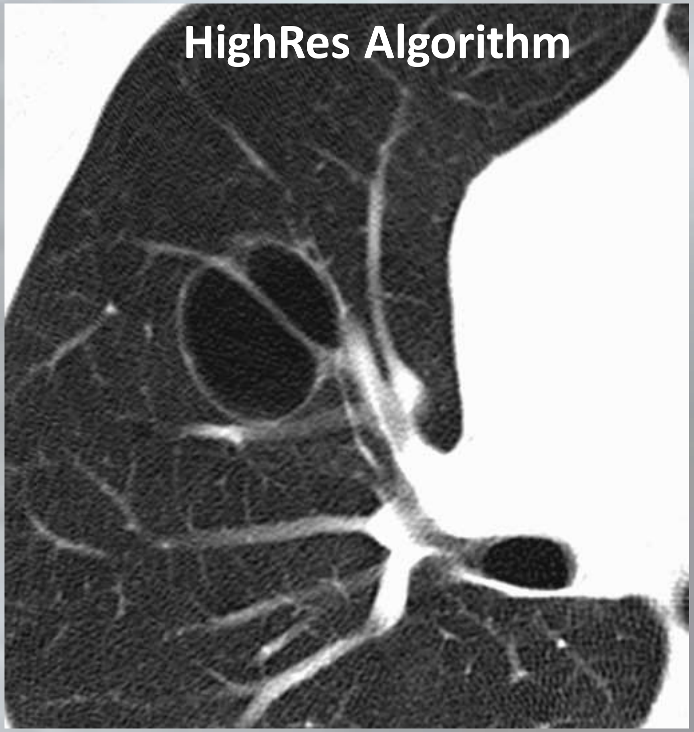



Soft algorithms provide better contrast detectability with less noise.

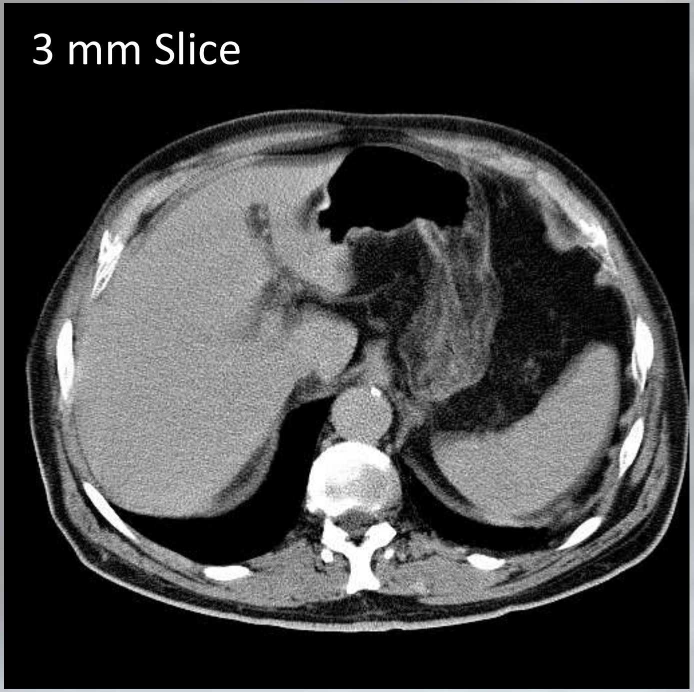
# Algorithms

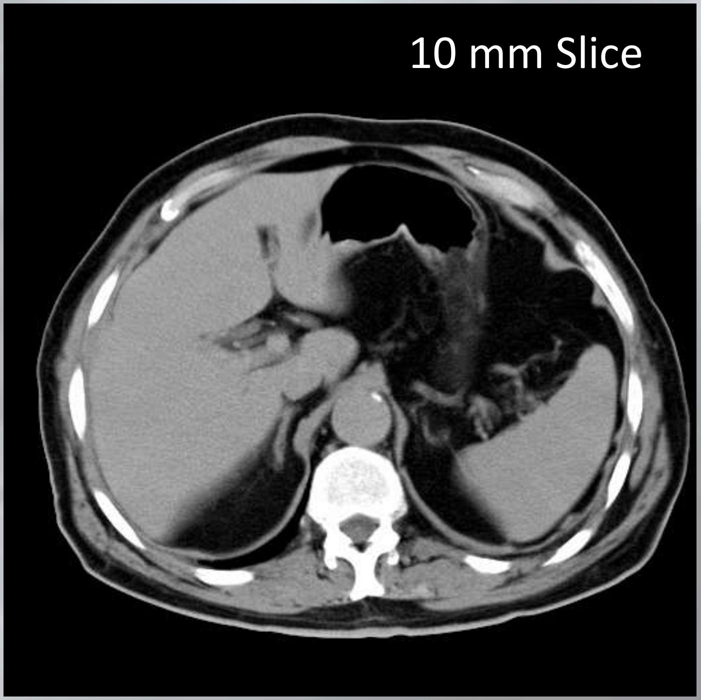



HighRes algorithms provide better spatial resolution, but with more noise.

# Slice Thickness…



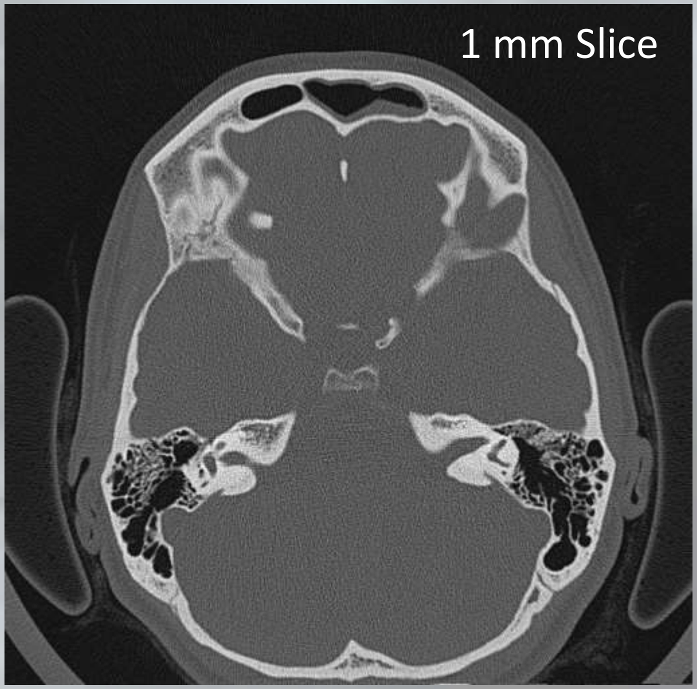




Thicker slices give less noise & better contrast detectability for soft tissue

high noise
poorer contrast resolution
better edge definition
no partial volume artifacts

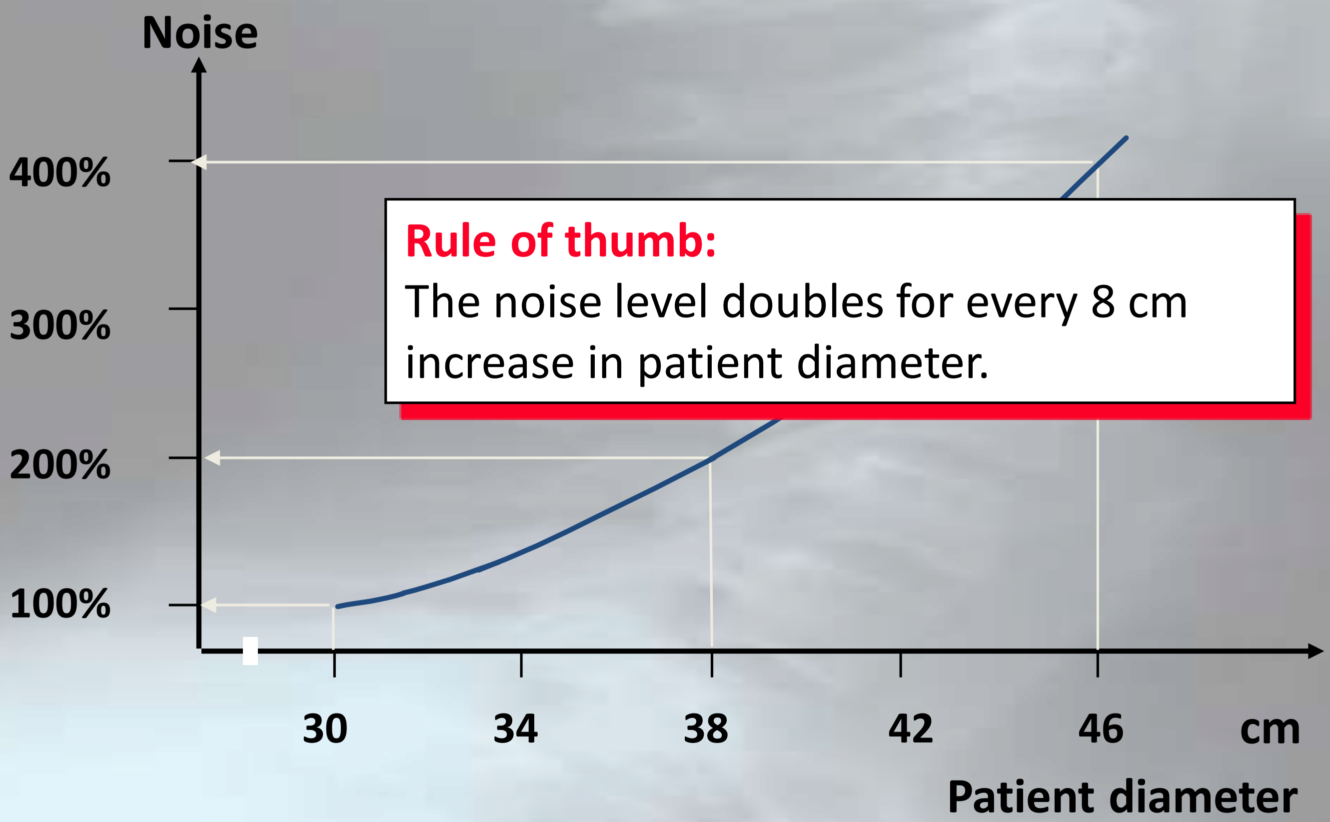
low noise
better contrast resolution
poorer edge definition
partial volume artifacts

# Slice Thickness

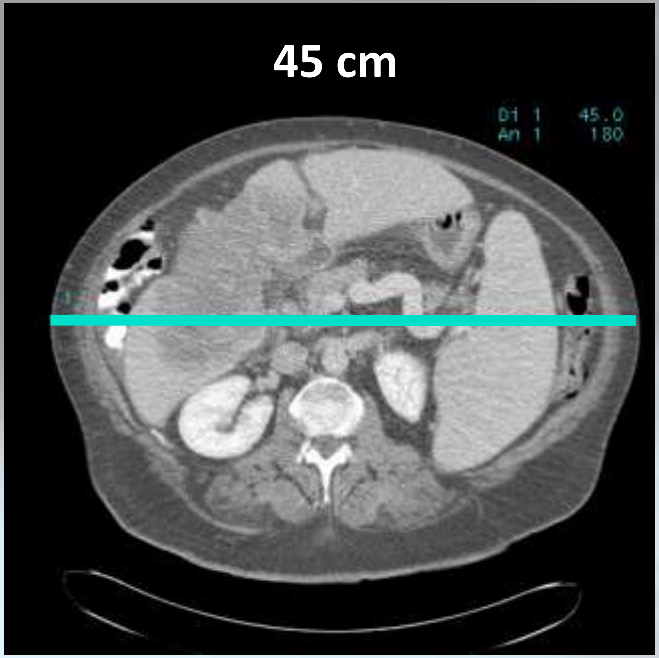

Thinner slices give better spatial resolution for bony structures.

# Patient Size…



# Patient Size…

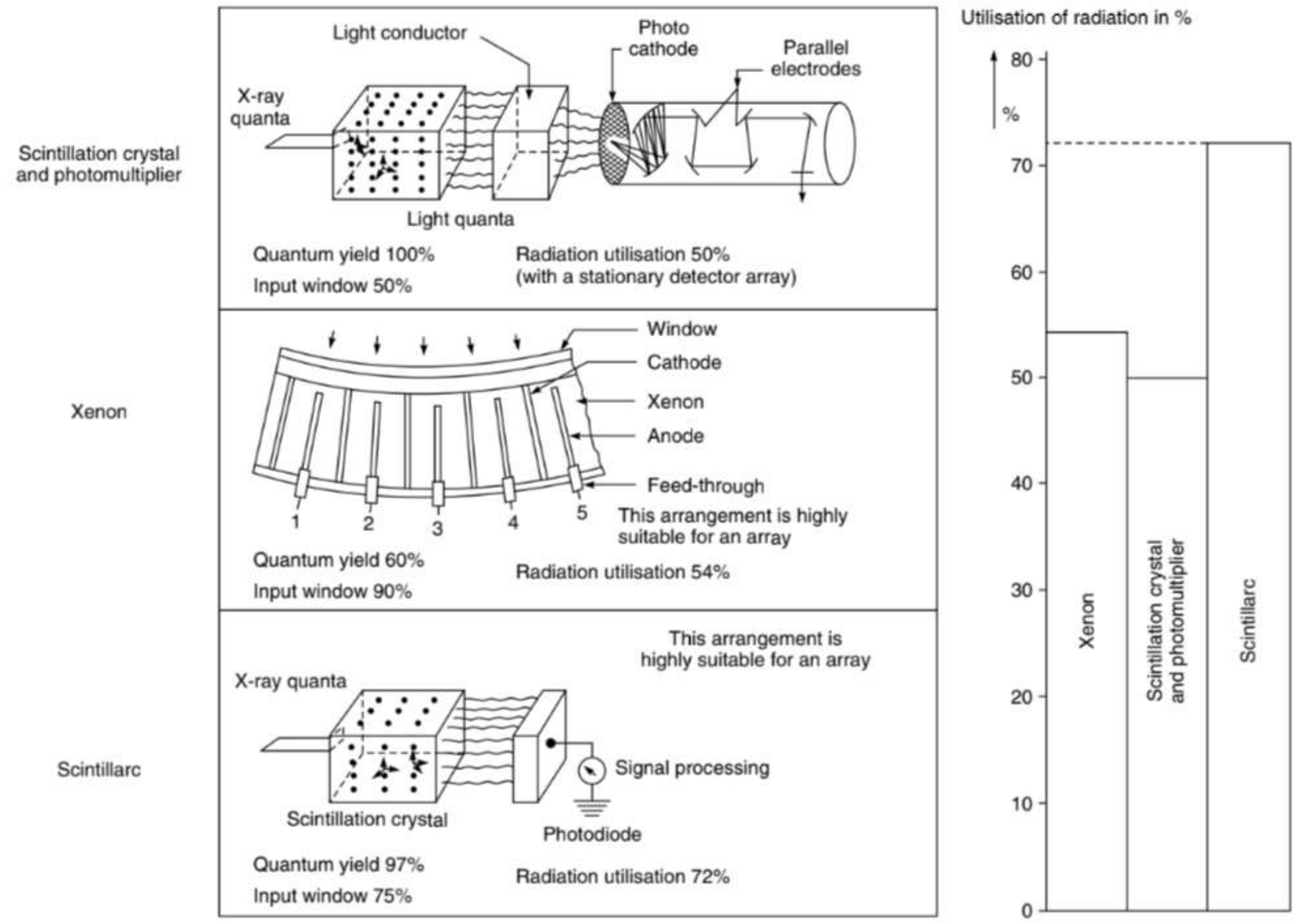
An attenuation by a factor of 2 results from each 4 cm increase in patient thickness, thus increasing the pixel noise.




# Patient Dose in CT scanners

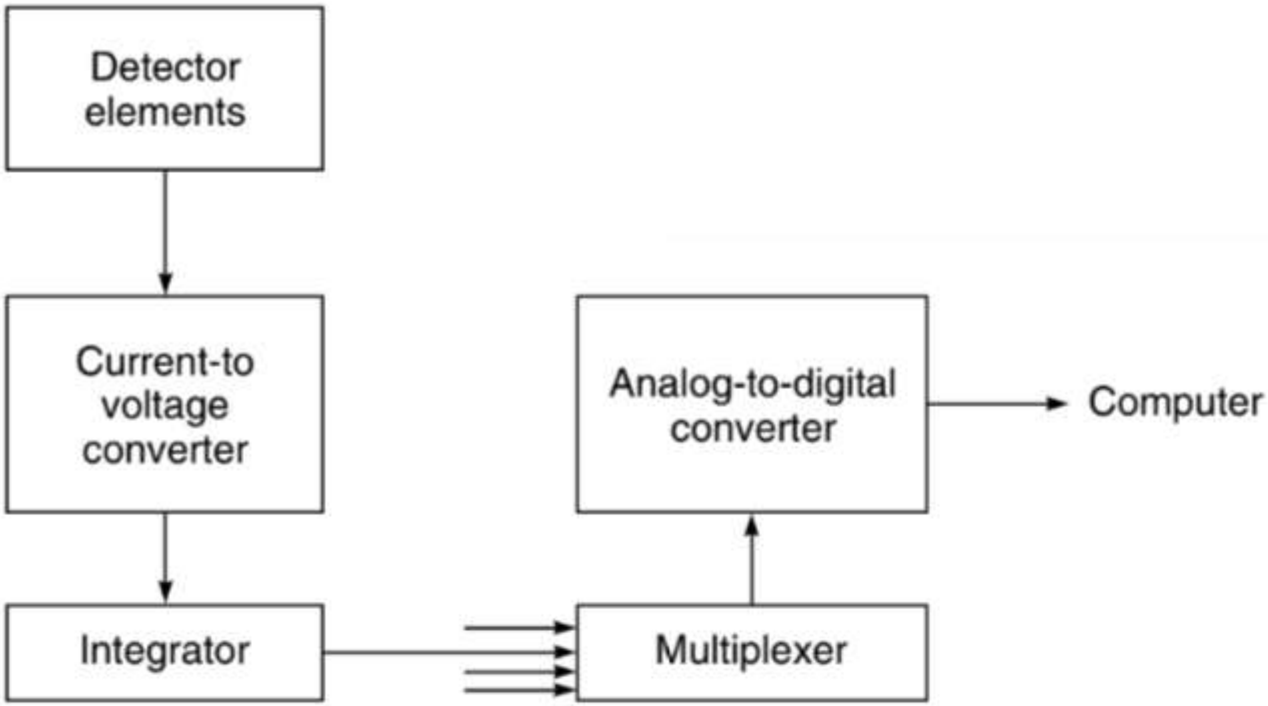
- It is desirable to obtain a diagnostic CT scan while administering a minimal dose to the patient.
- The radiation impinges upon the patient at a relatively high intensity in the small region of the slice width.
- Regions proximal to the slice are exposed to scattered radiation. In a CT system, with all of the Y factors (pixel size, algorithm, patient size and kV) held constant, the noise increases inversely as the square root of the dose.
- Similarly, as the algorithm and detector aperture are changed to improve the resolution, the noise of the system will go up.
- The dose must be increased to preserve the same noise level. In practice, it is a trade-off between resolution, noise and dose.
- In CT Systems, with 360° X-ray tube movement, the skin dose around the patient is largely constant.
- The various CT radiographic factors are arranged in such a way that dose units of 0.25, 0.50, 1 and 2 D result. D stands for the maximum skin dose 1.3 ± 0.1 rad (J/kg) of the single slice.
- For the various radiographic voltages, dose units have been defined. These dose units are derived from the generator output, number of pulses and the length of each pulse.
- Typical head and body doses for average patients scanned on the CT systems have been about 2.5 rads for heads and 1.0–2.0 rads for bodies. In multiple-slice operations, the overall dose profile is the sum of the individual skin dose profiles.

# Types of Detectors




➤ **Fig. 20.9** *Three types of detectors used in computer tomography (Courtesy: M/s Siemens, W. Germany)*

Data acquisition system



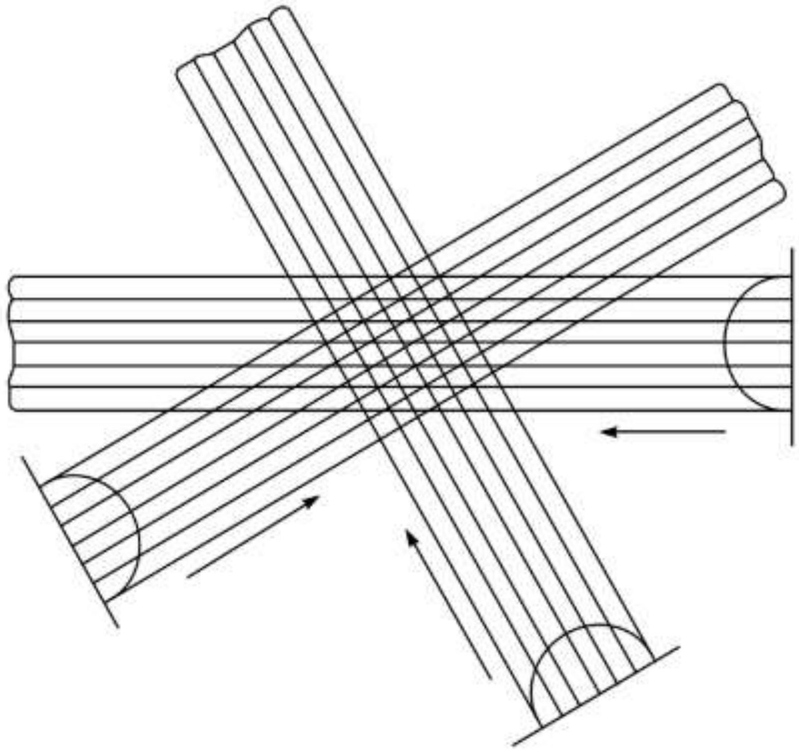

➤ **Fig. 20.10** *Data acquisition system in a CT scanner*

# Reconstruction can be done using the following techniques

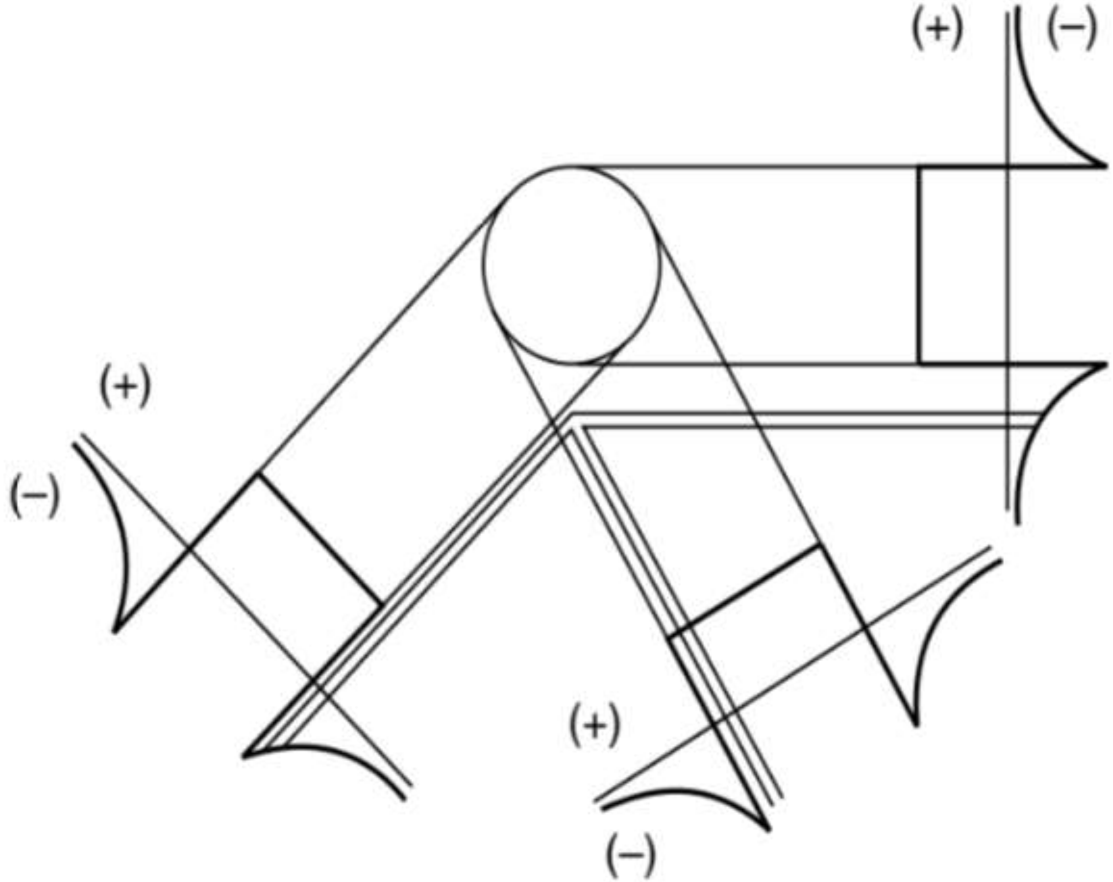
1. Back projection, which is analogous to a graphic reconstruction
2. Iterative methods, which implement some form of algebraic solution

3. Analytical methods, where an exact formula is used. Two of these are filtered-back projection, which incorporates the convolution of the data and Fourier filtering of the image, and the two-dimensional Fourier reconstruction technique.

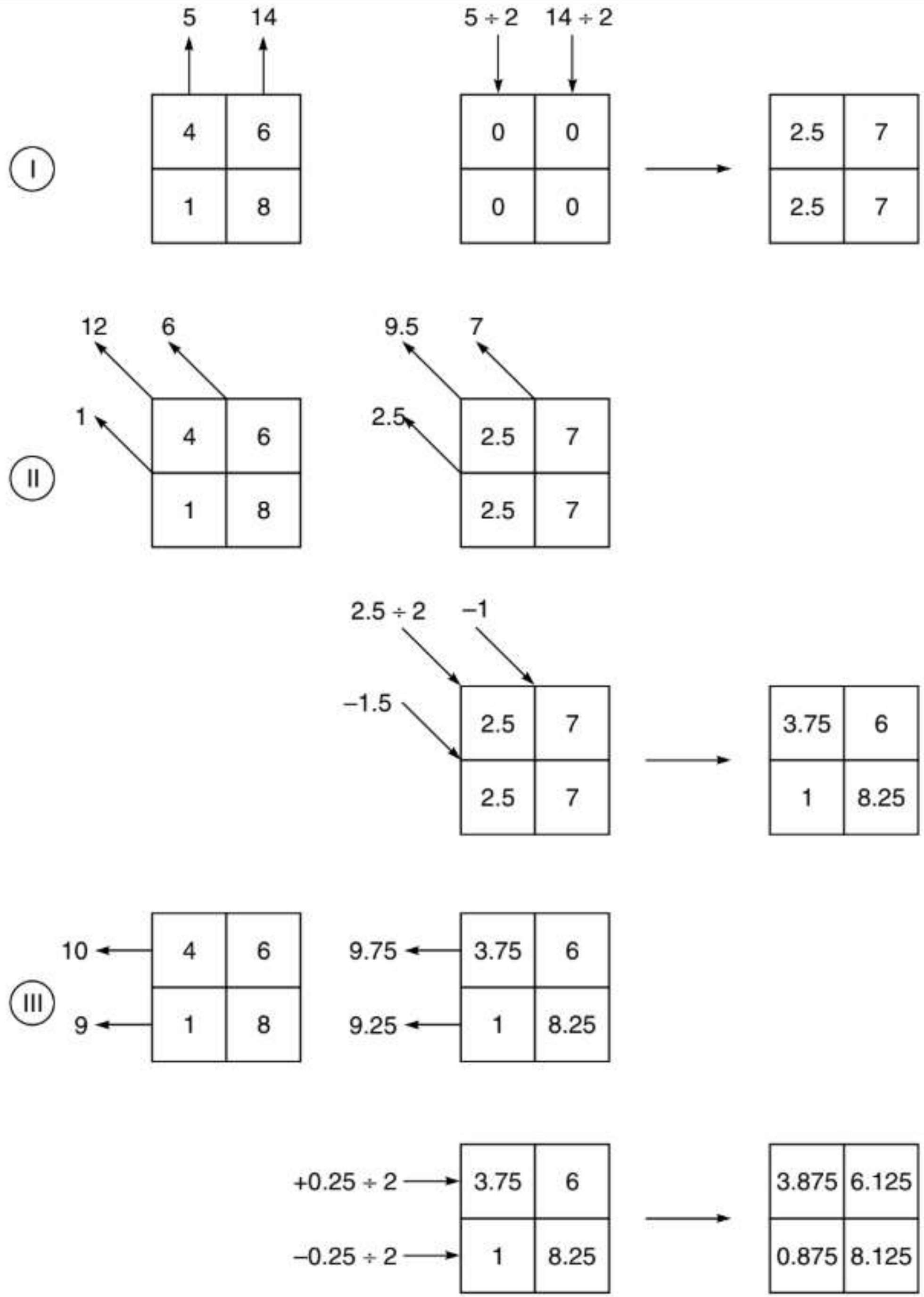
# Back projection method



*By adding the back projections produced by the shadow functions, the back-projected rays are added to the reconstructed image as artefacts or unwanted points. The original circular structure is transformed into a star shaped display*




***Filtered back projection technique of eliminating the unwanted cusp like tails of the projection. The projection data are convolved (filtered) with a suitable processing function before back projection. The filter function has negative side lobes surrounding a positive core, so that in summing the filtered back projections, positive and negative contribution cancel outside the central core, and the reconstructed image resembles the original object***



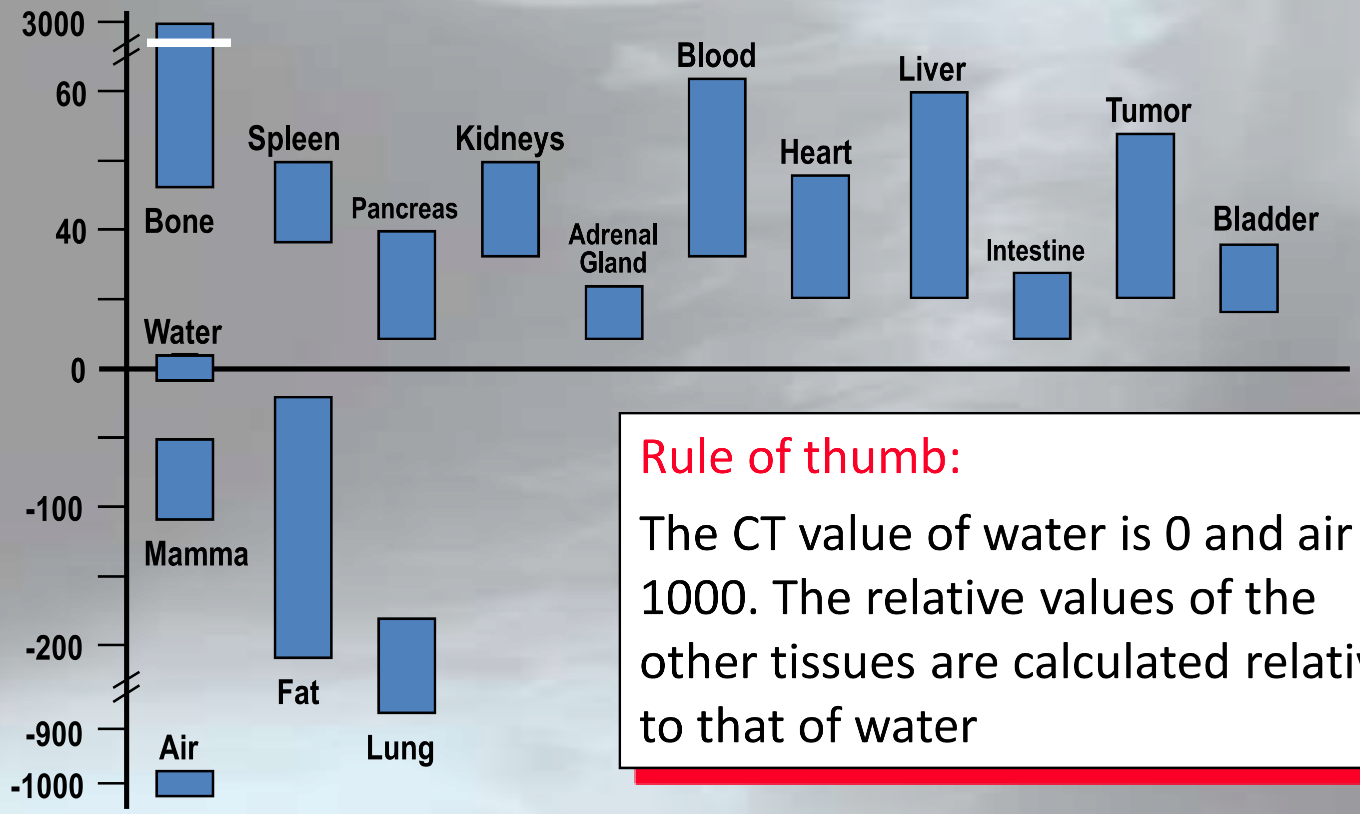

➤ **Fig. 20.11** *Principle of iterative reconstruction method*

# Successive approximation method

For scan I, Vertical sums 5 and 14 are obtained.
For scan II, diagonal sums are 1,12 and 6
For scan III, horizontal sums of 10 and 9 are obtained

This scan data will be used to calculate image matrix

# Image Display - Windowing




Rule of thumb:

The CT value of water is 0 and air -1000. The relative values of the other tissues are calculated relative to that of water

This is the so-called CT number in Hounsfield unit (HU)

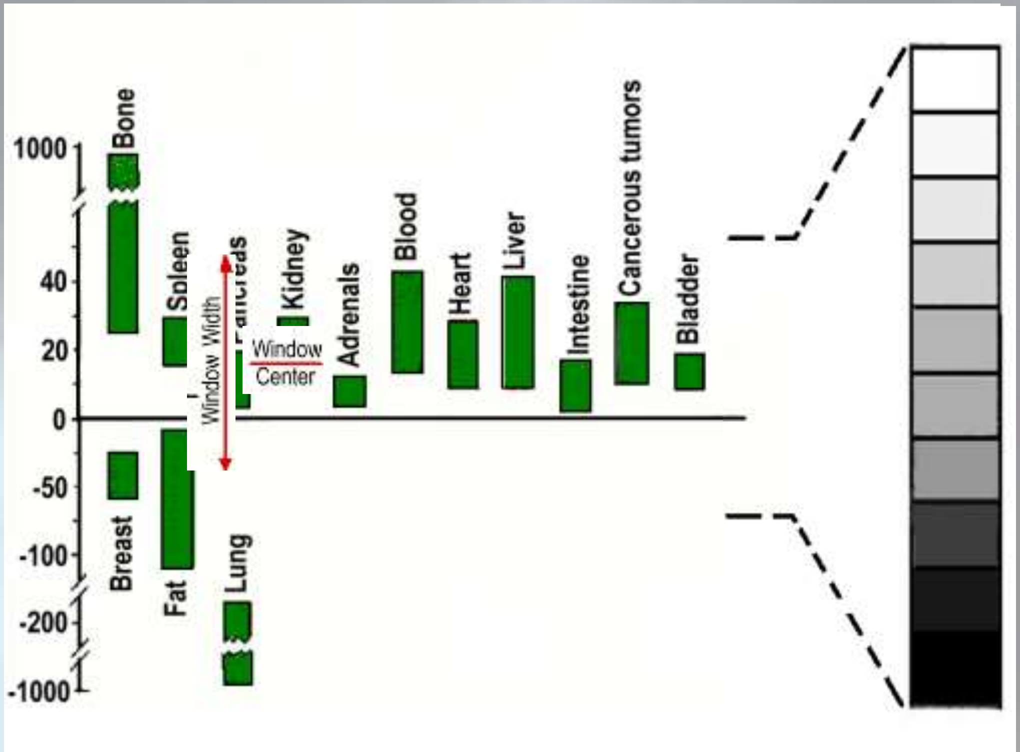
# Computed Tomography

## - *Hounsfield Units or CT numbers*

- CT numbers (or *Hounsfield units*) represent the percent difference between the x-ray attenuation coefficient for a voxel and that of water multiplied by 1000.

- Water has a CT number of zero and the numbers can be positive or negative depending on the absorption coefficient.

- This is how we assign a shade of gray, and 1000 is just a scaling factor set by the CT manufacturer.



# Computed Tomography

## - *Image Quality*

•*Contrast Resolution* – The ability to differentiate between different tissue densities in the image

• *High Contrast* - Ability to see small objects and details that have high density difference compared with background.

- These have very high density differences from one another.

- Ability to see a small, dense lesion in lung tissue and to see objects where bone and soft tissue are adjacent

• *Low Contrast* - Ability to visualize objects that have very little difference in density from one another.

- Better when there is very low noise and for visualizing soft-tissue lesions within the liver.

- Low contrast scans can differentiate gray matter from white matter in the brain.

# Computed Tomography

## - *Imaging artifacts*

- Artifacts can degrade image quality and affect the perceptibility of detail.
- Includes
  - Streaks – due to patient motion, metal, noise, mechanical failure.
  - Rings and bands – due to bad detector channels.
  - Shading - can occur due to incomplete projections.

Streaks

Rings and bands

Shading

# Computed Tomography

## - *Advantages & Disadvantages*

*Advantages:*

- Desired image detail is obtained
- Fast image rendering
- Filters may sharpen or smooth reconstructed images
- Raw data may be reconstructed post-acquisition with a variety of filters

*Disadvantages*

- Multiple reconstructions may be required if significant detail is required from areas of the study that contain bone and soft tissue
- Need for quality detectors and computer software
- X-ray exposure

# Recent developments
# Digital radiography

- The advent of digital computers and integrated circuits has made image processing and acquisition in digital format at a reasonable cost and within a short period of time a reality
- The major advantage of computed radiography is that the image information is available in digital format that allows easy implementation of image processing algorithms on the image such as spatial filtering, signal compression, and fast image storage and transmission.
- It has been described as one of the missing links in the full implementation of picture archiving and communication systems (PACS) needed for the total digitization

# Digital subtraction angiography (DSA)

- The conventional film subtraction technique has been found useful in eliminating the background noise and enhancing the image of the object of interest.
- An important example is temporal subtraction angiography in which the image before the injection of a contrast medium is subtracted from the image obtained shortly following the injection.

# Digital subtraction angiography

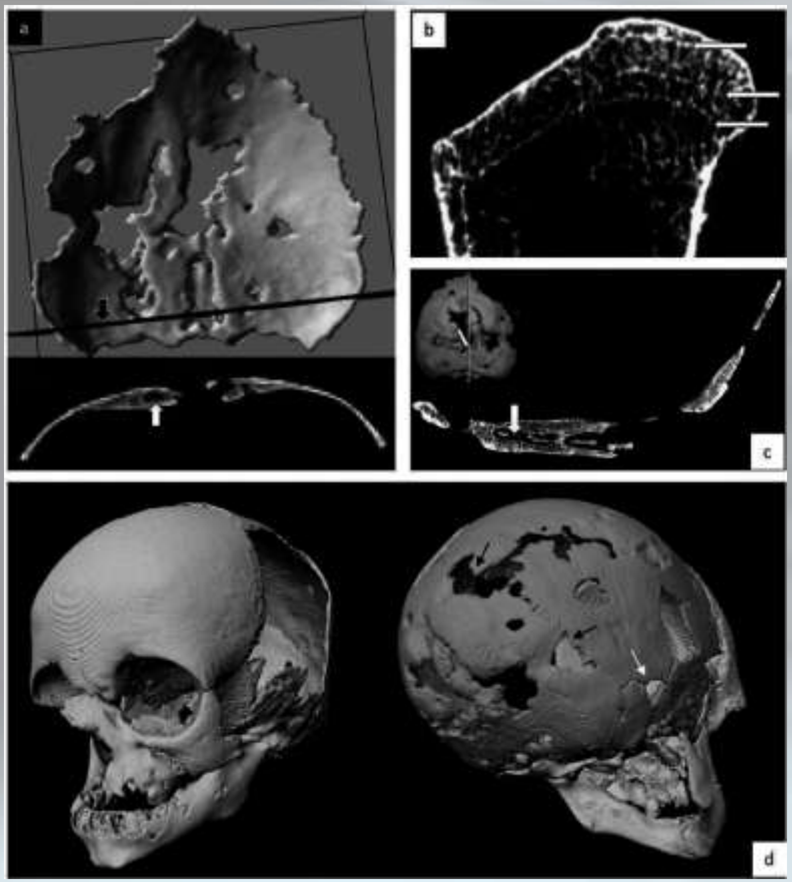
DSA still possesses a number of advantages over film subtraction angiography (High, 1988):

- DSA allows further image processing;
- Because of better sensitivity, smaller concentrations of contrast medium may be used, with a reduction in the probability of patient allergic reaction, the injection can be performed with a smaller catheter, lessening the risk associated with puncturing an artery, and DAS may be performed as an outpatient procedure;
- The problem caused by patient motion is reduced since there is less discomfort associated with the injection of smaller amount of the contrast agent;
- It is less costly in the long run due to saving in material costs (mainly film); and
- There is improvement in speed and efficiency.

# 3D Reconstruction

- If multiple slices of cross-sectional CT images are obtained and stored in computer memory in an organized format (attenuation coefficient at a certain voxel and the coordinates of the voxel), it seems intuitive that the image of a slice along any plane (e.g., coronal or saggital plane) or the image of the object in 3-D can be reconstructed (Udupa, 1983; Herman, 1988).
- There are now a number of companies that specialize in 3-D imaging software. This software can be categorized into two different approaches: surface and volume rendering. The 3-D image of a human skull reconstructed from multiple CT slices.

# 3D reconstructions of the skull




- (a) 3D reconstruction of the occipital bone, and location of a diploic osteolytic lesion not visible on the cranial tables (black arrow) but observable on the CT scan corresponding slice (white arrow);
- (b) longitudinal slice of a m CT scan of the right humeral proximal metaphysic showing linear organization of the trabecular microstructure parallel to the physis (white arrows show the linear organization);
- (c) transversal slice of a m CT scan of the occipital bone, white arrows indicate the sequestrum location (on the bone, and in the slice);
- (d) left anterolateral view and right posterolateral view of the 3D virtual reconstruction of S37 skull showing pathological damages on the skull vault (black arrows show suture overlapping, white arrow indicates a punched out lytic lesion revealed thanks to virtual reconstruction of the skull).

https://www.researchgate.net/profile/Antony-Colombo/publication/272475564/figure/fig4/AS:294674569940998@1447267301041/Medical-imaging-and-3D-reconstructions-of-the-skull-a-3D-reconstruction-of-the.png

# Advantages and disadvantages of 3-D image

- The advantage of a 3-D image is that a global view of the structure is obtained.
- There is no need for the physicians to reconstruct the object from 2-D views in their mind.
- The disadvantages are

  (1) More and thinner slices (1 to 3-mm slices as opposed to 10 mm) have to be taken. This means that patient radiation exposure is increased.

  (2) Smoothing algorithms are used to improve the image but they may also smear out diagnostically important information.

  (3) More operator time and skill is needed.

  (4) Image can be distorted by motion artifact.
- It is because of these problems that the significance of 3-D imaging in medicine is uncertain, although it has been found useful for planning orthopedic and cranial surgery and for planning cancer therapy

# Dynamic Spatial Reconstructor

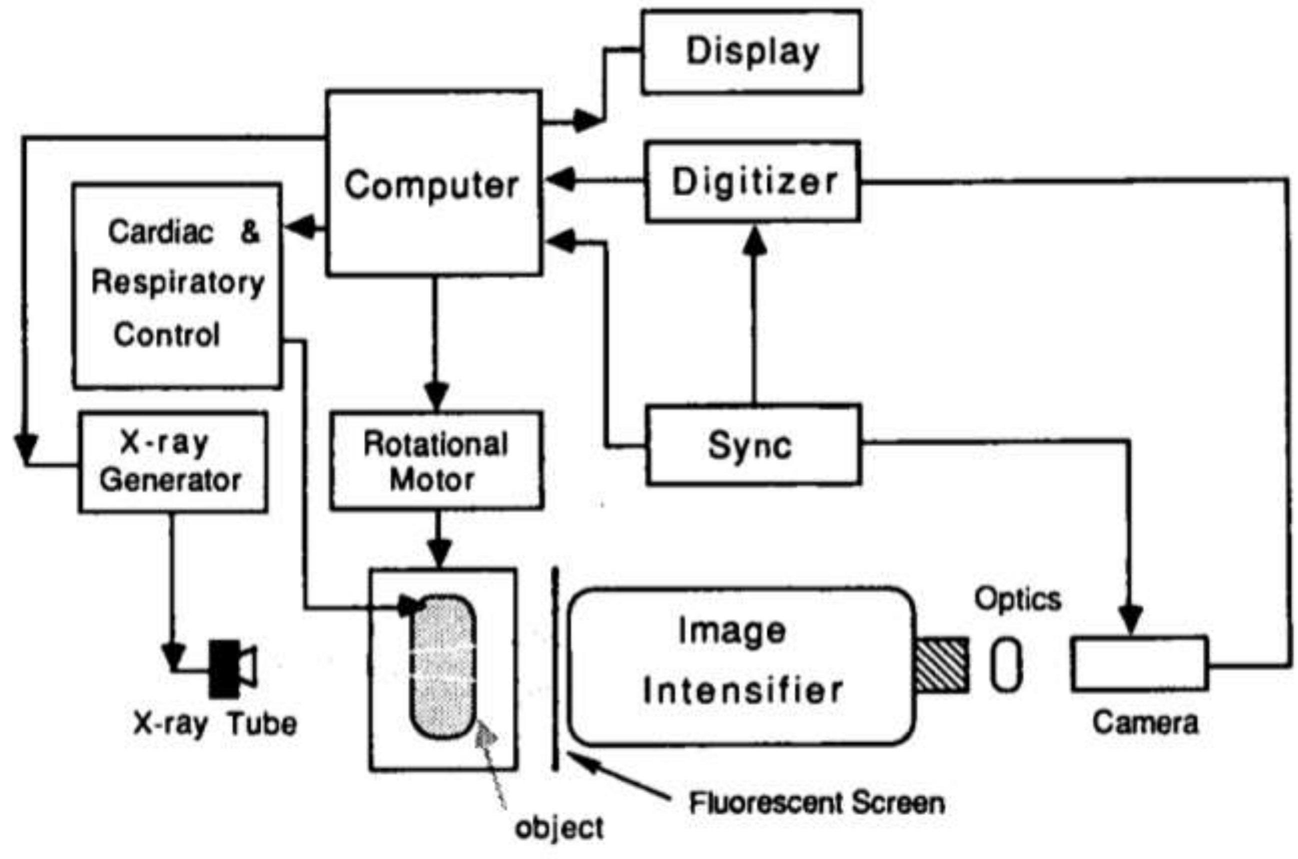



**Figure 53** Block diagram of an early DSR.

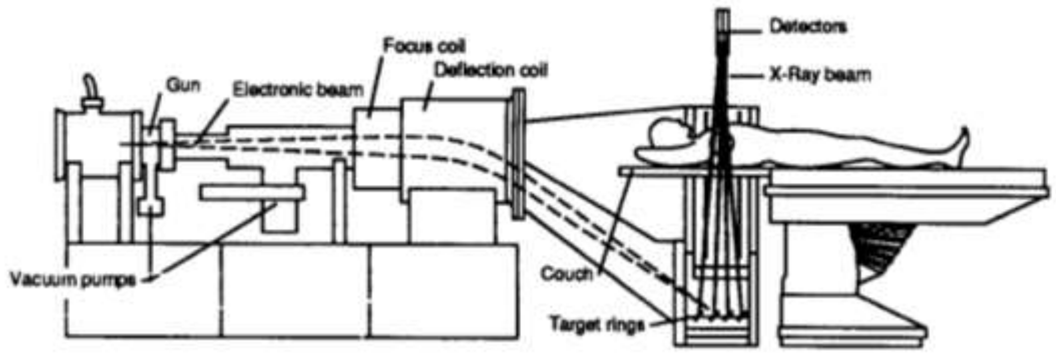
# Dynamic Spatial Reconstructor

- The central part of the system is a digital fluoroscopic system, shown at the bottom of the figure.
- The object to be imaged is positioned in the X-ray field and rotated under computer control.
- The fluoroscopic image at each successive angle of view is scanned by the video camera 60 frames/second.
- The video image is made up of about 100 to 200 horizontal scan lines. Measurements of the transmitted X-ray intensity are achieved by digitizing each scan line with the video digitizer.
- To image a moving object such as the heart, the cardiac, and respiratory cycles, the Xray tube, the rotation motor, and the computer are all under the control of the master oscillator labeled SYNC.
- Since each video image is the projection image of the entire chest, the 60 images accumulated at one angle in one second will include the whole cycle of a heart beat.
- When the object is rotated to another angle, the temporal relationships among the cardiac pacesetting pulse, respiratory motion, and the video scans are exactly maintained by 60 per second oscillator pulses.

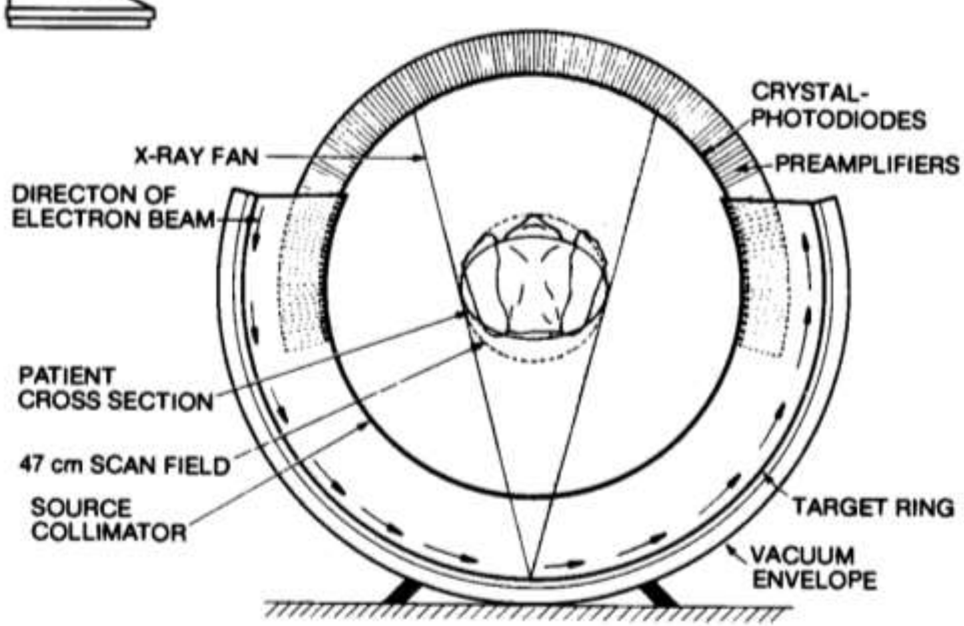
# Electron Beam Technology

- The mechanically moved gantry in conventional CT is too slow to image a fast-moving structure like a heart.
- To shorten the scanning time, either multiple sources and detectors, as in DSR, or other means to sweep the X-ray beam will have to be used.
- Scanning electron-beam technique is a method belonging to the latter category.

# Electron Beam Technology




(a)




(b)

**Figure 55** (a) Schematic diagram of an electron beam CT; (b) physical construction of its gantry. (Courtesy of Picker International Inc, Cleveland, Ohio and Imatron Inc, South San Francisco, California).

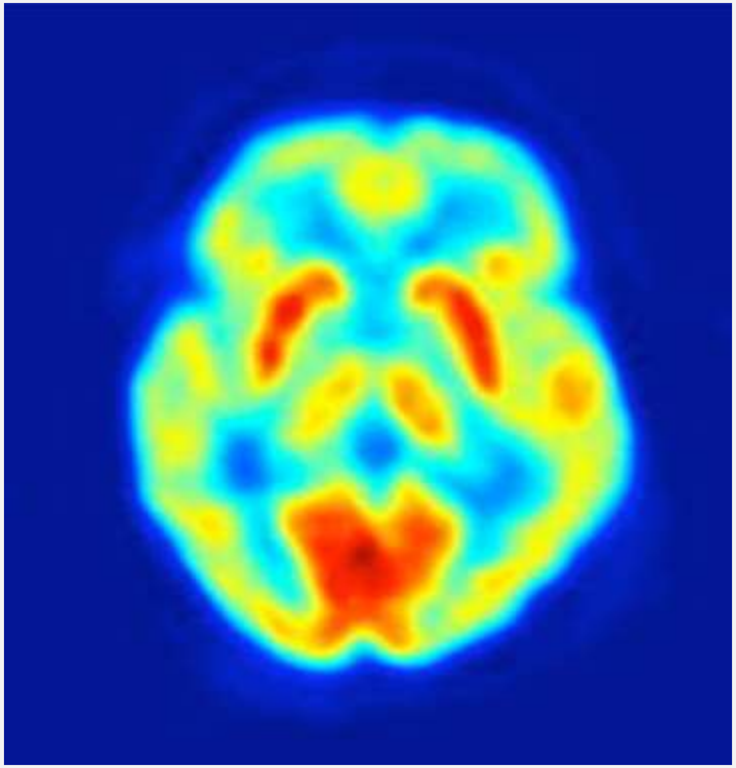
# Electron Beam Technology

- An electron beam is focused by a set of focusing coils and deflected to the target consisting of four tungsten rings spanning 210° by a set of deflection coils.
- Opposite the tungsten rings is an array of luminescent crystal silicon photodiodes, spanning an arc of 216°, acting as detectors.
- During scanning, which takes approximately 50 msec/scan, the electron beam is swept by the deflection coil.
- As the electron beam strikes the tungsten target, X-rays are generated and are collimated into a fan beam by the collimator. Four different imaging slices can be selected by striking different tungsten rings.
- It can achieve an impressive maximal scanning rate of 17 scans/sec.
- This type of scanner has been found useful in diagnosing a number of cardiac problems

# RADIONUCLIDE IMAGING

# MOLECULAR IMAGING METHOD

- Patients are injected with radioactive pharmaceuticals. The exact radiopharmaceutical is dependent on the exam requested
- Gamma cameras detect the energy from the radioactive decay of the injected isotope
- The acquired images represents the concentration of radiopharmaceutical in the organ of the interest
- It gives functional view of human body



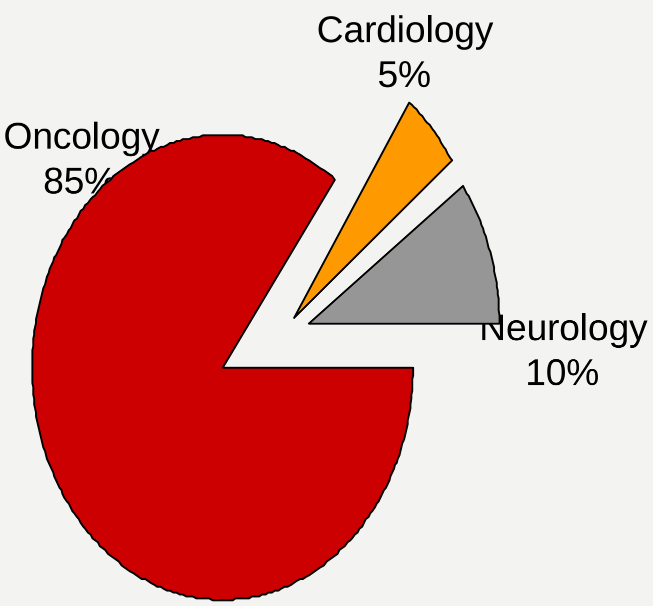
For example, healthy tissue use glucose for energy so some of the tagged glucose will show in PET image. But cancer cells use more glucose than normal tissues so they will appear brighter

# WHAT ARE SOME COMMON USES OF THE PROCEDURE?

Detect cancer and to examine the effects of cancer therapy by characterizing biochemical changes in the cancer.

PET scans of the heart can be used to determine blood flow to the heart muscle and help evaluate signs of coronary artery disease.

PET scans of the brain are used to evaluate patients who have memory disorders



# PHYSIOLOGICAL IMAGING

- Radioactive isotopes which emit gamma rays or other ionizing forms (half life for most is hours to days)
- Radionuclides are injected intravenously or inhaled where, depending on substance, they concentrate in organ of study
- The emitted gamma rays are then picked up by gamma camera and displayed

# WIDELY USED RADIONUCLIDES

- 99мTC - T1/2- - 6 hours, for brain tumors, thyroid gland, skeletal system, respiratory system diagnostics.
- 131I – T1/2 – 8,04 days, for iodine metabolism, liver, kidneys function
- 51Cr / 27.7 days/ -/ In hematology..
- 198Au /2.697 days
- 111In – for liver, brain diagnostics

- Target organ – is organ in which the Radio Pharmaceutical is maximally accumulated and which is exposed by excessive radiation. Mostly it is the organ we want to examine..
- There are 3 groups of target organs due to decreasing or radiosensitivity

  group I— whole body, genitals, bone marrow, small intestine mucosa
- group 2— muscles, thyroid, fat, liver, kidneys, spleen GI tract, lungs
- group 4— skin, bones

# PHYSICS OF NUCLEAR MEDICINE, SPECT AND PET

# OUTLINE

- Radionuclides in Nuclear Medicine
- Radiation Dose
- Gamma Camera Basics
- SPECT (Single Photon Emission Computed Tomography)
- PET (Positron Emission Tomography

# RADIONUCLIDES USED IN NUCLEAR MEDICINE

Less than 20 radionuclides but hundreds of labeled compounds

| Radionuclide | Decay Mode | Principal Photon Emissions | Half-Life | Primary Use |
|---|---|---|---|---|
| $^{11}C$ | $\beta^+$ | 511 keV | 20.3 min | Imaging |
| $^{13}N$ | $\beta^+$ | 511 keV | 10.0 min | Imaging |
| $^{15}O$ | $\beta^+$ | 511 keV | 2.07 min | Imaging |
| $^{18}F$ | $\beta^+$ | 511 keV | 110 min | Imaging |
| $^{32}P$ | $\beta^-$ | — | 14.3 d | Therapy |
| $^{67}Ga$ | EC | 93, 185, 300 keV | 3.26 d | Imaging |
| $^{82}Rb$ | $\beta^+$ | 511 keV | 1.25 min | Imaging |
| $^{89}Sr$ | $\beta^-$ | — | 50.5 d | Therapy |
| $^{99m}Tc$ | IT | 140 keV | 6.03 hr | Imaging |
| $^{111}In$ | EC | 172, 247 keV | 2.81 d | Imaging |
| $^{123}I$ | EC | 159 keV | 13.0 hr | Imaging |
| $^{125}I$ | EC | 27–30 keV x rays | 60.2 d | In vitro assays |
| $^{131}I$ | $\beta^-$ | 364 keV | 8.06 d | Therapy/imaging |
| $^{153}Sm$ | $\beta^-$ | 41, 103 keV | 46.7 hr | Therapy |
| $^{186}Re$ | $\beta^-$ | 137 keV | 3.8 d | Therapy |
| $^{201}Tl$ | EC | 68–80 keV x rays | 3.05 d | Imaging |

EC, electron capture; IT, isomeric transition.

# EFFECTIVE DOSE OF NM PROCEDURES

| Examination* | Effective Dose (mSv) | Administered Activity (MBq)† | Effective Dose (mSv/MBq)‡ |
|---|---|---|---|
| Brain ($^{99m}$Tc-HMPAO–exametazime) | 6.9 | 740 | 0.0093 |
| Brain ($^{99m}$Tc-ECD–Neurolite) | 5.7 | 740 | 0.0077 |
| Brain ($^{18}$F-FDG) | 14.1 | 740 | 0.019 |
| Thyroid scan (sodium iodine 123) | 1.9 | 25 | 0.075 (15% uptake) |
| Thyroid scan ($^{99m}$Tc-pertechnetate) | 4.8 | 370 | 0.013 |
| Parathyroid scan ($^{99m}$Tc-sestamibi) | 6.7 | 740 | 0.009 |
| Cardiac stress-rest test (thallium 201 chloride) | 40.7 | 185 | 0.22 |
| Cardiac rest-stress test ($^{99m}$Tc-sestamibi 1-day protocol) | 9.4 | 1100 | 0.0085 (0.0079 stress, 0.0090 rest) |
| Cardiac rest-stress test ($^{99m}$Tc-sestamibi 2-day protocol) | 12.8 | 1500 | 0.0085 (0.0079 stress, 0.0090 rest) |
| Cardiac rest-stress test (Tc-tetrofosmin) | 11.4 | 1500 | 0.0076 |
| Cardiac ventriculography ($^{99m}$Tc-labeled red blood cells) | 7.8 | 1110 | 0.007 |
| Cardiac ($^{18}$F-FDG) | 14.1 | 740 | 0.019 |
| Lung perfusion ($^{99m}$Tc-MAA) | 2.0 | 185 | 0.011 |
| Lung ventilation (xenon 133) | 0.5 | 740 | 0.00074 |
| Lung ventilation ($^{99m}$Tc-DTPA) | 0.2 | 1300 (40 actually inhaled) | 0.0049 |
| Liver-spleen ($^{99m}$Tc–sulfur colloid) | 2.1 | 222 | 0.0094 |
| Biliary tract ($^{99m}$Tc-disofenin) | 3.1 | 185 | 0.017 |
| Gastrointestinal bleeding ($^{99m}$Tc-labeled red blood cells) | 7.8 | 1110 | 0.007 |
| Gastrointestinal emptying ($^{99m}$Tc-labeled solids) | 0.4 | 14.8 | 0.024 |
| Renal ($^{99m}$Tc-DTPA) | 1.8 | 370 | 0.0049 |
| Renal ($^{99m}$Tc-MAG3) | 2.6 | 370 | 0.007 |
| Renal ($^{99m}$Tc-DMSA) | 3.3 | 370 | 0.0088 |
| Renal ($^{99m}$Tc-glucoheptonate) | 2.0 | 370 | 0.0054 |
| Bone ($^{99m}$Tc-MDP) | 6.3 | 1110 | 0.0057 |
| Gallium 67 citrate | 15 | 150 | 0.100 |
| Pentreotide ($^{111}$In) | 12 | 222 | 0.054 |
| White blood cells ($^{99m}$Tc) | 8.1 | 740 | 0.011 |
| White blood cells ($^{111}$In) | 6.7 | 18.5 | 0.360 |
| Tumor ($^{18}$F-FDG) | 14.1 | 740 | 0.019 |

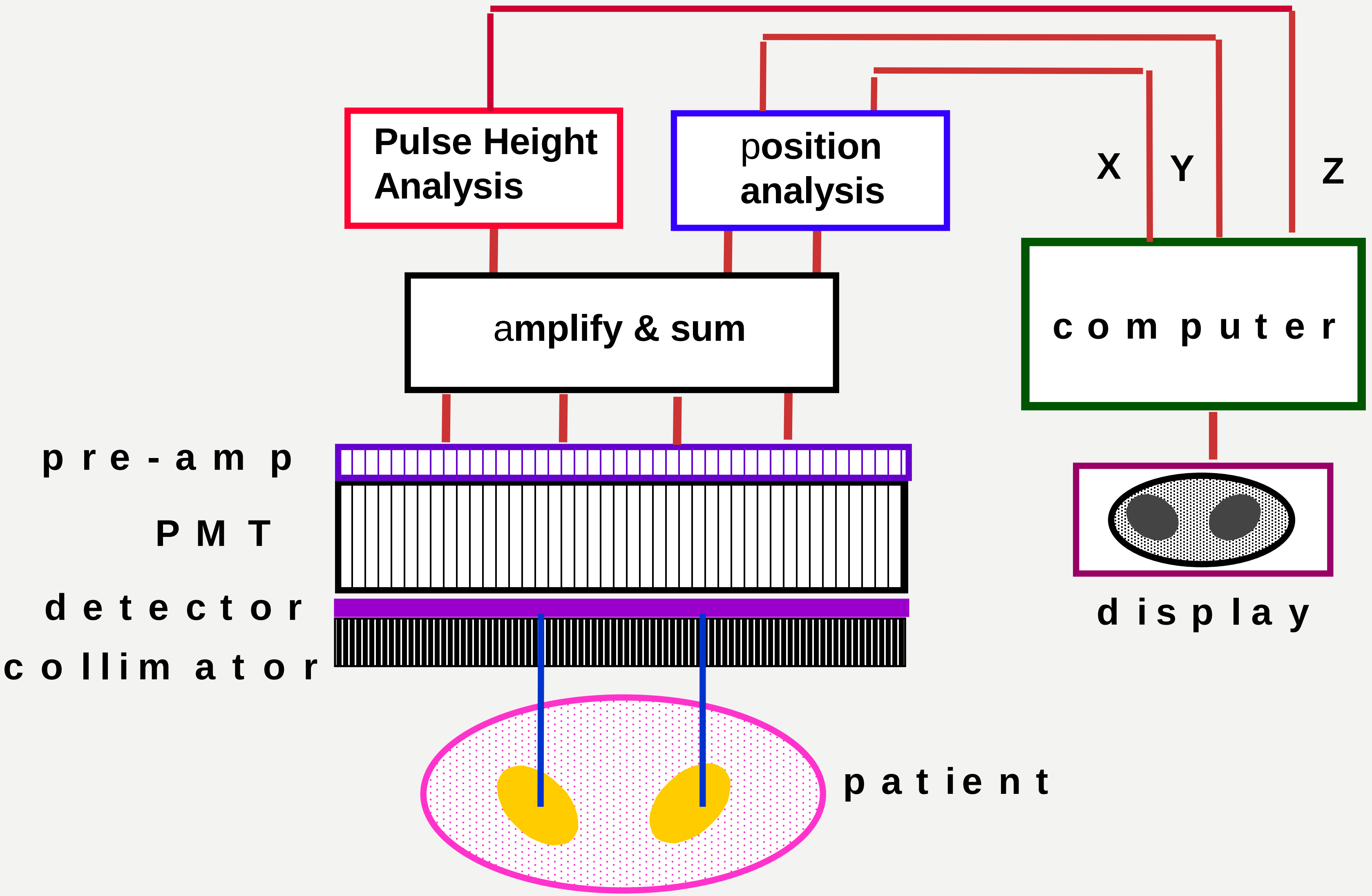
# DOSE DEFINITION

- Effective dose E (Sv): measure of absorbed dose to whole body, the product of equivalent dose and organ specific weighting factors
  - Whole body dose equivalent to the nonuniform dose delivered

# HOW TO OBTAIN A NM IMAGE ?

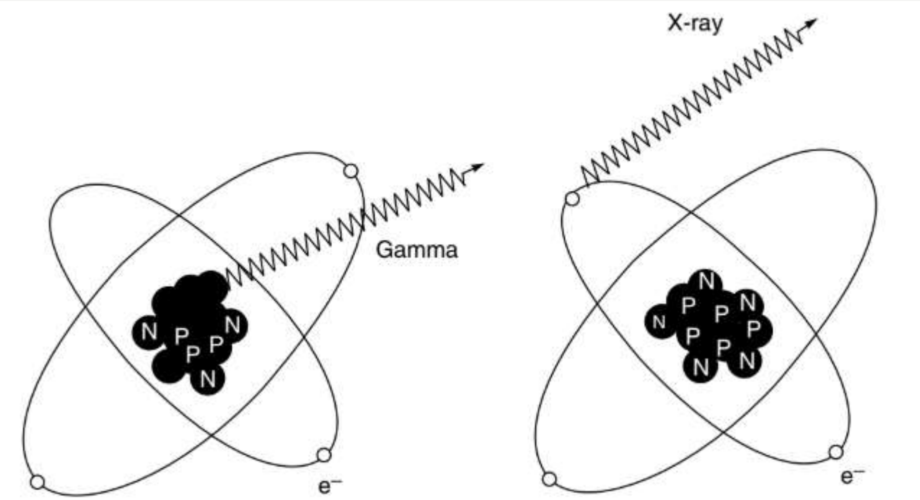
- Administer radiopharmaceutical (a radionuclide labeled to a pharmaceutical)
- The radiopharmaceutical concentrates in the desired locations
- Nucleus of the radionuclide decays to emit photons ($\gamma$ , x-ray)
- Detect the photons using a "gamma camera"

# GAMMA CAMERA BASICS



# PHYSICS OF RADIOACTIVITY

- Theory of atomic structure, states, that some elements are naturally unstable and exhibit natural radioactivity.
- On the other hand, elements can be made radioactive by bombarding them with high-energy charged particles or neutrons, which are produced by either a cyclotron or a nuclear reactor.
- This process will alter the ratio of photons to neutrons in the atoms, thus creating a new unstable nucleus which could undergo radioactive decay. The extra neutron disintegrates and in the process, releases energy in the form of gamma radiation.




➤ **Fig. 21.1** *Difference between X-ray and gamma emissions*

Unit of radioactivity is curie Ci or ci.
Very high degree of activity. – $3.7*10^{10}$ disintegrations per second
Typical amount of organ scanning would be 3mci to 25mci

# TYPES OF RADIOACTIVE DECAY

There are four types of radioactive decay that produce radiation

- Positron Decay - In this, the nucleus is unstable because there are more protons than neutrons.
- For the atom to become stable, it must reduce the number of protons contained in its nucleus by emission of a positively charged particle. This is called positron decay.
- It occurs in man-made radioactive materials, wherein protons are added to the nucleus through bombardment using a ‘cyclotron’. Cyclotrons are part of expensive equipment and are not typically available in the hospital.

# TYPES OF RADIOACTIVE DECAY

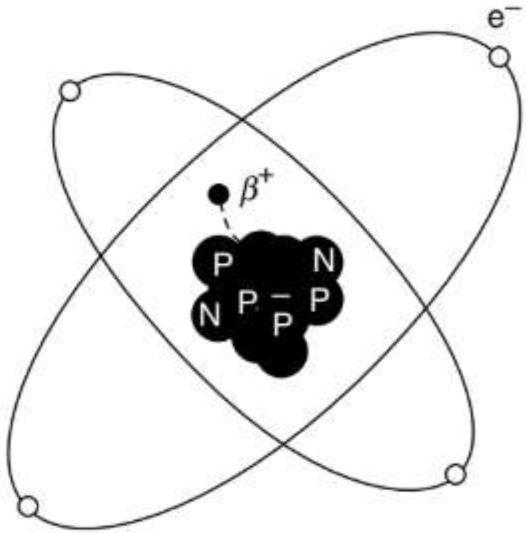
- Beta Decay (Sometimes called Negatron): In this the nucleus is unstable because there is an excess of neutrons.
- This negatively charged particle, which is an electron with a high kinetic energy, is emitted from the nucleus. This is called (-) decay.
- Many of the radio nuclides used in nuclear medicine decay by the emission of a (-) particle, which in turn, triggers gamma emission

# TYPES OF RADIOACTIVE DECAY

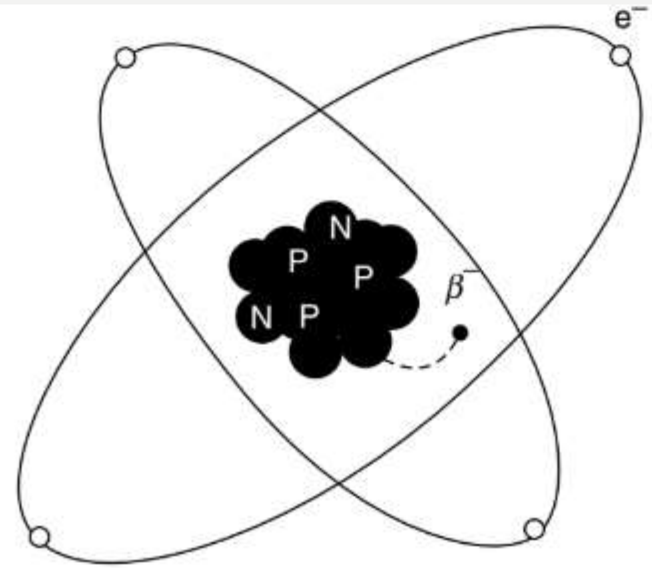
- In Electron Capture: In this the nucleus captures an orbital electron from one of the surrounding energy shells.
- The captured electron then combines with a proton to form a neutron.
- During this process, energy in the form of photons or gamma rays is emitted from the nucleus, and X-rays are emitted from the electron orbits

# TYPES OF RADIOACTIVE DECAY

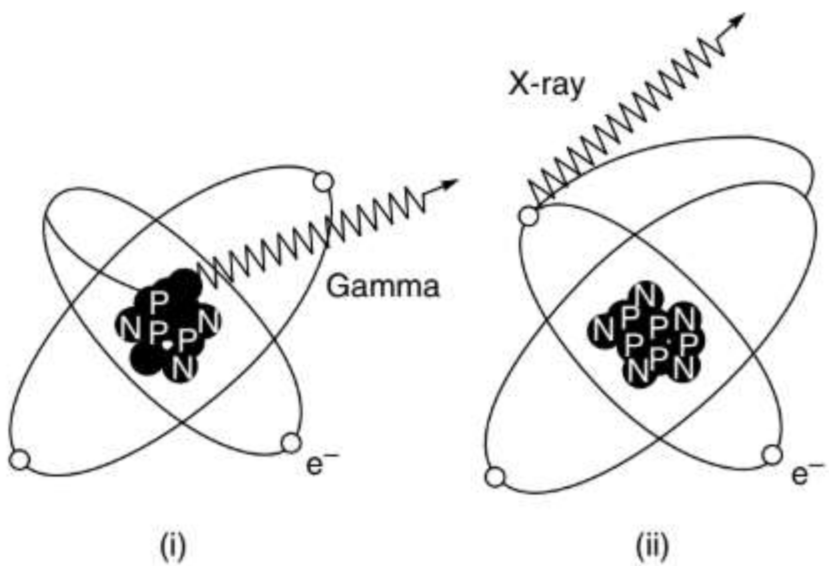
- Isomeric Transition: Sometimes, when a nucleus in an excited state begins the decay process to become more stable,
- it goes through more than one stage of decay. The intermediate stage is called the 'metastable' state.
- A nuclide in a metastable state eventually decays to a stable atom, through a process called isomeric transition.
- This type of decay is very important in nuclear medicine because it is the process by which Tc-99m decays. 'm' here means 'metastable'.



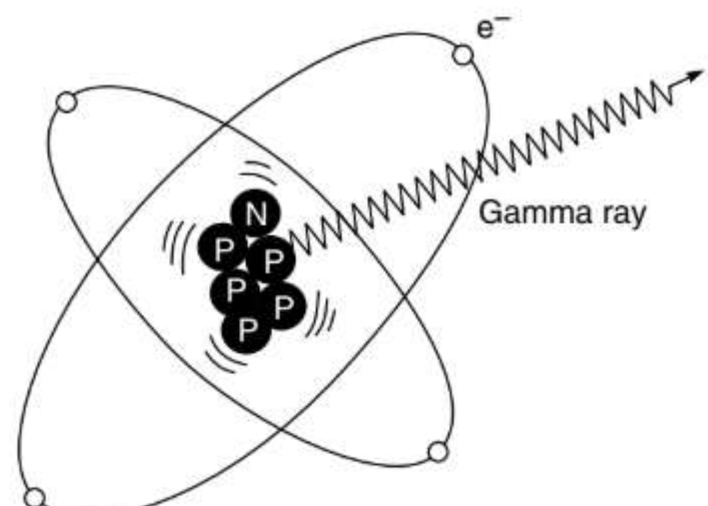

(a) Positron decay ($\beta^+$)




(b) $\beta^-$ decay




(c) Electron capture




(d) Isomeric transition

# TYPES AND PROPERTIES OF PARTICLES EMITTED

Upon interaction with matter, gamma rays lose energy by three modes:

(i) The photo-electric effect transfers all the energy of the gamma ray to an electron in an inner orbit of an atom of the absorber. This involves the ejection of a single electron from the target atom. This effect predominates at low gamma energies and with target atoms having a high atomic number

(ii) The Compton effect occurs when a gamma ray and an electron make an elastic collision. The gamma energy is shared with the electron and another gamma ray of lower energy is produced, which travels in a different direction. The Compton effect is responsible for the absorption of relatively energetic gamma rays

(iii) When a high energy gamma ray is annihilated following interaction with the nucleus of a heavy atom, pair production of a positron and an electron results. Pair production becomes predominant at the higher gamma ray energies and in absorbers with a high atomic number. The number of ion pairs per centimetre of travel is called specific ionization

# PHOTOMULTIPLIER TUBE (PMT)

- 40 to 100 PM tubes (d = 5 cm) in a modern gamma camera
- photocathode directly coupled to detector or connected using plastic light guides
- ultrasensitive to magnetic fields

# WHY COLLIMATOR? – IMAGE FORMATION

**w/o collimator**

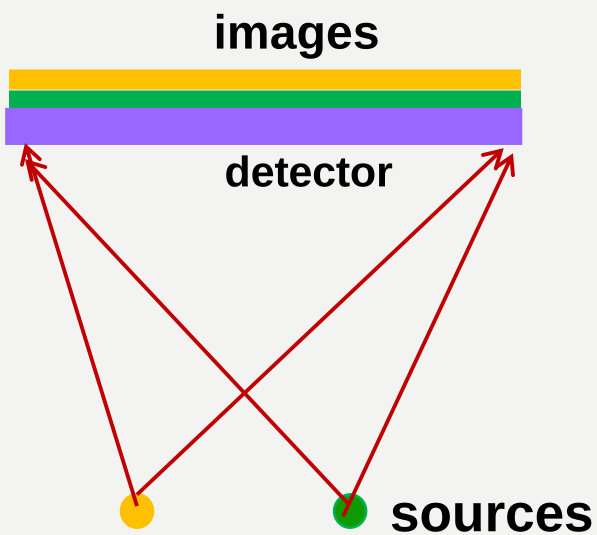



**Image of a point source is the whole detector.**

**with collimator**

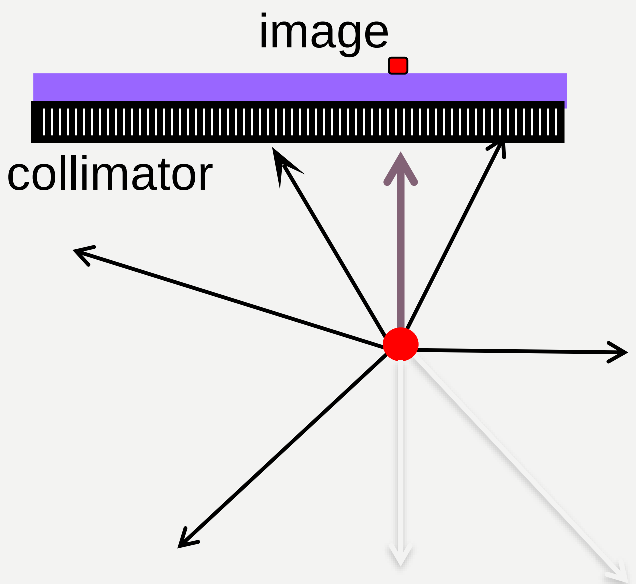
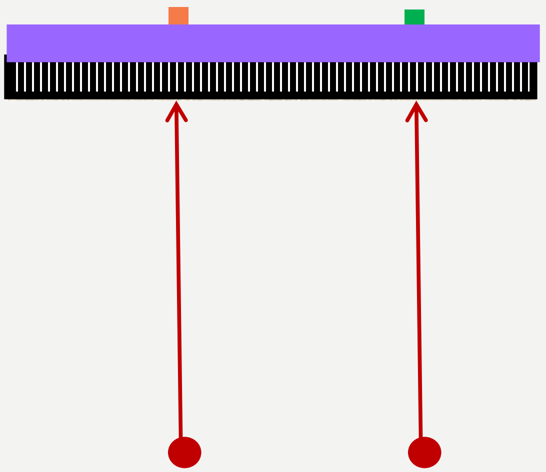


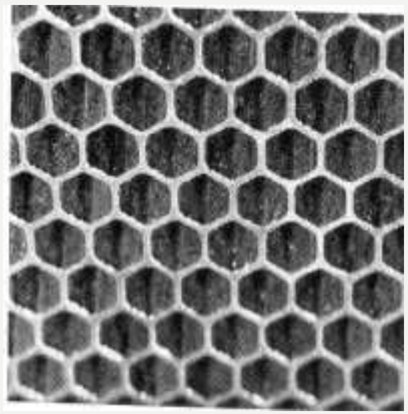

Image of a point source is a point.

# WHY COLLIMATOR? – IMAGE FORMATION

- to establish geometric relationship between the source and image
- The collimator has a major affect on gamma camera sensitivity (count rate) and spatial resolution

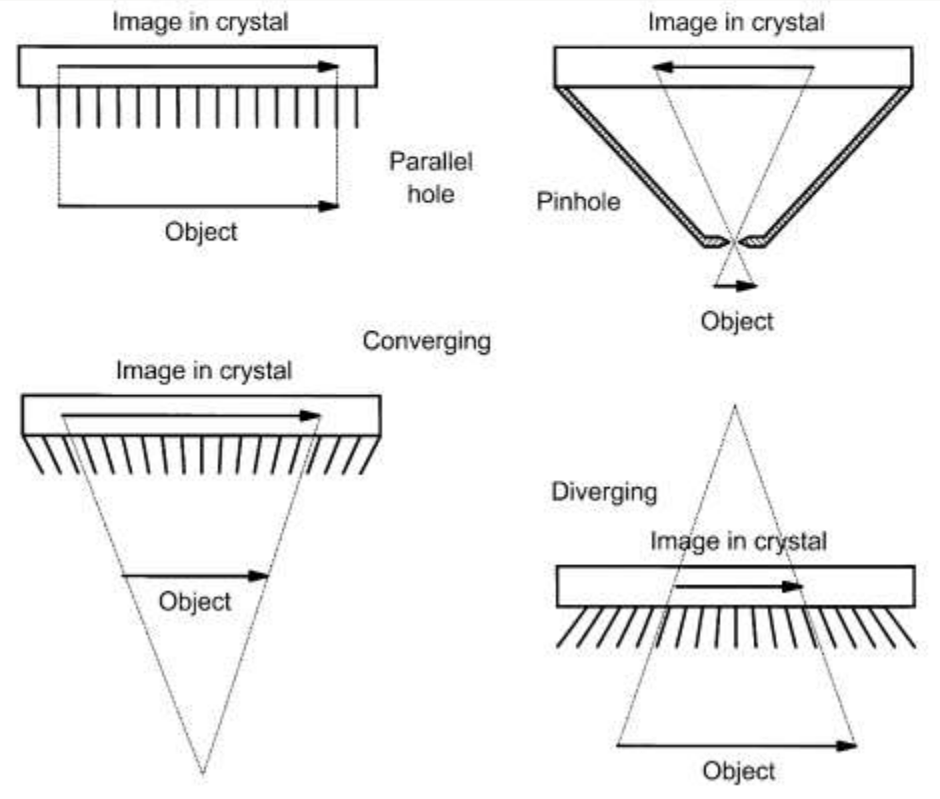


parallel-hole collimator



# Collimators

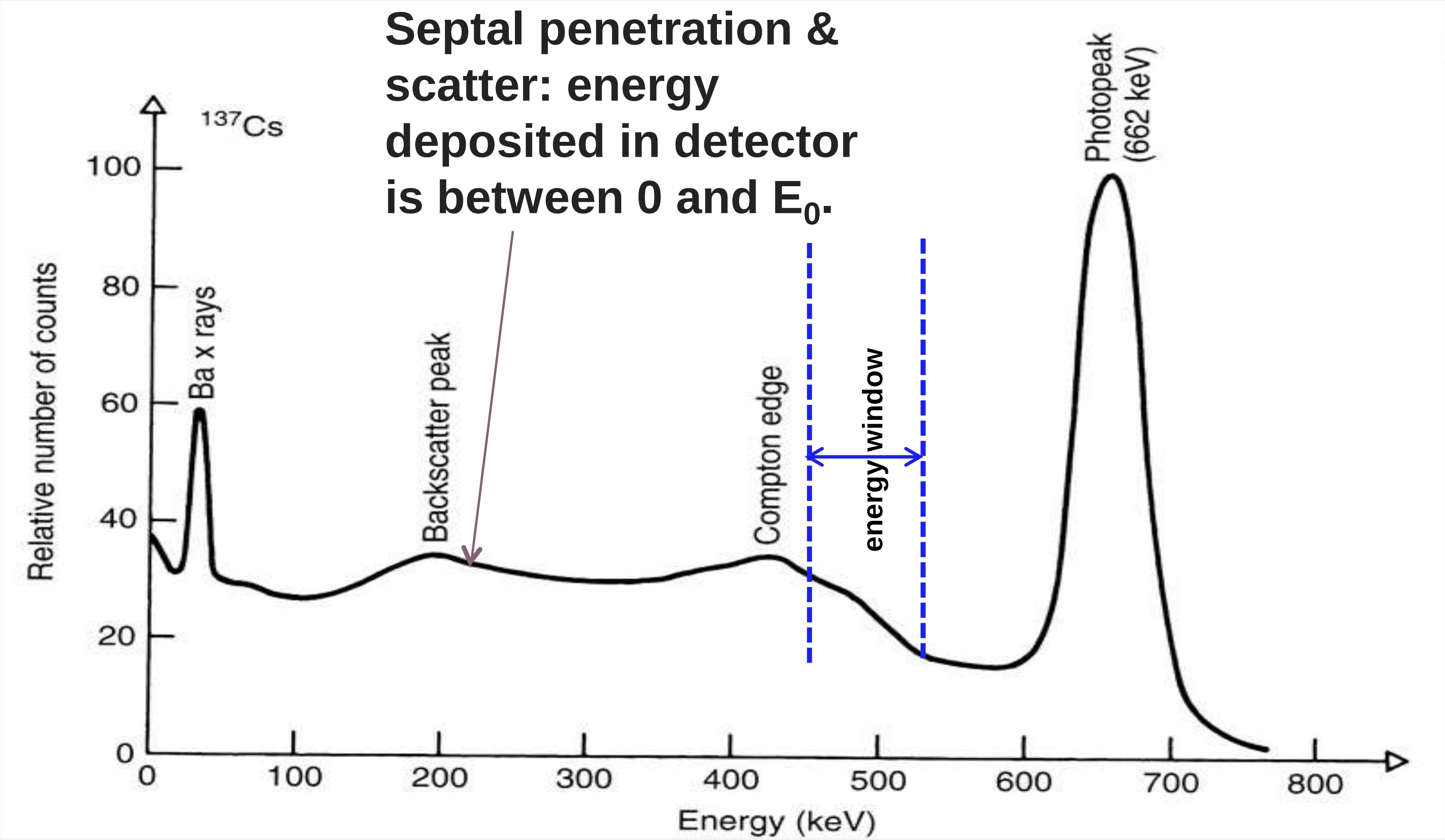
- Most often used: parallel-hole collimator
- For thyroid and heart: pin-hole collimator
- For brain and heart: converging collimator



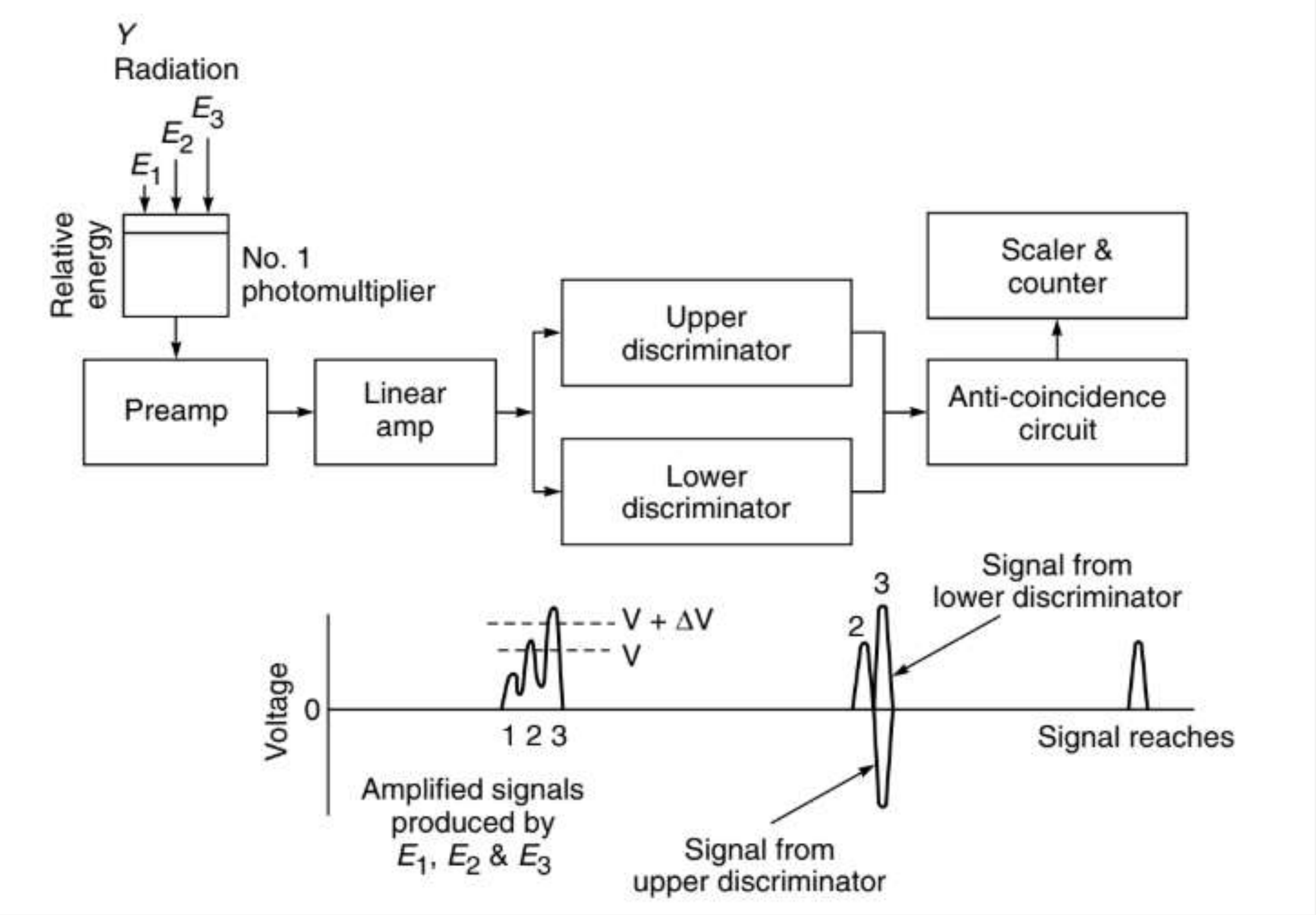
# COLLIMATOR SUMMARY

- Collimator must be matched to energy of radionuclide
- Efficiency changes little with distance to source (patient)
- Resolution falls off quickly with distance to source (patient)

# ENERGY SPECTRUM OF DETECTOR



# PULSE HEIGHT ANALYZER



# PULSE HEIGHT ANALYZER

- The output pulses from the photo-multiplier are amplified in a high input impedance low-noise pre-amplifier
- Amplified pulses are fed into a linear amplifier of sufficient gain to produce output pulses in the amplitude range of 0–100 V. These pulses are then given to two discriminator circuits
- A discriminator is nothing but a Schmitt trigger circuit, which can be set to reject any signal below a certain voltage. This is required for excluding scattered radiation and amplifier noise.
- Discriminator circuit rejects all but signal 3 and the lower discriminator circuit rejects signal 1 only and transmits signals 2 and 3. The two discriminator circuits give out pulses of constant amplitude.
- The pulses with amplitudes between the two triggering levels are counted. This difference in two levels is called the window width, the channel width or the acceptance slit and is analogous to monochromators in optical spectrometry.

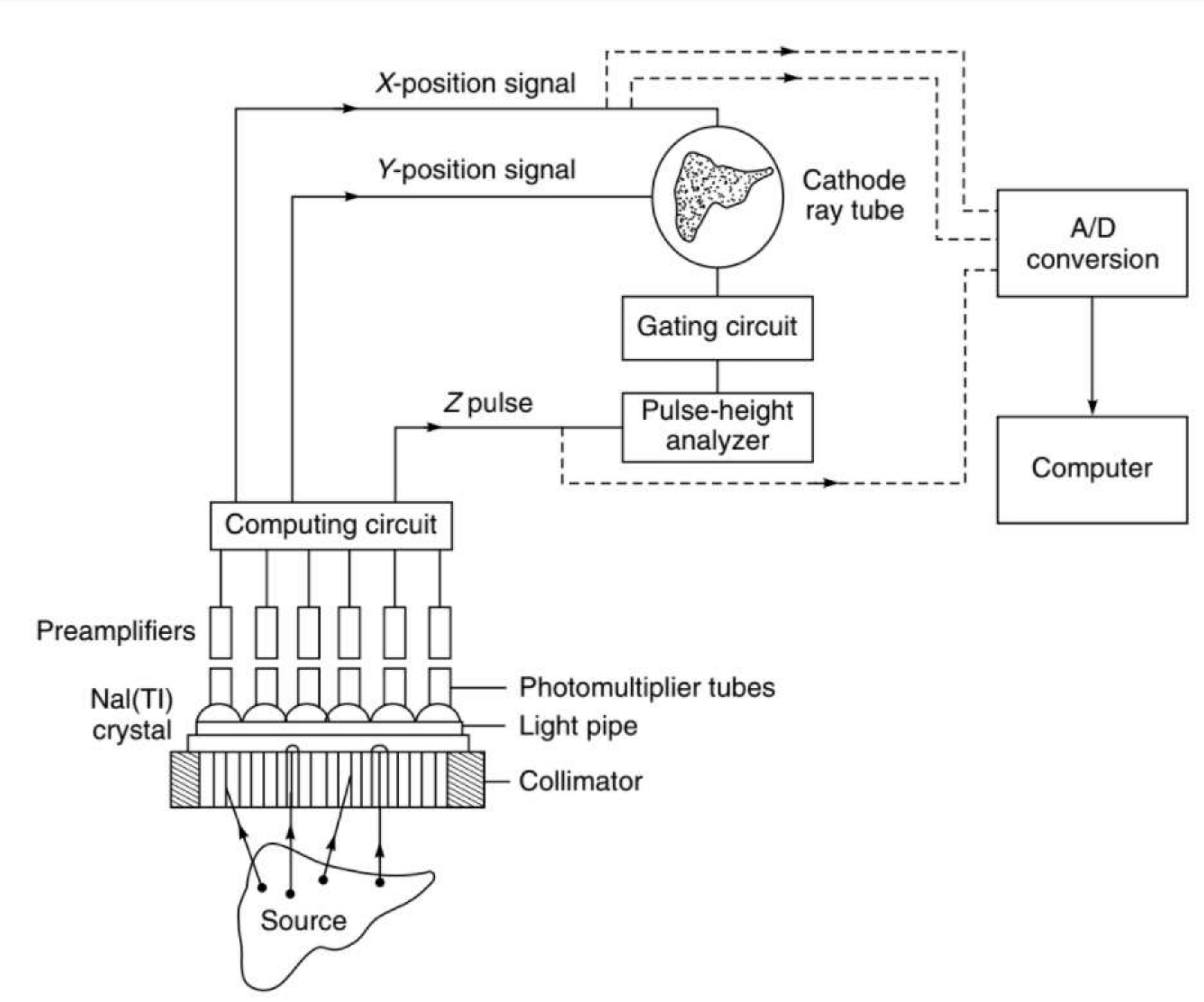
# PULSE HEIGHT ANALYZER

- Schmitt trigger circuits are followed by an anti-coincidence circuit.
- This circuit gives an output pulse when there is an impulse in only one of the input channels.
- It cancels all the pulses which trigger both the Schmitt triggers. This is accomplished by arranging the upper discriminator circuit, in such a way that its output signal is reversed in polarity and thus cancels out signal 3 in the anti- coincidence circuit.
- As a consequence, the only signal reaching the counter is the one lying in the window of the pulse height analyser.
- The window can be manually or automatically adjusted to cover the entire voltage range with a width of 5–10V. Scaler and counter follow the anti-coincidence circuit.
- The scaling unit counts down the pulses from the analyser, so that they are digitally displayed.
- A decade system of counting is employed, which displays units, tens, hundreds time taken to record to definite number of counts, or number of counts which occur within a definite time interval.

# PULSE HEIGHT ANALYZER

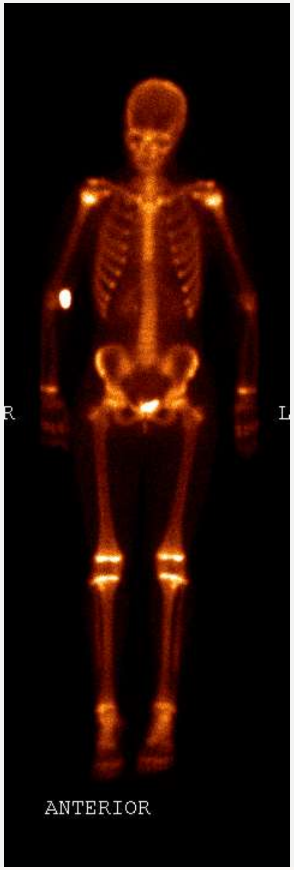
- Multi-channel pulse height analyzers are often used to measure a spectrum of nuclear energies and may contain several separate channels, each of which acts as a single-channel instrument for a different voltage span or window width.
- The Schmitt trigger discriminators are adjusted to be triggered by pulses of successively longer amplitude.
- This arrangement permits the simultaneous counting and recording of an entire spectrum.
- A parallel array of discriminators is generally used, provided the number of channels is ten or less.
- If the number of channels is more than ten, the problems of stability of discrimination voltages and adequate differential non-linearity arise.

# GAMMA CAMERA



# MODERN CAMERA DESIGN

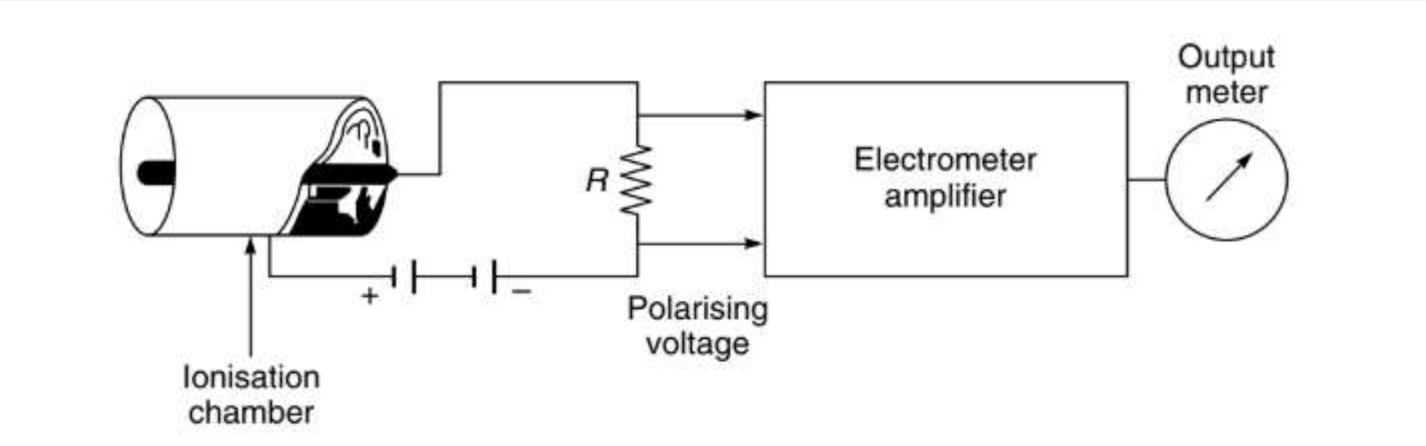
- Most cameras use rectangular heads
- Most cameras are designed to do SPECT imaging
- The dual head is the most common design



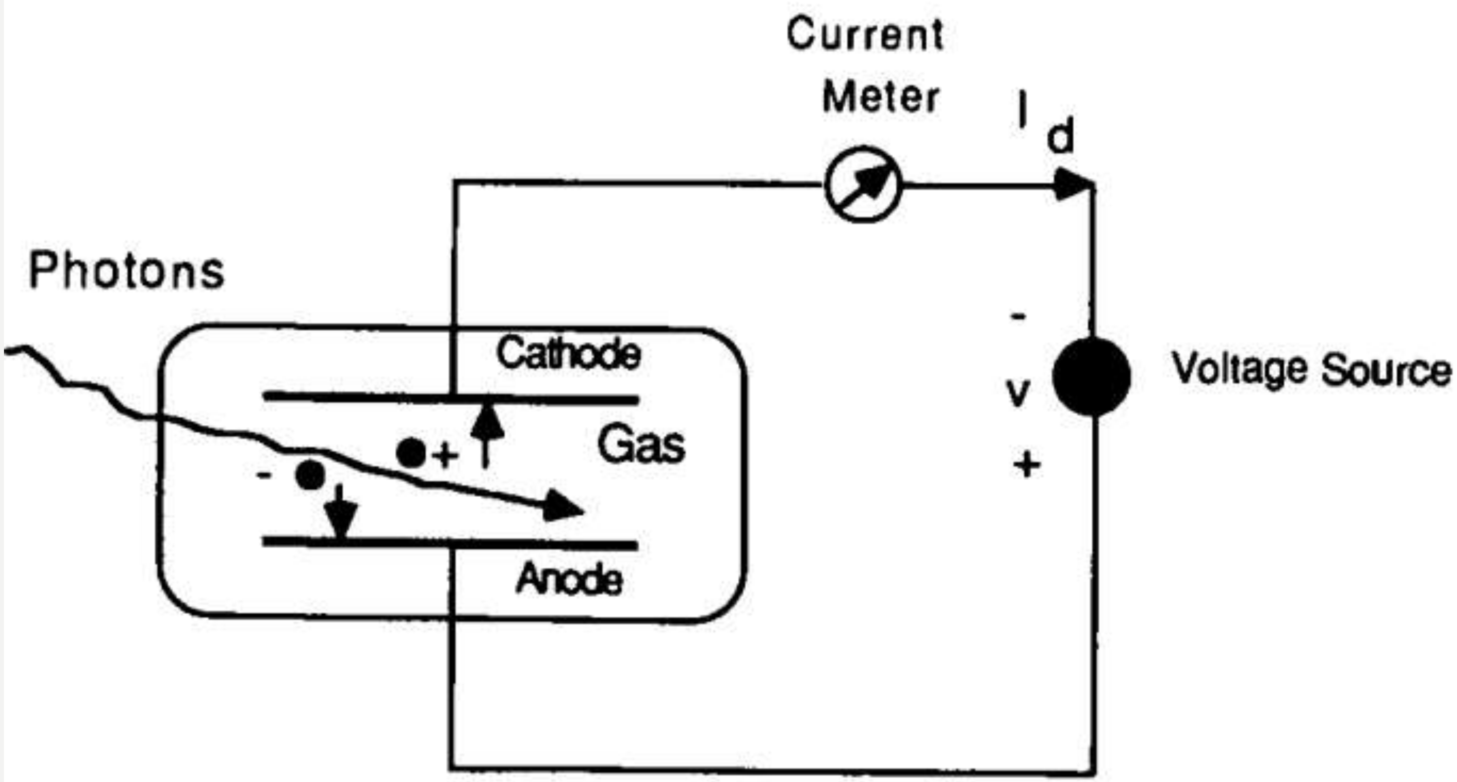

# RADIATION DETECTORS

- Ionization chamber
- Scintillation detector
- Semiconductor Detectors
- Solid state detectors

Ionization chamber



# ION COLLECTION DETECTOR




Schematic diagram of an ion collection detector.

# IONIZATION CHAMBER

- An ionization chamber consists of a chamber which is filled with gas and is provided with two electrodes.
- A material with a very high insulation resistance such as polytetrafluoroethylene is used as the insulation between the inner and outer electrodes of the ion chamber.
- A potential difference of a few hundred volts is applied between the two electrodes.
- The radioactive source is placed very dose to the chamber. The charged particles moving through the gas undergo inelastic collisions to form ion pairs.
- The voltage placed across the electrodes is sufficiently high to collect all the ion pairs. The chamber current will then be proportional to the amount of radioactivity in the sample.
- Ionization chambers are operated either in the counting mode, in which they respond separately to each ionizing current, or in an integrating mode involving collection of ionization current over a relatively long period.

# SCINTILLATION DETECTOR

- Gamma radiations cannot be detected directly in a scintillating material, because gamma rays possess no charge or mass
- The gamma ray energy must be converted into kinetic energy of electrons present in the scintillating material
- Conversion power of the scintillating material will be proportional to the number of electrons (electron density) available for interaction with the gamma rays. Because of its high electron density, high atomic number and high scintillating yield, the scintillating material which is generally used as gamma ray detector, is a crystal of sodium iodide activated with about 0.5% of thallium iodide
- Presently, thallium-activated sodium-iodide NaI(TI) scintillation crystal is used in all commercial cameras
- 140 keV gamma ray absorbed in the crystal produces about 4200 light photons (in the blue-green region of the spectrum where each light photon has an energy of around 3 eV). The decay time of this light flash has a half-life of approximately 0.2 ms, sufficiently fast for most clinical applications

# SOLID STATE DETECTORS

- Detectors are highly sensitive to gamma rays because of the high atomic number of cadmium (48) and telluride (52). The limited thickness of solid state detectors makes them inferior to NaI (Tl) detectors with respect to gamma ray detection sensitivity.

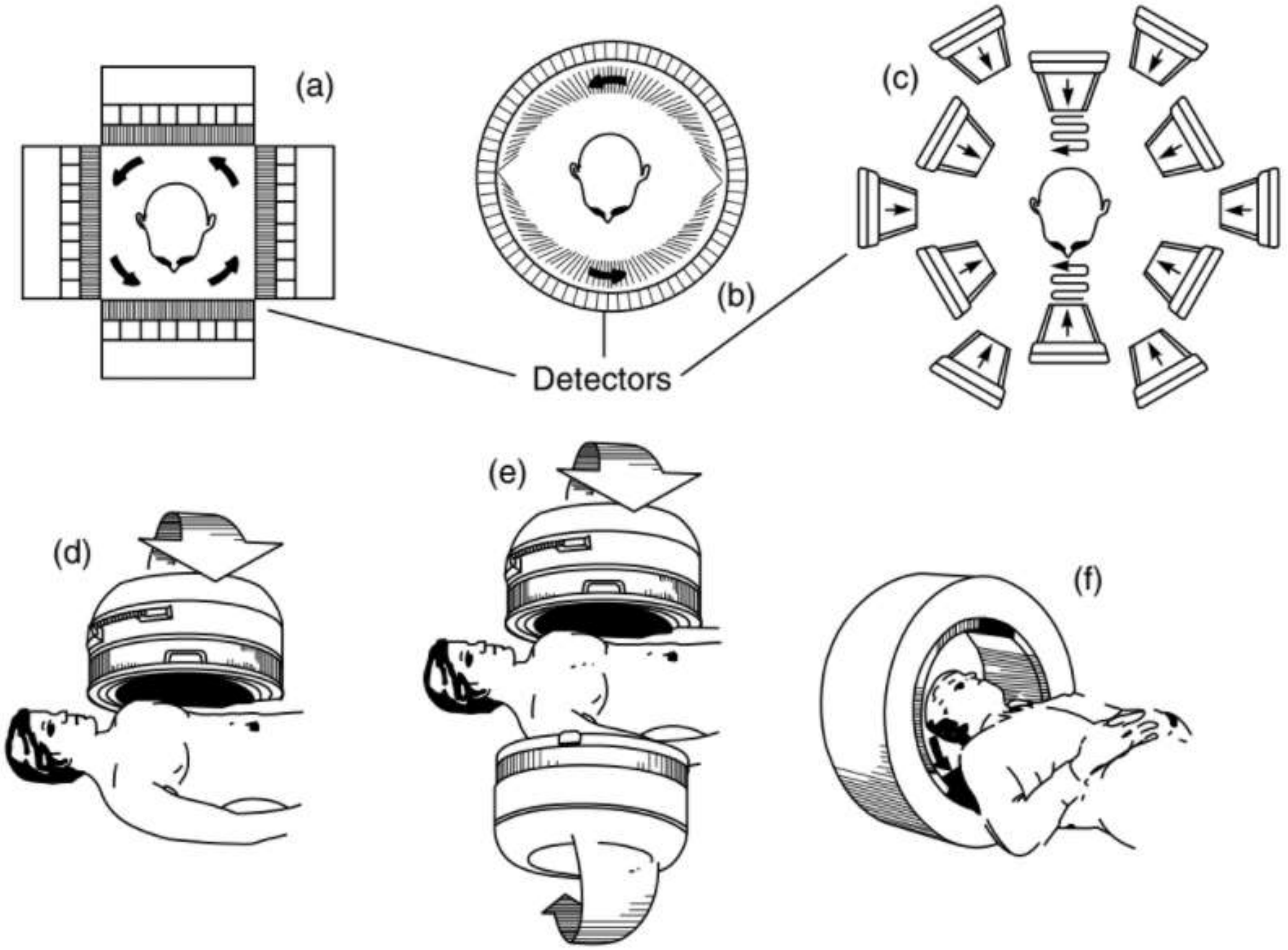
# NUCLEAR MEDICINE
## PHYSIOLOGICAL IMAGING

- Conventional Nuclear Medicine
    - Emitted gamma rays create image
- SPECT (Single Photon Emission Computed Tomography)
    - Tomographic images of emitted gamma rays
    - Rotating gamma camera creates 3-D data set
    - Data set is then manipulated to create volume images (sum of all images in stack), multiplanar thin section images and 3-D volume data sets

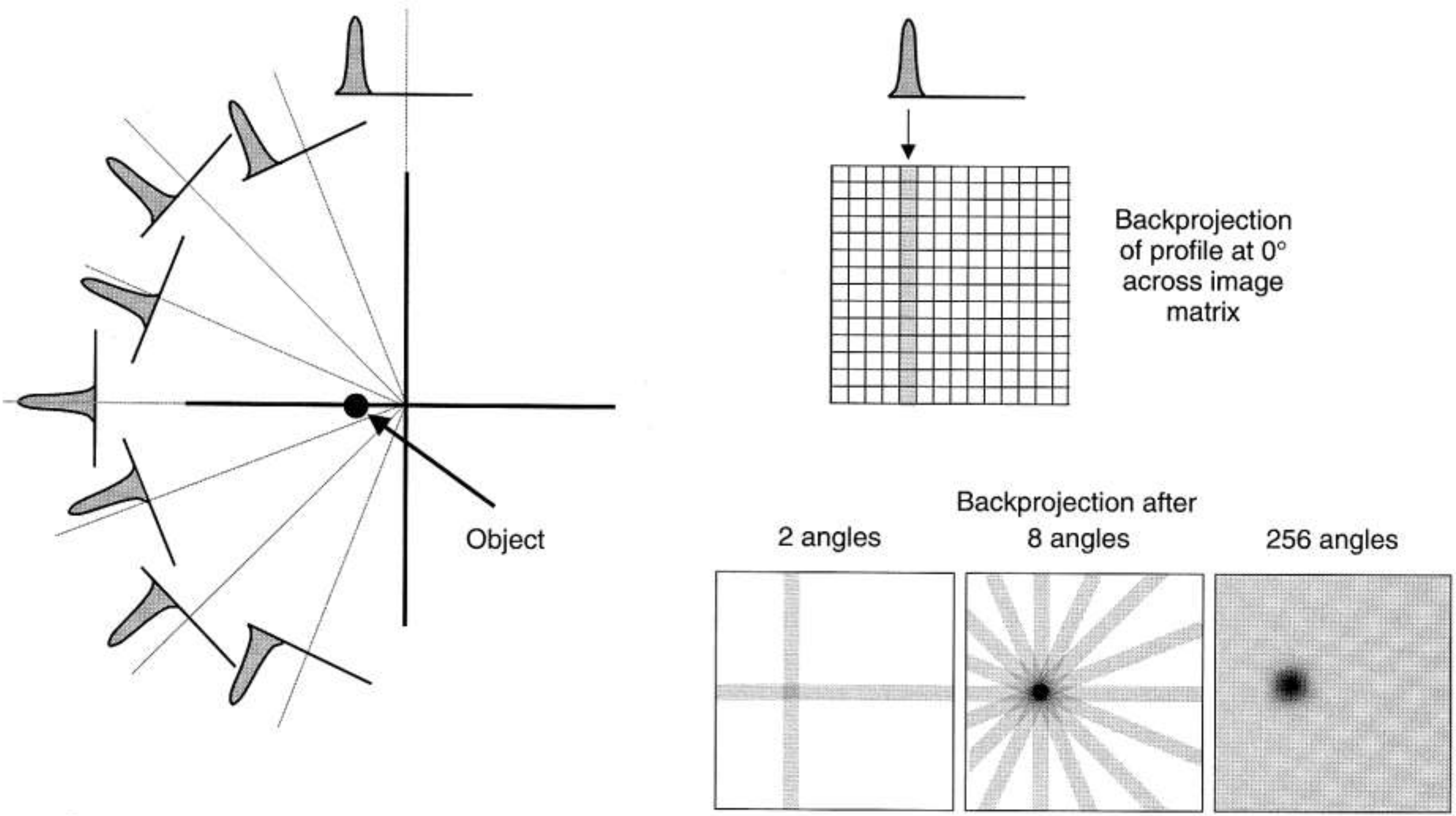
# SPECT (Single Photon Emission Computed Tomography)

- Tomographic images can be produced by acquiring conventional gamma camera projection data at several angles around the patient
  - Similar to CT

# SPECT DETECTOR ARRANGEMENT

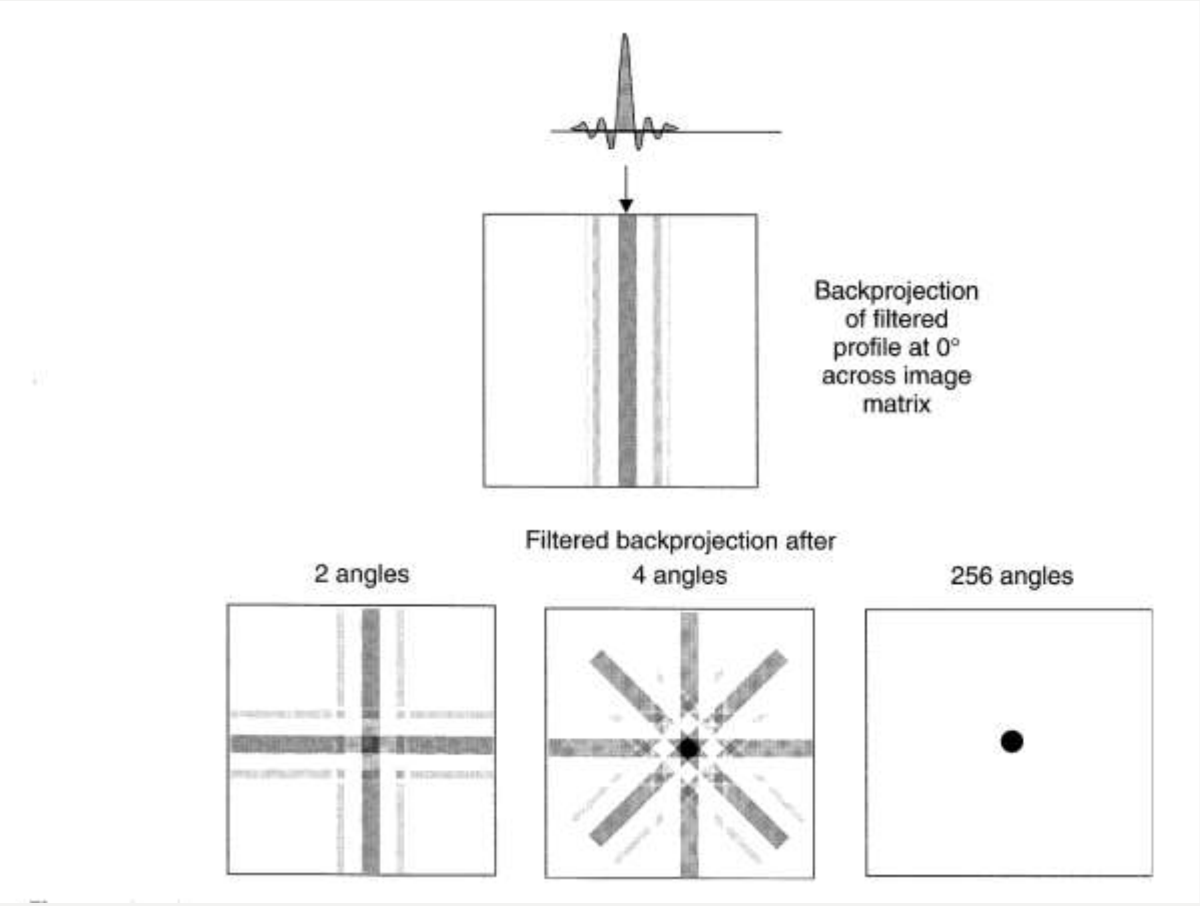



. 21.15 *Examples of several discrete detector and camera-based approaches for SPECT (Jaszczak , 1988)*


Object
Backprojection
of profile at 0°
across image
matrix
Backprojection after
2 angles
8 angles
256 angles

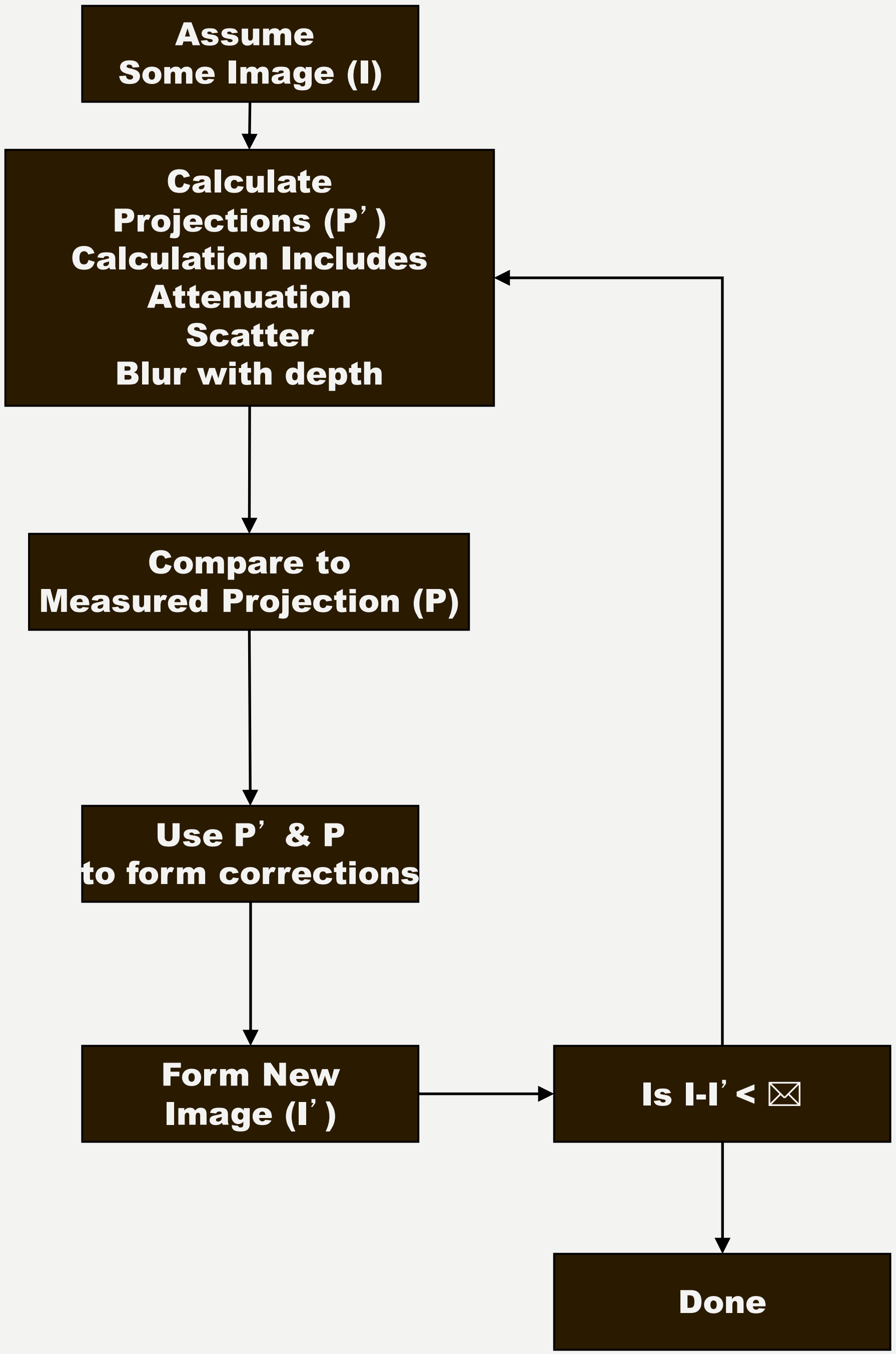
# FILTERED BACK PROJECTION

- Attenuates streaks by filtering the projections



# ITERATIVE RECONSTRUCTION

- Quantitatively more accurate
  - Can model various corrections
    - Collimator
    - Scatter
    - System geometry
    - Detector resolution
- Slow
- Being used increasingly in SPECT


Assume
Some Image (I)
Calculate
Projections (P')
Calculation Includes
Attenuation
Scatter
Blur with depth
Compare to
Measured Projection (P)
Use P' & P
to form corrections
Form New
Image (I')
Is I-I' < ⊠
Done

# ATTENUATION CORRECTION: CHANG METHOD

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

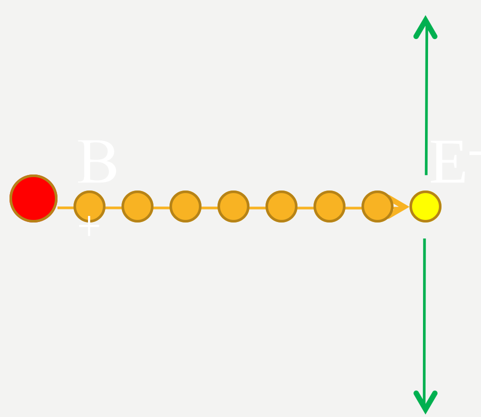
- Assume uniform attenuation
- $\mu$ = linear attenuation coefficient of soft tissue (0.15 per cm for Tc-99m)
- X is tissue thickness along projection from emission data

# PET (POSITRON EMISSION TOMOGRAPHY)

- Positron decay characteristics
- Coincidence and angular correlation
- Time of flight
- PET detector/scanner design
- Data corrections

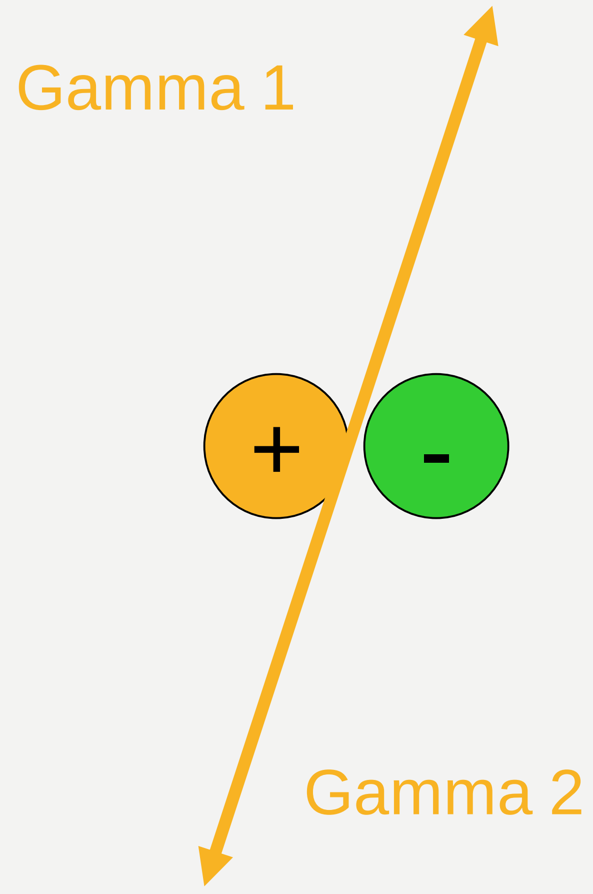
# NUCLEAR MEDICINE
## PHYSIOLOGICAL IMAGING

- Positron Emission Tomography
    - Radionuclide emits positrons which interact with electrons to eject gamma rays at 180°
    - Use computer to localize in space



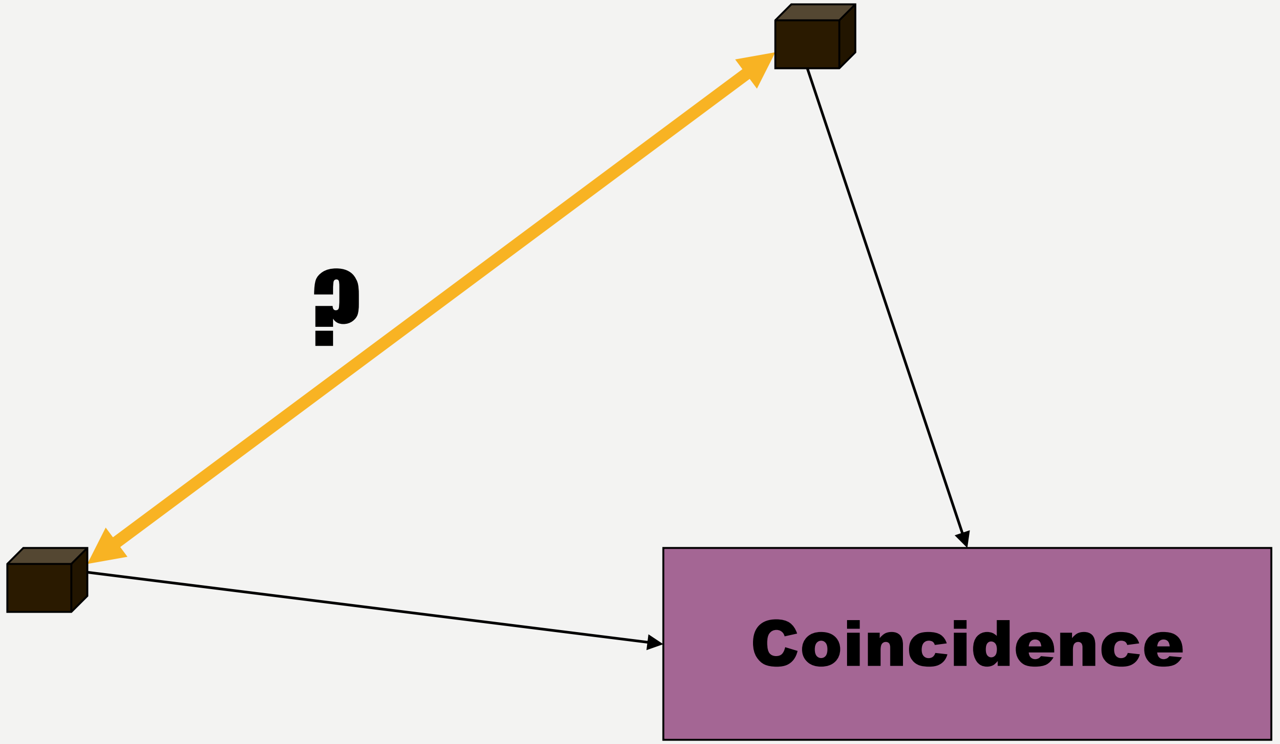
# POSITRON IS AN ANTI-PARTICLE

- When a particle and antiparticle interact they annihilate
  - Both particles are destroyed
  - Two photons(Gamma-rays) are created
  - Two photons are emitted in ~opposite directions (± 0.25 degrees for F-18)

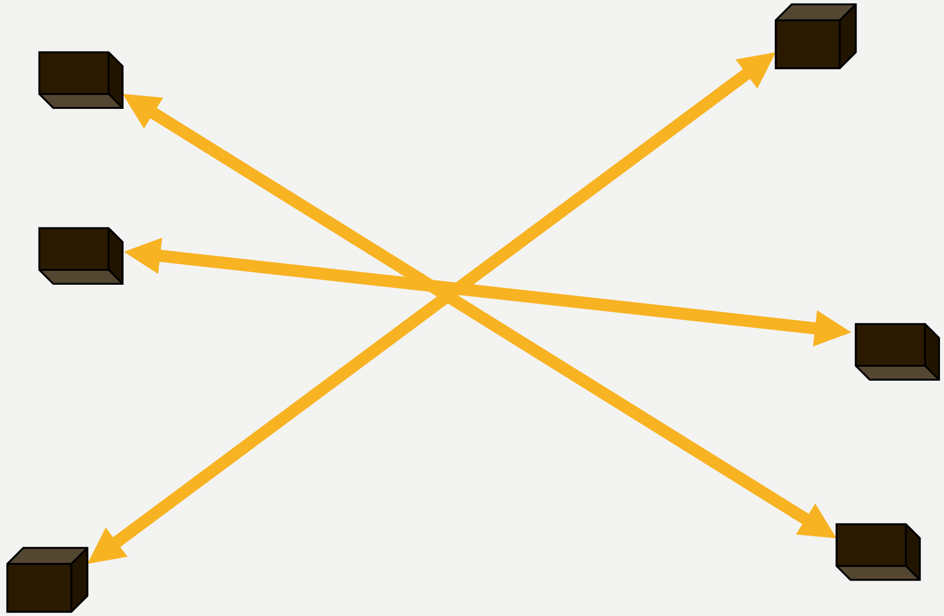


# PET Imaging Concepts

## WHERE WAS THE EVENT?

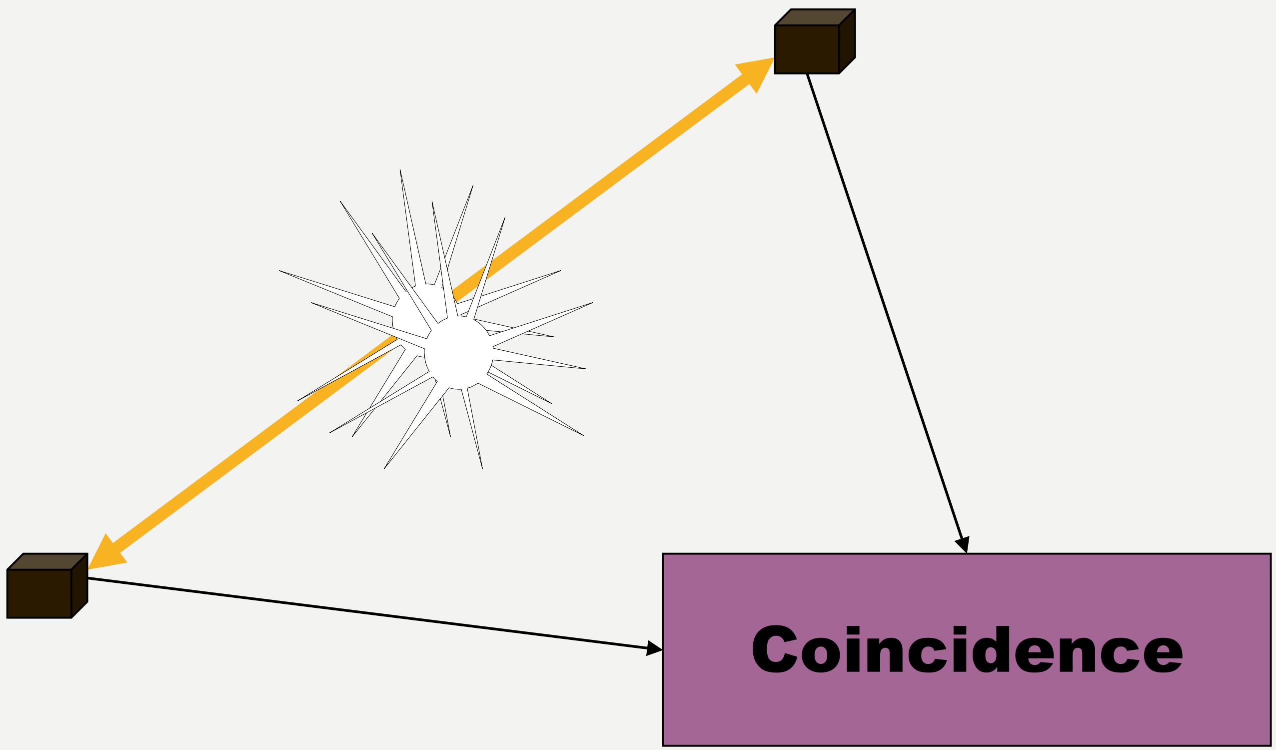


# WHERE WAS THE EVENT?



# ANNIHILATION DETECTION

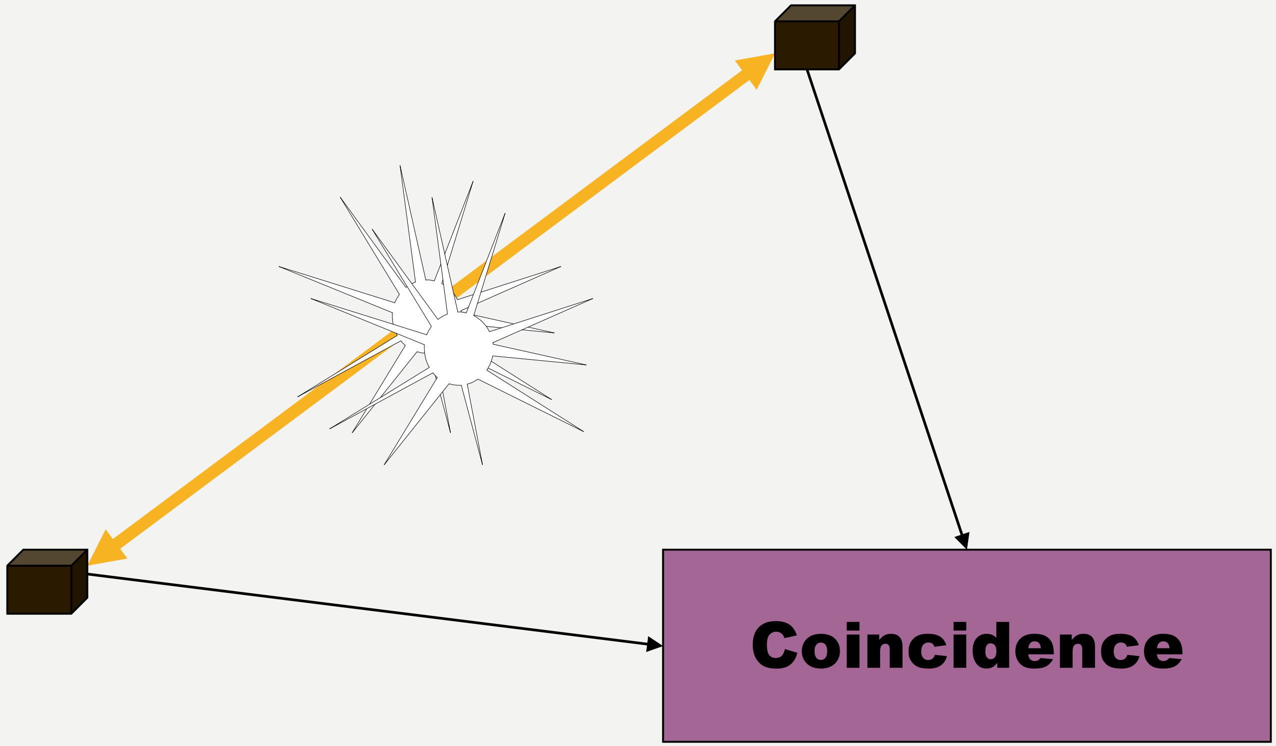
In coincidence counting an event is ONLY registered if a signal is received from two detectors within a narrow window of time.
A few nanoseconds is usually used.



# TIME-OF-FLIGHT PET

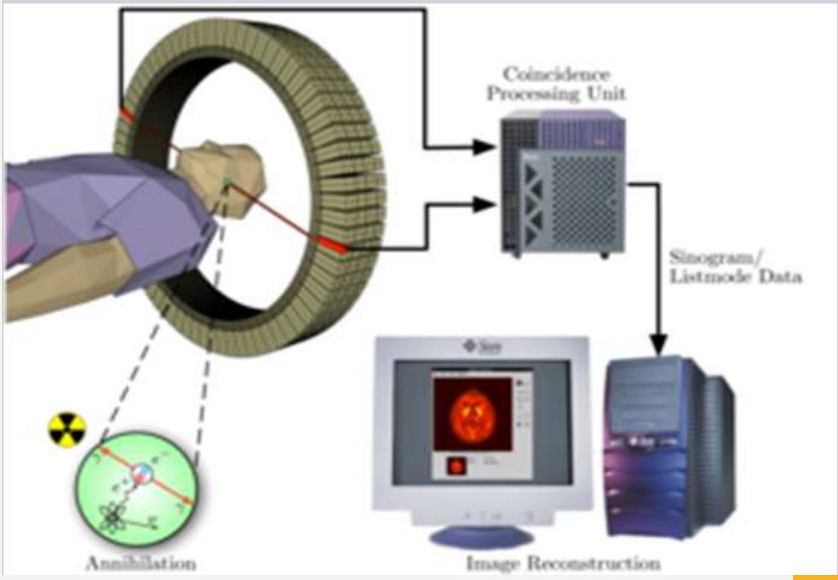
In “Time-of-Flight” PET, use of a very small time window (<100 picoseconds) can localize an annihilation event to within a few cm along the line of coincidence.

Time-of-Flight PET can improve SNR.



# WHAT IS POSITRON EMISSION TOMOGRAPHY?

- Positron emission tomography involves acquisition of physiologic images based on the detection of radiation from the emission of positrons.
- Positrons are tiny particles emitted from a radioactive substance administered to the patient.
- Before scan, a radioactive substance is injected into patient's body which localizes in appropriate areas of body which are subsequently detected by the PET scanner
- Different colors or degrees of brightness on a PET image represent different levels of tissue or organ function.



# POSITRON EMISSION TOMOGRAPHY

- PET (Positron Emission Tomography)
  - Tomographic images of emitted positrons
  - Can be used to study metabolic processes
  - 511 kEv gamma ray Photons emitted simultaneously at 180 degrees to each other
  - Evaluate location in space
  - Fusion imaging with CT scanning for precise localization

# PET

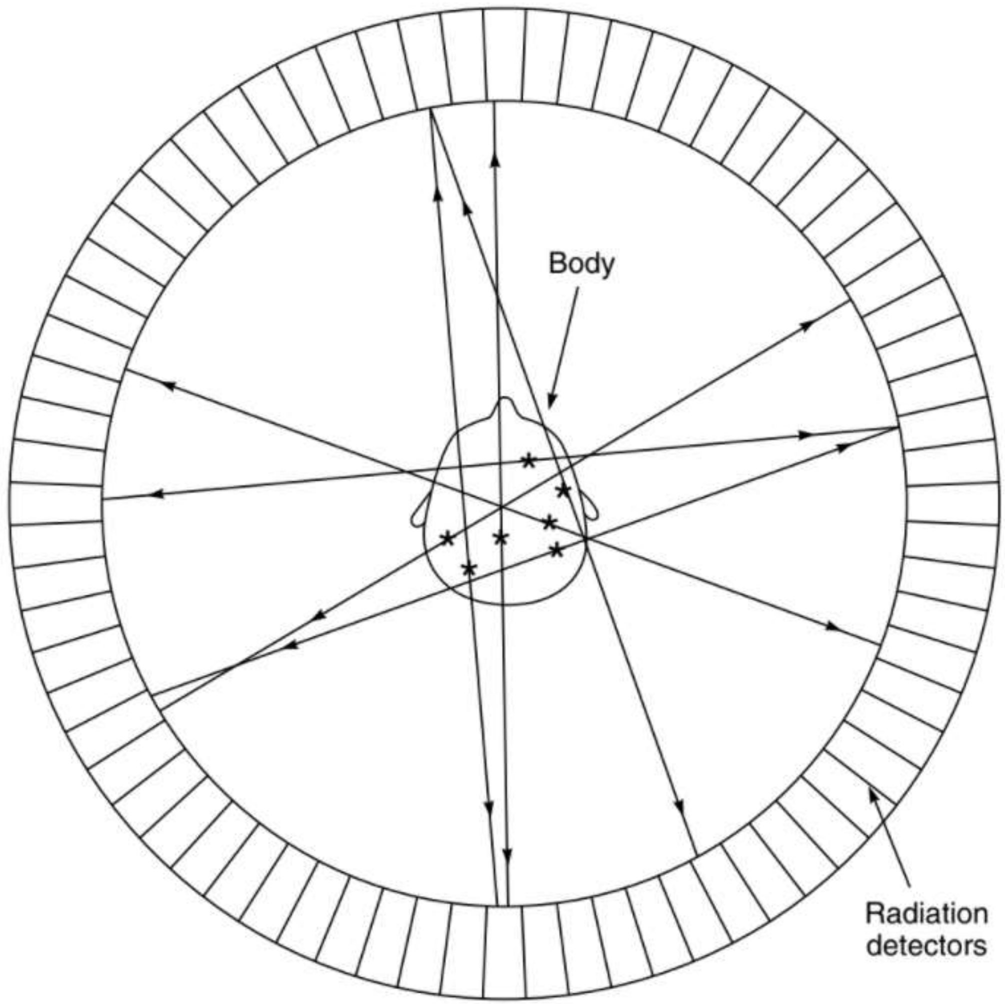
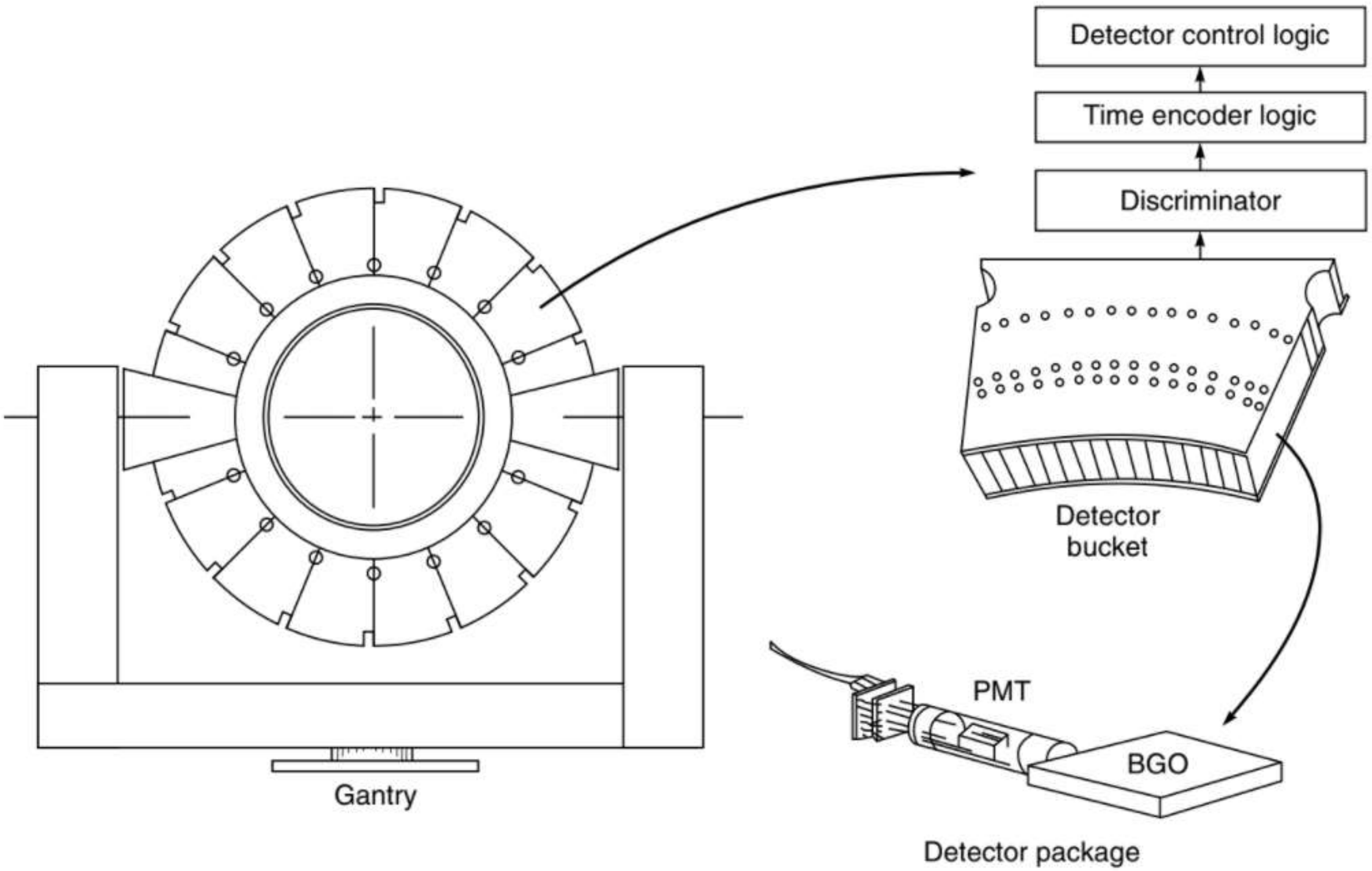



Fig. 21.17 *Principle of positron emission tomography (PET Scanner)*

# PET




➤ **Fig.** 21.19 *Gantry and detector modules used in PET Scanner (after Hoffman et al. 1985)*

# PET – DATA ACQUISITION SYSTEM

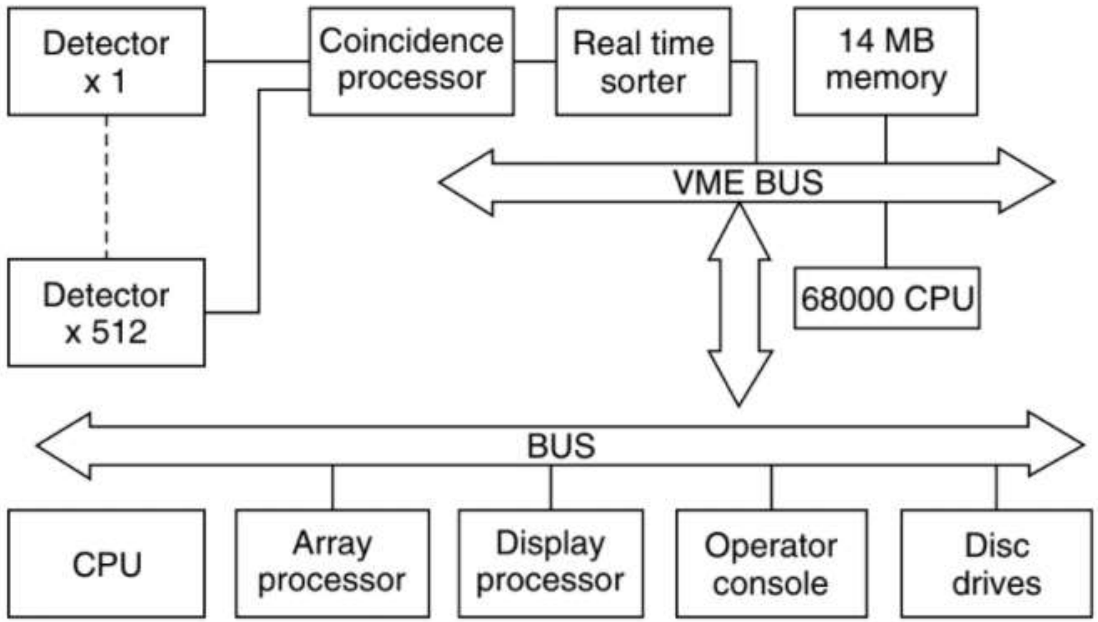



**Fig.** 21.20 *Data acquisition system for a PET Scanner (after Hoffman et. al. 1985)*

# PET – DATA ACQUISITION SYSTEM

- Distributed processors are used throughout the system to maximize speed for simultaneous data collection.
- Individual and analog detector signals are amplified and the time of interaction is then determined using a constant fraction discriminator.
- A time encoder converts the event into a 14 bit word containing the detector number and event time within 8 ns. This word is passed to the coincidence processor every 224 ns.
- The energy window is controlled automatically by the microprocessor located in each detector bucket. A threshold of 200 keV is typically used to allow for detection of gamma rays that have been scattered within a detector and escaped.
- The system consists of a fan beam geometry with an angular sampling of 0.7 degrees. The linear sampling is 2.9 mm.

# POSITRON EMISSION TOMOGRAPHY

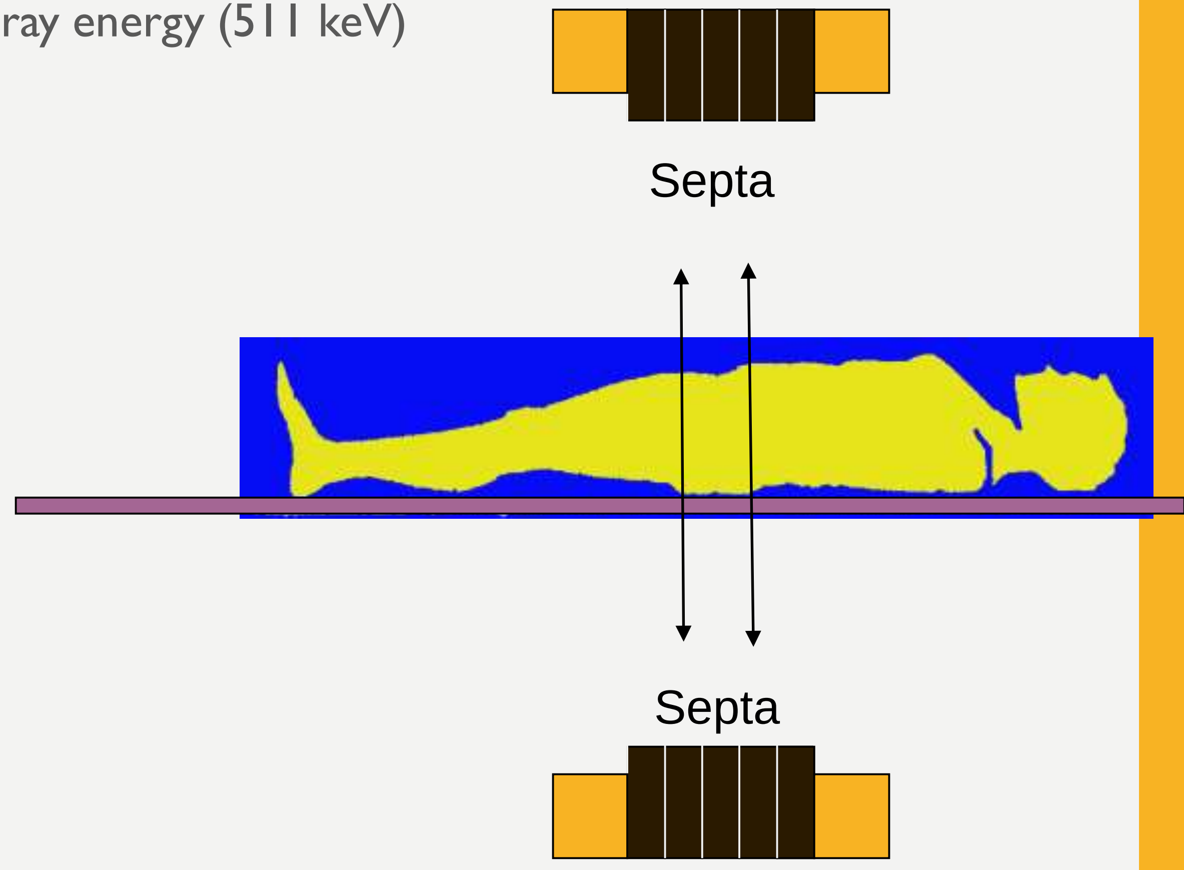
- Oncology - Lung Cancer
- Metastases
- Obstructed right ureter
- Function
- Metabolism

# PET SCANNER

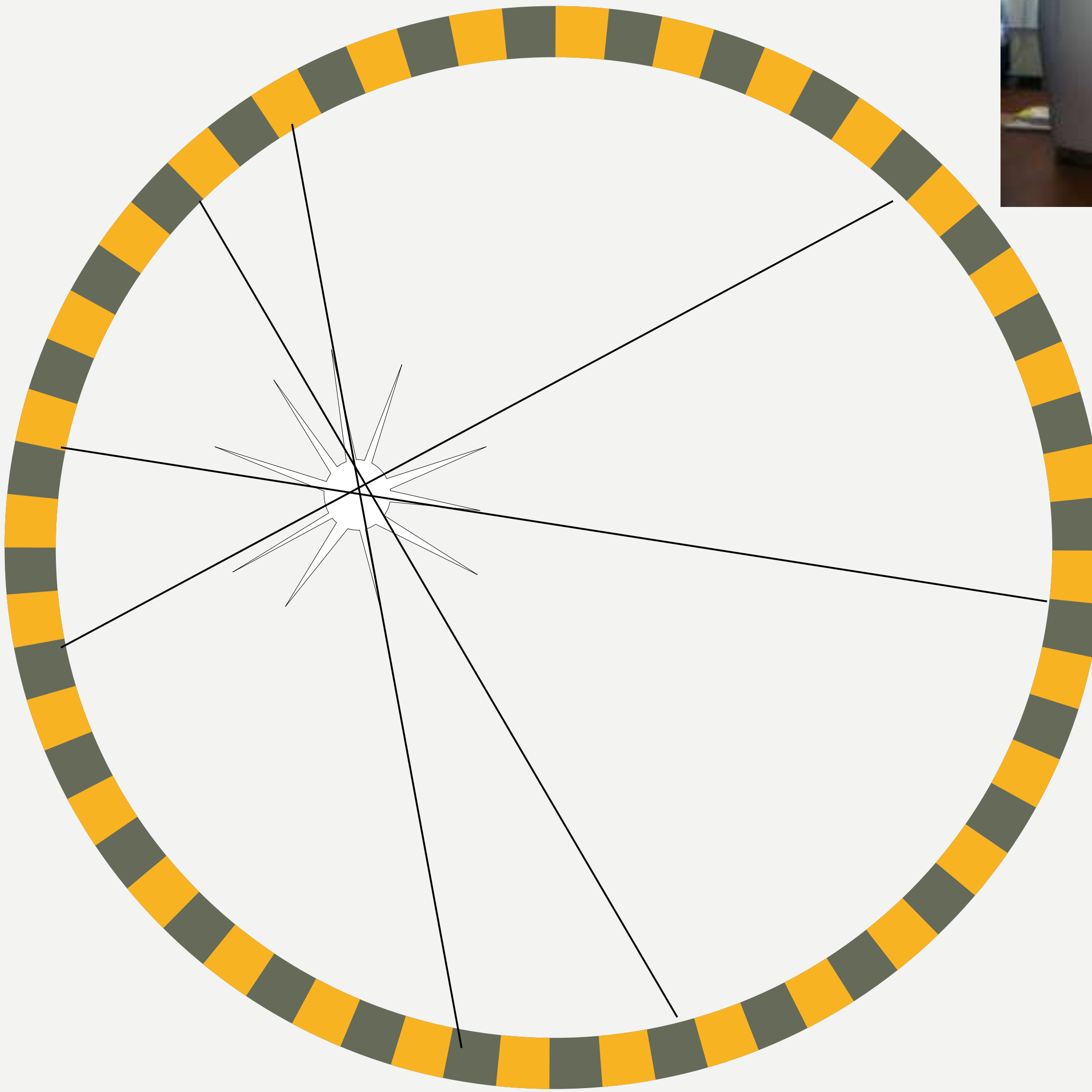
- Ring (multiple rings) with lots of little detectors (up to 23,040)
- Rings have axial coverage of up to 26cm.
- Detectors must have good stopping power
- Detector must be fast for accurate coincidence measurements

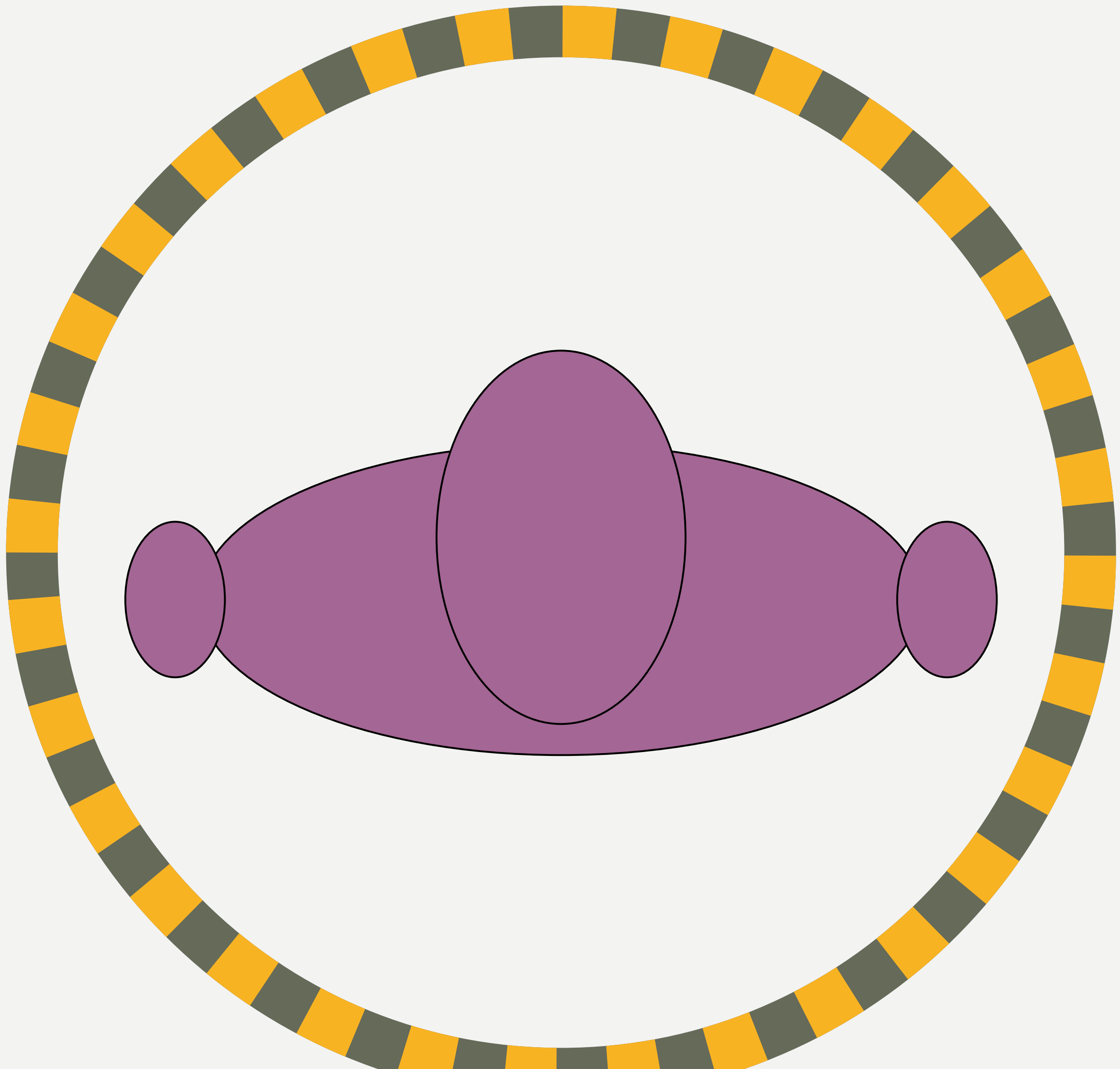
# PET SCANNER

- PET scanners lack conventional collimation so they have a high geometric efficiency
- Some had septal rings to reduce cross talk from ring to ring
- Detector should have high Stopping Power
  - Much higher gamma ray energy (511 keV)

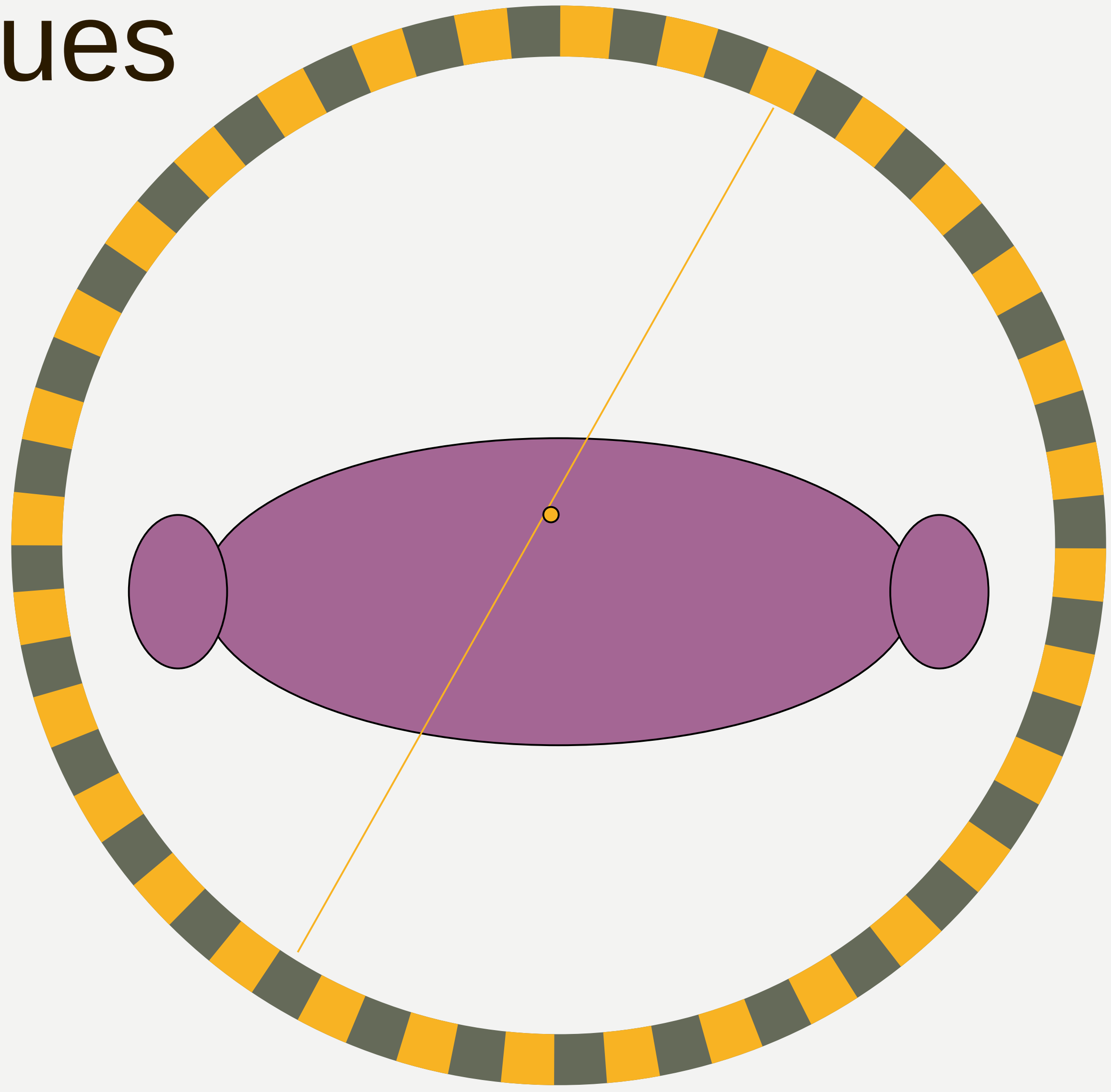


# EVENTS IN PET SCANNERS





# Trues



# CORRECTIONS

- PET scanners use energy discrimination (pulse height analysis) system like the gamma camera to help eliminate scatter
- Randoms are corrected for by measuring coincidence rates with a delay of time between 511 keV photon arrivals (so there are no trues).

# ATTENUATION CORRECTION

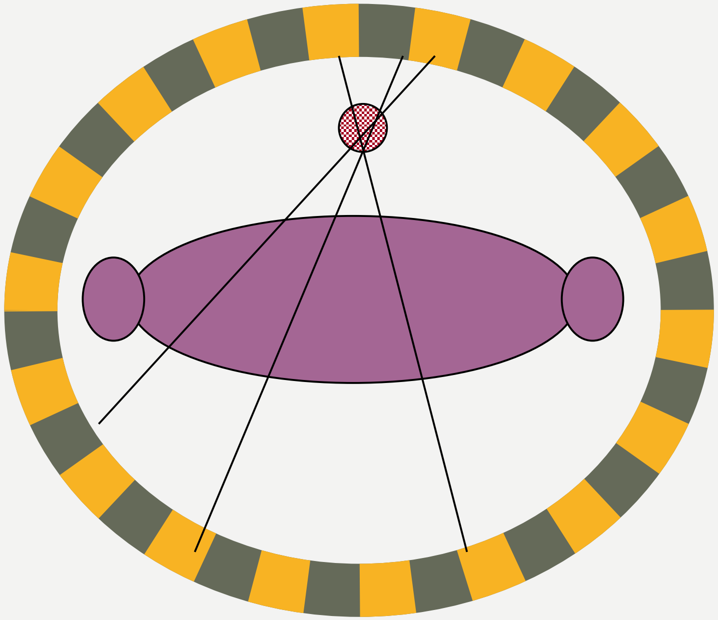
Like all radionuclide imaging there is a problem due to attenuation.

- It is much less for PET than for Tc-99m imaging

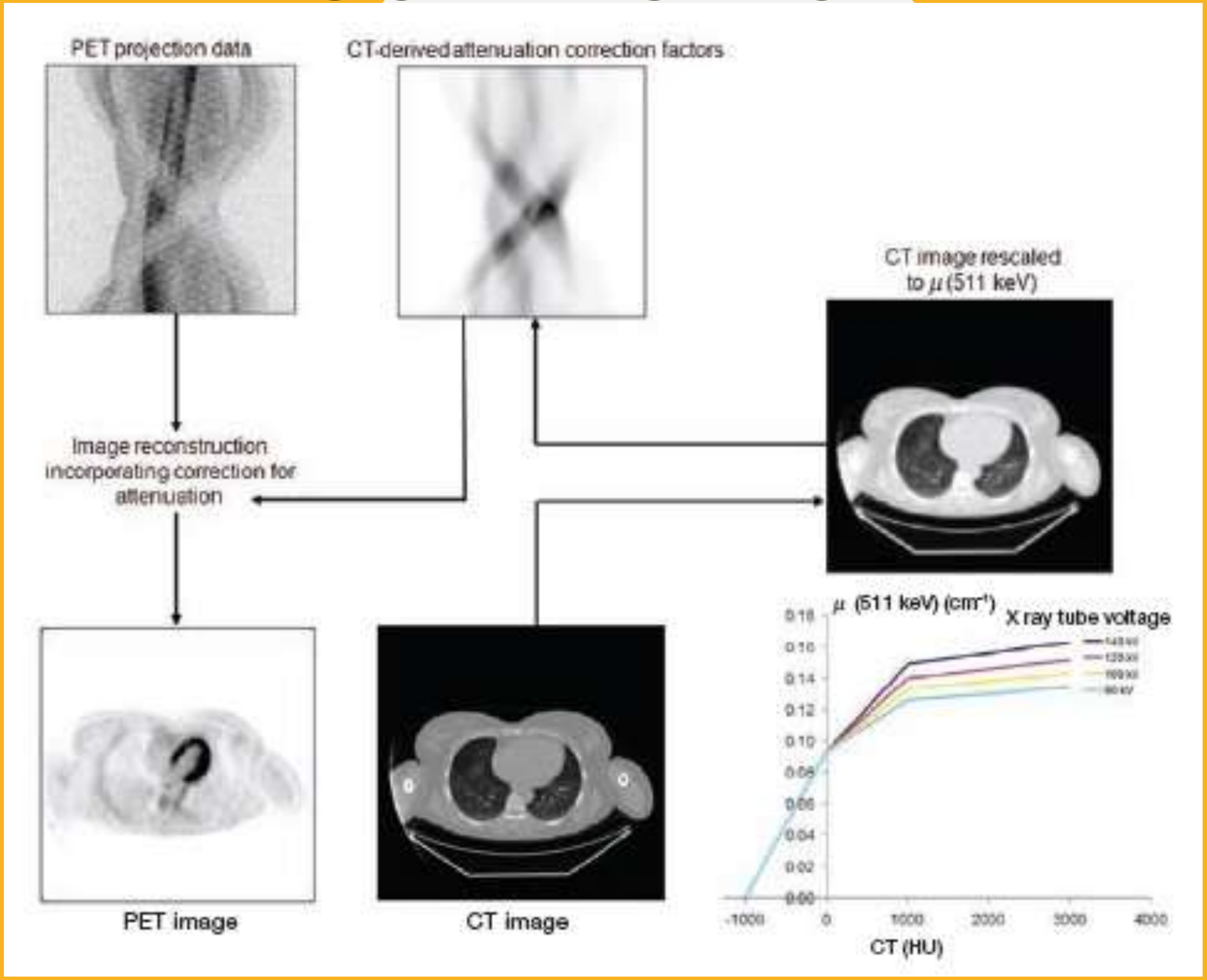
Correction is important for quantifying the metabolic activity of lesions (SUVs)

# ATTENUATION CORRECTION

- CT data reconstructed to make a attenuation map of the body
  - Attenuation map information is used in image reconstruction



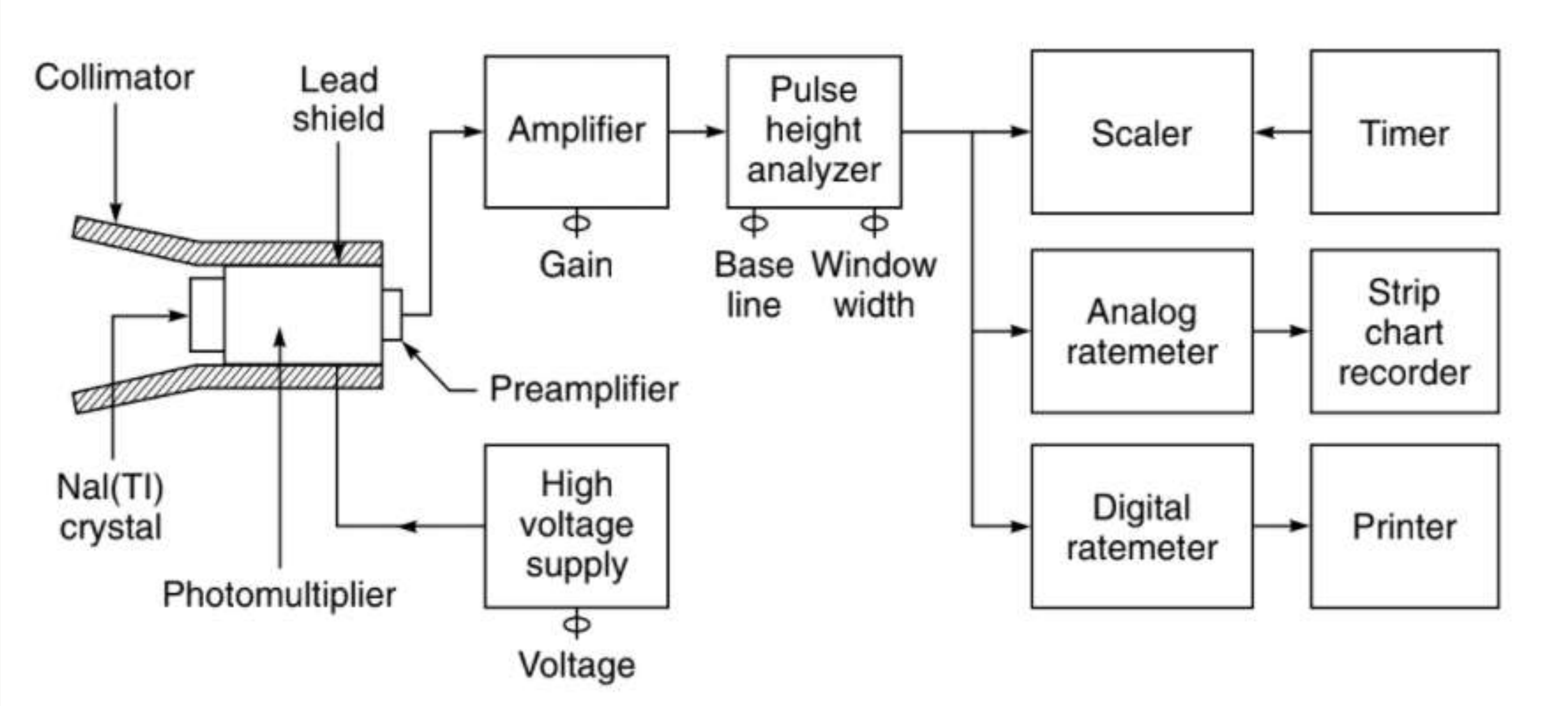
# PET: CT BASED ATTENUATION CORRECTION



# UPTAKE MONITORING EQUIPMENT

- The clinical use of a radio-nuclide in medical investigations depends on obtaining a suitable distribution of the radio-nuclide in the patient. This is achieved by administering a suitable chemical substance tagged with a radio-nuclide, emitting gamma radiations.
- The biological system under investigation selectively assimilates the administered dose to carry out its function.
- Since the gamma ray gets transmitted through the body tissues, an external monitoring system can be used to detect them and provide the measurement of the chemical substance. The fraction of the chemical present in the organ at any time would indicate the functional status or what is called the uptake of the organ. The most suited gamma energy range for uptake monitoring studies is from 100 keV to 500 keV.

# GAMMA COUNTING SYSTEM FOR IN VIVO MEASUREMENTS



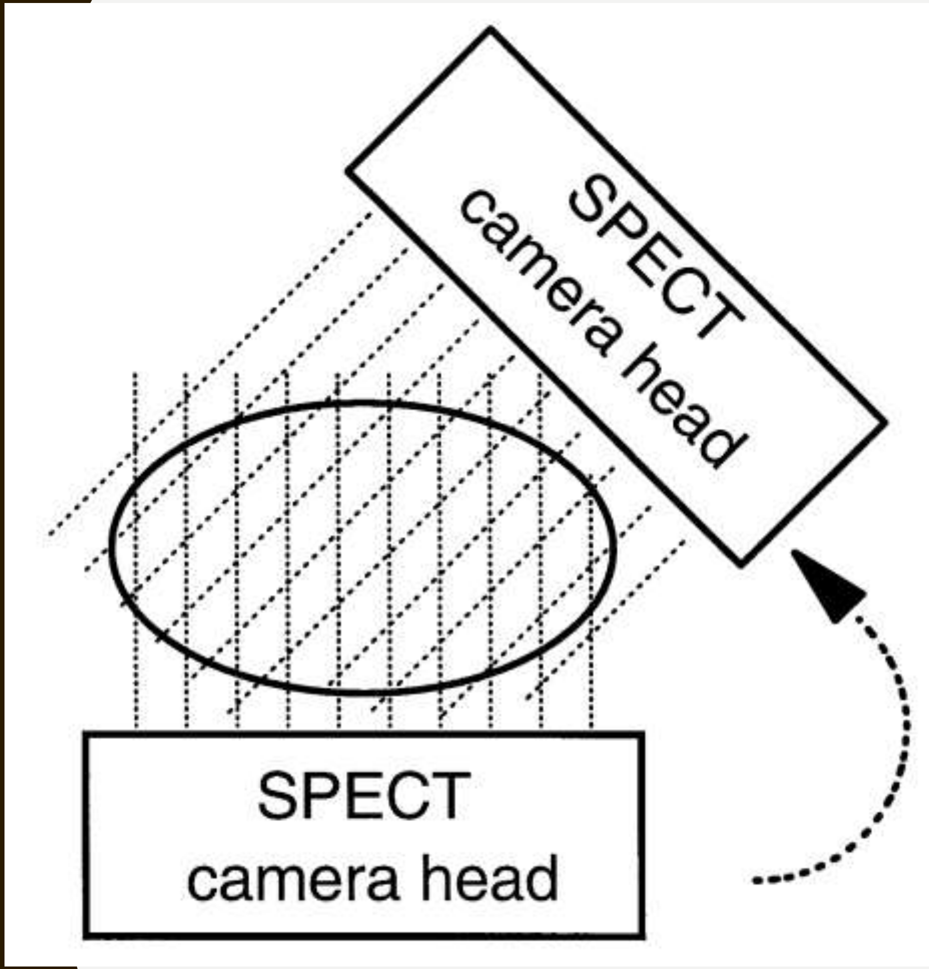
# GAMMA COUNTING SYSTEM FOR IN VIVO MEASUREMENTS

- It basically makes use of a NaI (TI) scintillation crystal for detection of gamma rays. This is followed by the photo-multiplier which converts the scintillations into an electrical signal.
- The output from the photo-multiplier is given to a pre-amplifier followed by a pulse shaping circuit and a pulse height analyser.
- The output of the analyser drives a counter/timer which displays the information on a digital counter and a strip chart recorder.
- A vital component in the system is the collimator the function of which is to exclude from the detector all gamma rays except those travelling in the preferred direction.

# GAMMA COUNTING SYSTEM FOR IN VIVO MEASUREMENTS

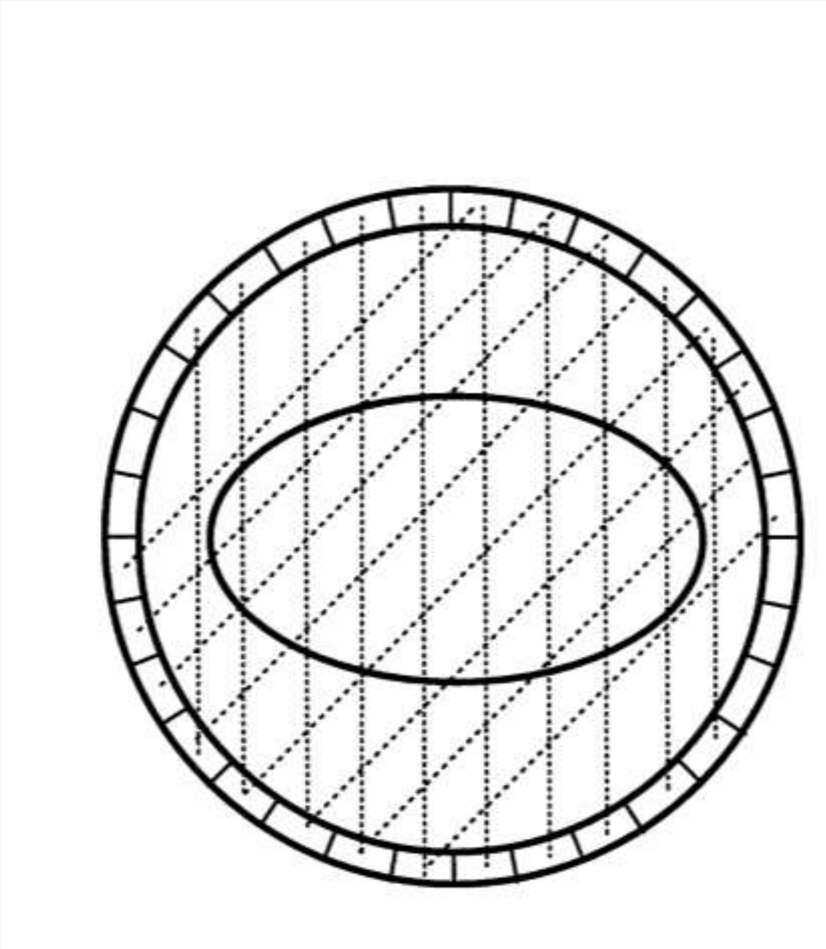
- A simple collimator consists of a single tapered hole in a cylindrical lead block.
- The sides of the lead block must be sufficiently thick to absorb the majority of the gamma rays impinging obliquely, and the detector must be surrounded by an adequate thickness of lead to effectively shield it from all gamma rays except those entering through the aperture.
- The shielded and collimated detector is called a probe.
- The probe is mounted on an adjustable support allowing it to be appropriately positioned in relation to the patient. The measurement can be carried out using the single probe or multi-probe counting system.

# SPECT VS PET




**SPECT**

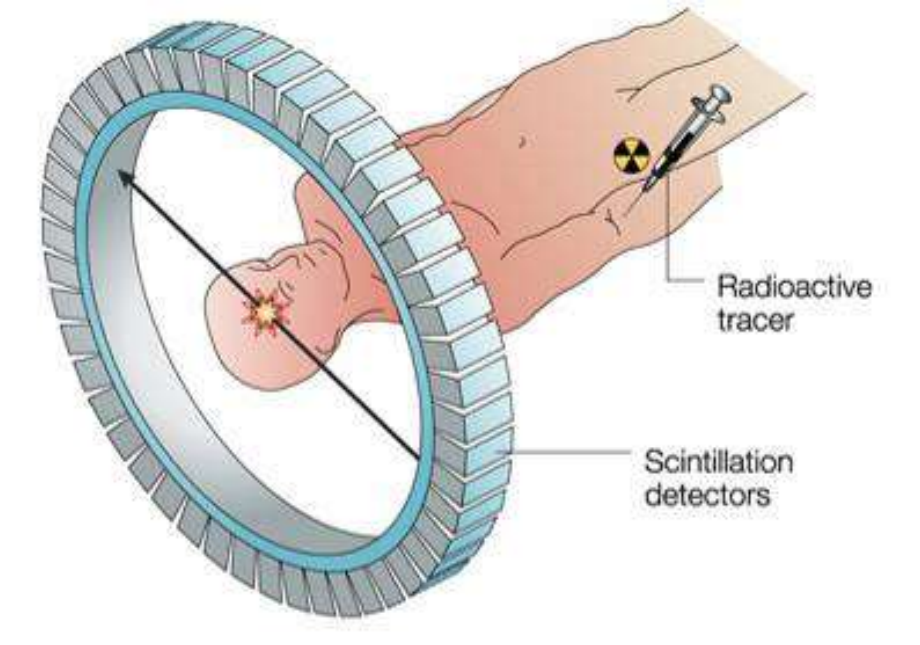
(Step-and-shoot acquisition)



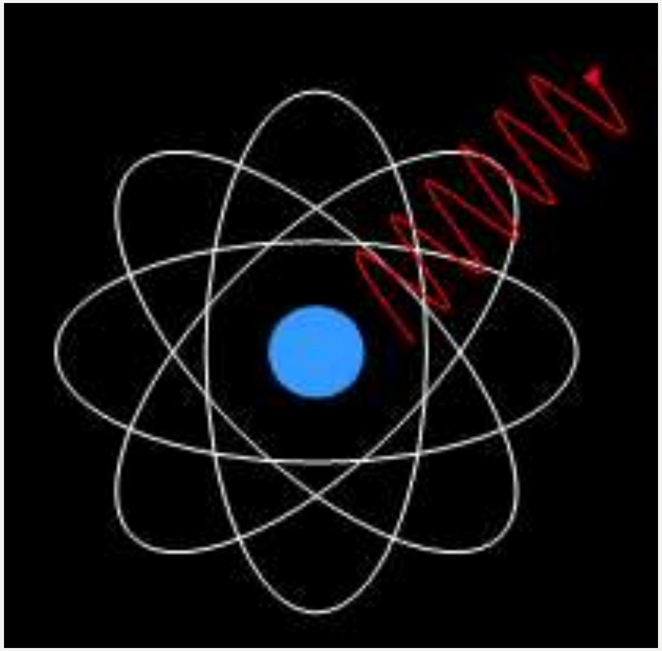
**PET**

(Simultaneous acquisition)

# PET AND SPECT IMAGING




Positron Emission Tomography

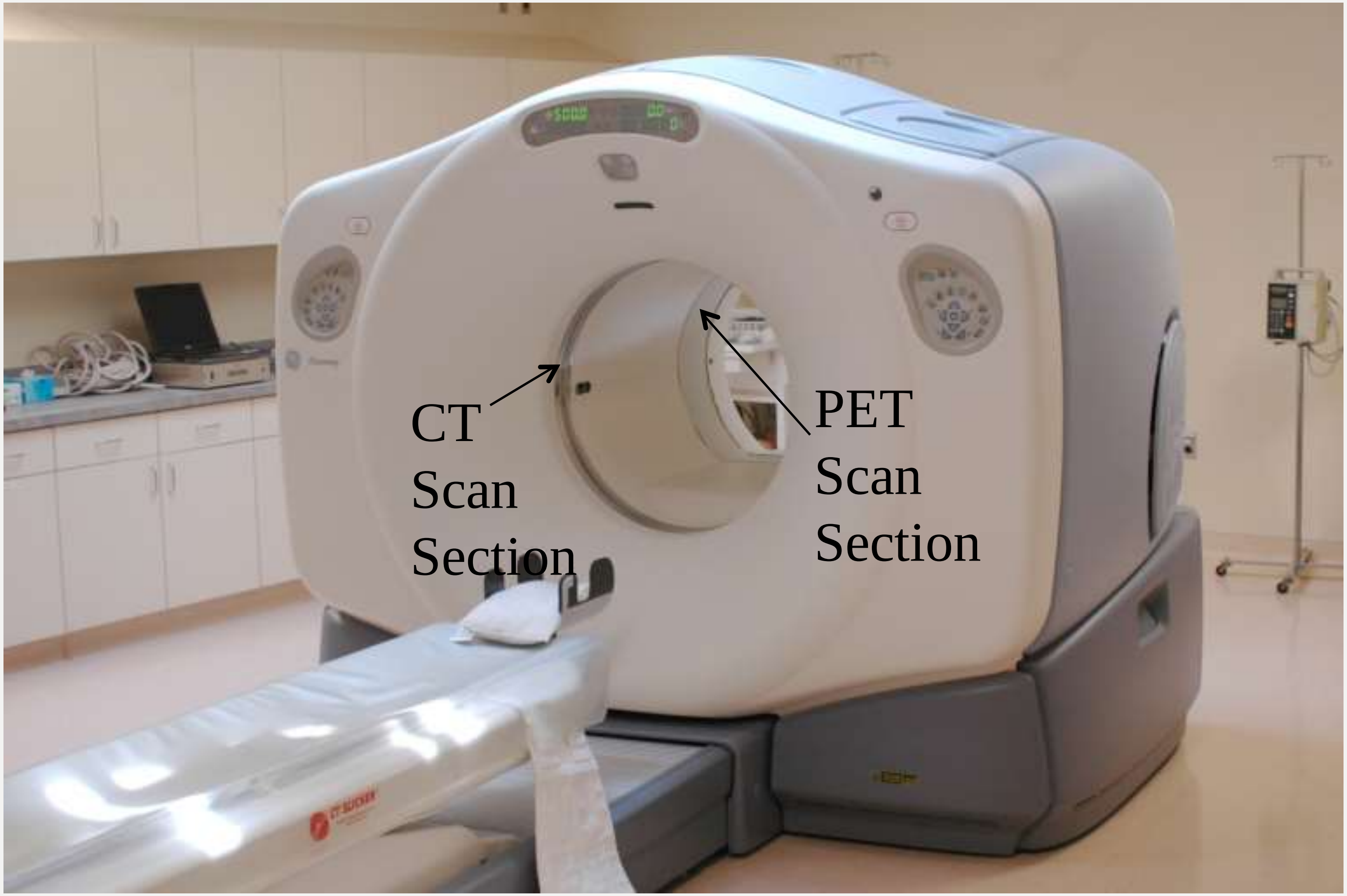


Single Photon Emission Computed Tomography

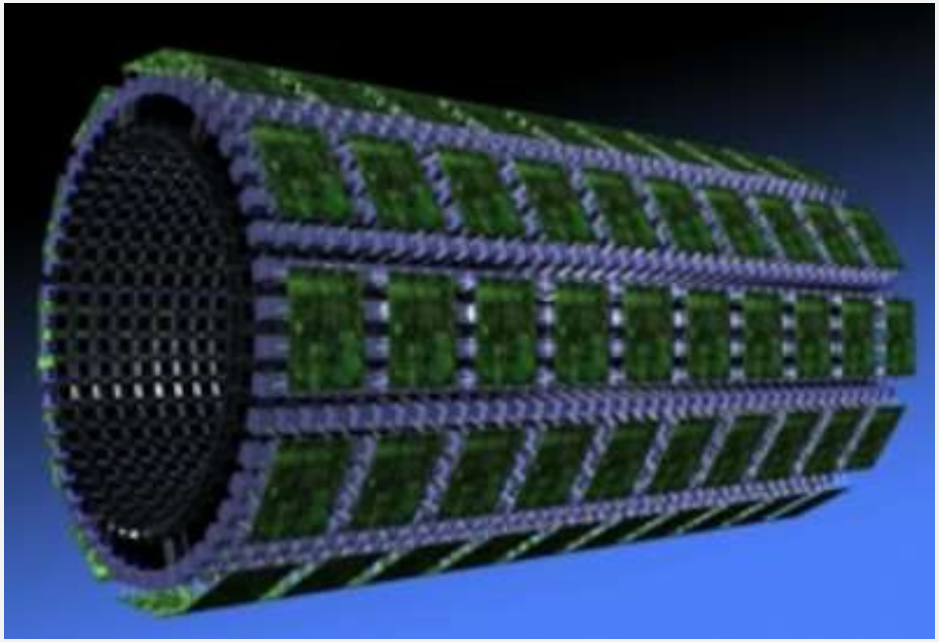
# SPECT & PET

- SPECT – 2 views from opposite sides
  - Res. ~ collimator res., which degrades rapidly with increasing distance from collimator face
- PET – Simultaneous acquisition
  - Res. ~ detector width; is max in center of ring
- SPECT sensitivity ~ 0.02%
  - Huge losses due to absorptive collimators
- PET sensitivity- 2D ~ 0.2%; 3D ~ 2% or higher
  - High sensitivity due to ACD (electronic collimation)
  - Allows higher frequency filters / higher spatial resolution

# CT- PET



- October 7, 2015 -- Researchers at the University of California, Davis (UC Davis) have received a five-year, $15.5 million grant to develop what they are calling the world's first total-body PET scanner.
  - The total-body PET scanner would image an entire body all at once, and it would acquire images much faster or at a much lower radiation dose by capturing almost all of the available signal from radiopharmaceuticals. … the design would line the entire inside of the PET camera bore with multiple rings of PET detectors.
  - such a total-body PET design could reduce radiation dose by a factor of 40 or decrease scanning time from 20 minutes to 30 seconds



http://www.auntminnie.com/index.aspx?sec=sup&sub=mol&pag=dis&ItemID=112051

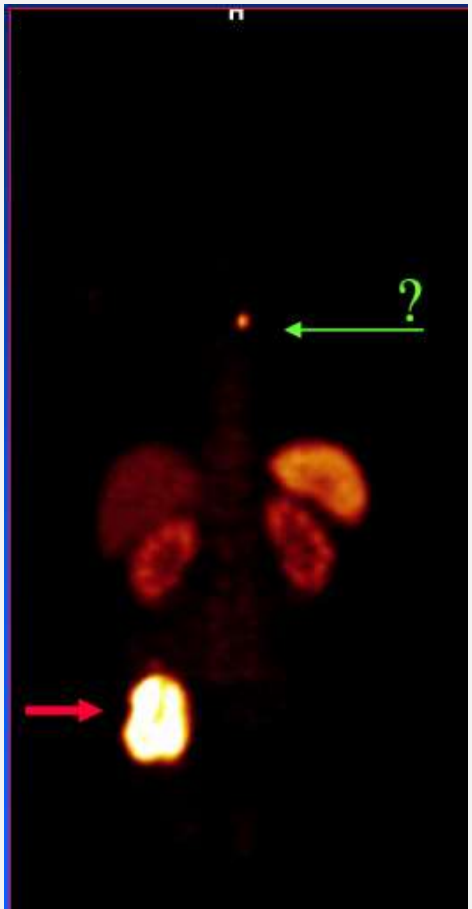
# WHAT ARE THE BENEFITS VS. RISKS?

- Because PET allows study of body function, it can help physicians detect alterations in biochemical processes that suggest disease before changes in anatomy are apparent with other imaging tests, such as CT or MRI.
- Because the radioactivity is very short-lived, your radiation exposure is low. The substance amount is so small that it does not affect the normal processes of the body.
- PET can give false results if a patient's chemical balances are not normal. Specifically, test results of diabetic patients or patients who have eaten within a few hours prior to the examination can be adversely affected because of blood sugar or blood insulin levels
- Value is enhanced when done along with a CT or MRI

- However, it does not give structural details hence exact localization and measurements need support of another modality
- Resolution is less

# ADVANTAGES OF DUAL MODALITY

PET

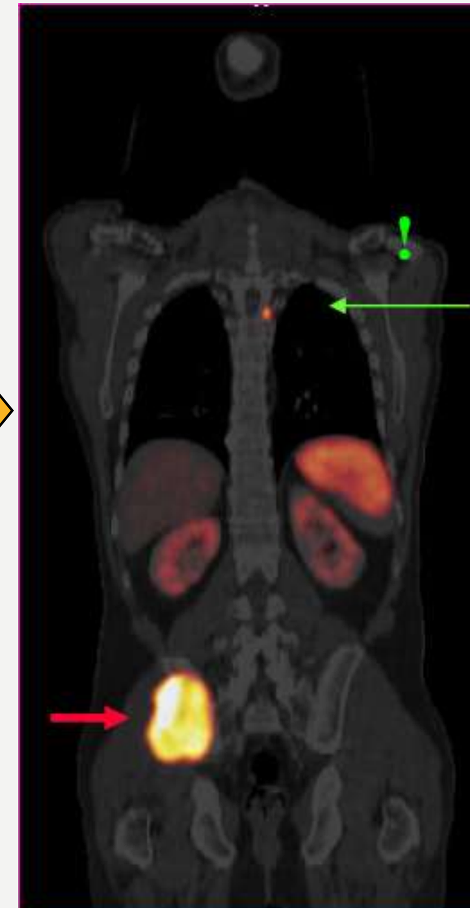



Only Functional Information

CT


Only Anatomical Information

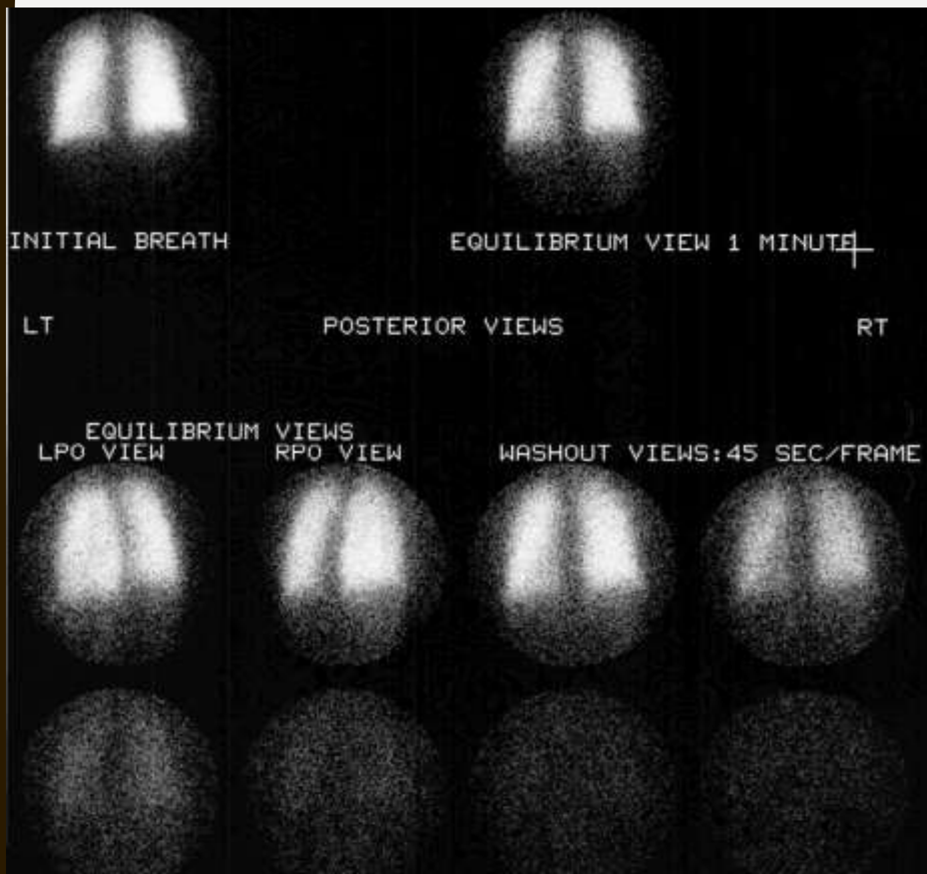
PET/CT



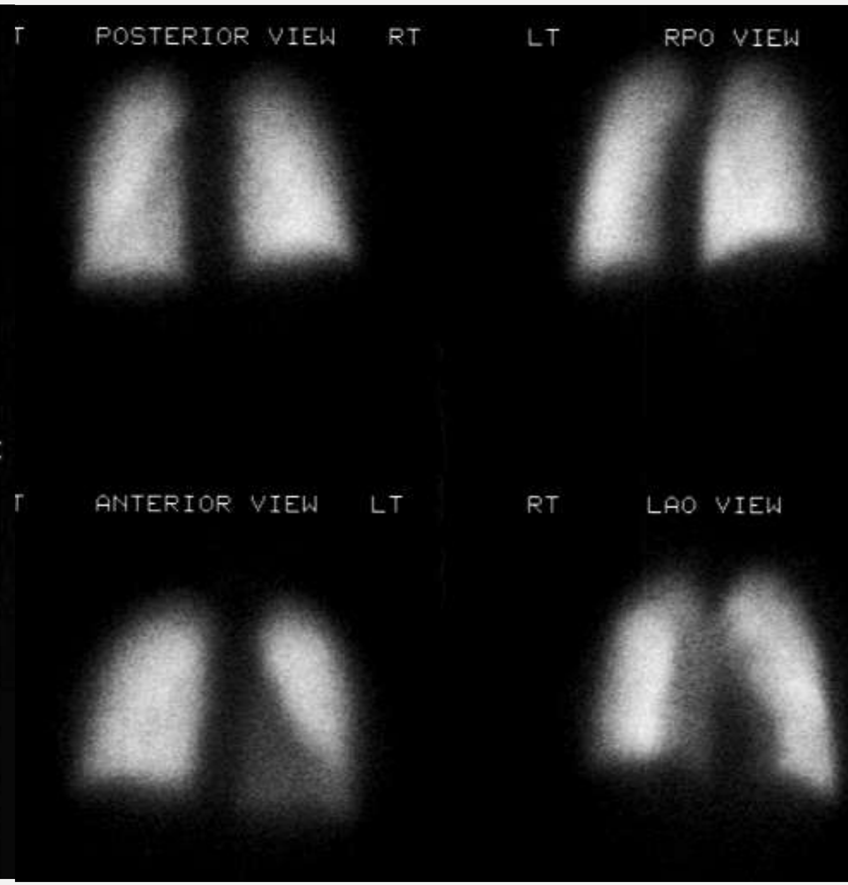

Both Functional and Anatomical Information

# BONE SCAN

# LUNG SCAN



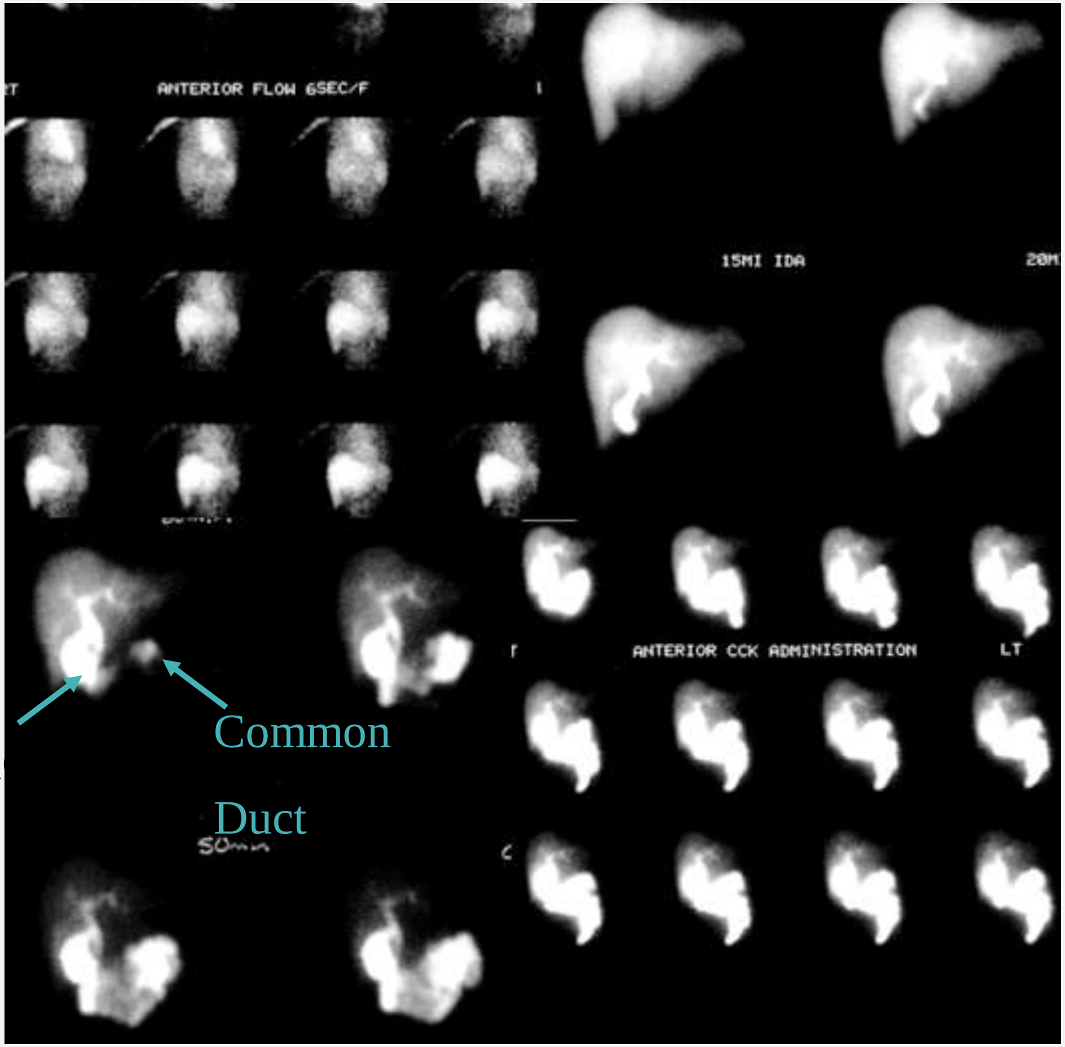

Ventilation




Perfusion

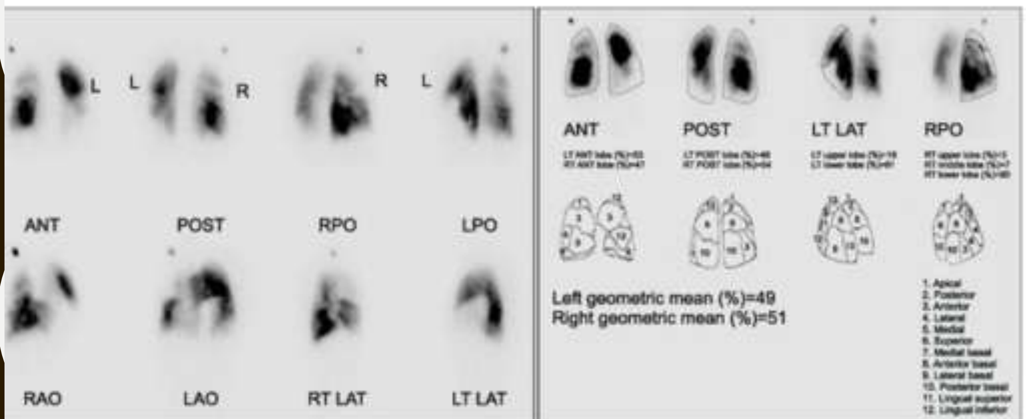
# HIDA SCAN - HEPATOBILIARY IMINODIACETIC ACID (HIDA)

Gallbladd




hepatobiliary scintigraphy

# HIDA SCAN – HEPATOBILIARY IMINODIACETIC ACID (HIDA)




## Figure

Caption

Figure 2. A lung perfusion scan was performed, and large-size perfusion defects were found in the anterior segment of the right upper lobe and superior and inferior segments of the left upper lobe. ANT: anterior; POST: posterior; LT: left; RT: right; LAT: lateral; RPO: right posterior oblique; LPO: left posterior oblique; RAO: right anterior oblique; LAO: left anterior oblique.