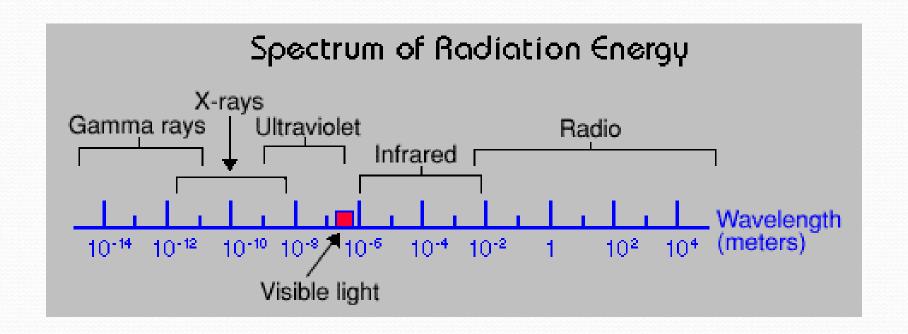


# Physics of Diagnostic X-rays



# What are X-rays?



# What are X-rays?

Made of photons

Travel at speed of light

Travels in a straight line

Has no mass nor charge (cannot be focused by magnets)

X-ray beam has a mix of energies

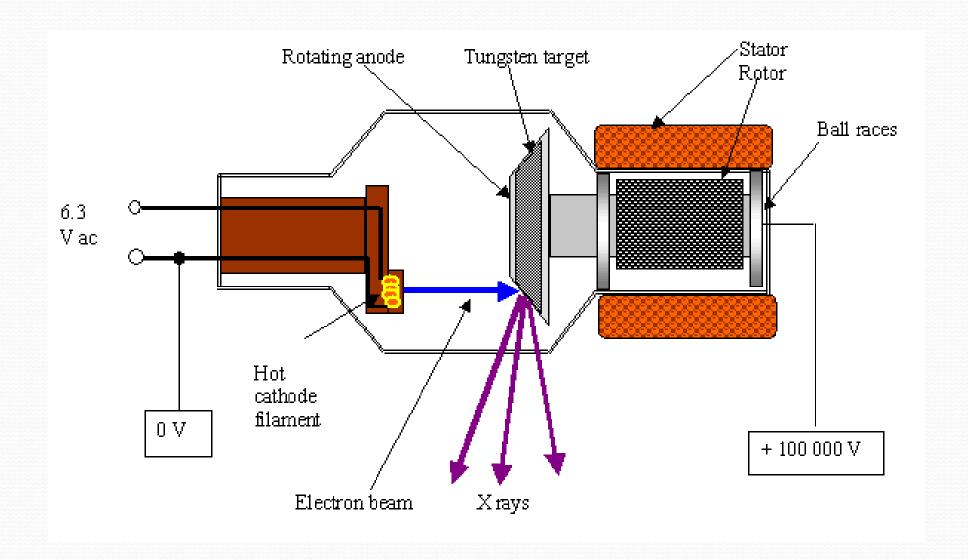
Maximum energy in a beam = kVp

Diagnostic X-ray range 20-150 kVp



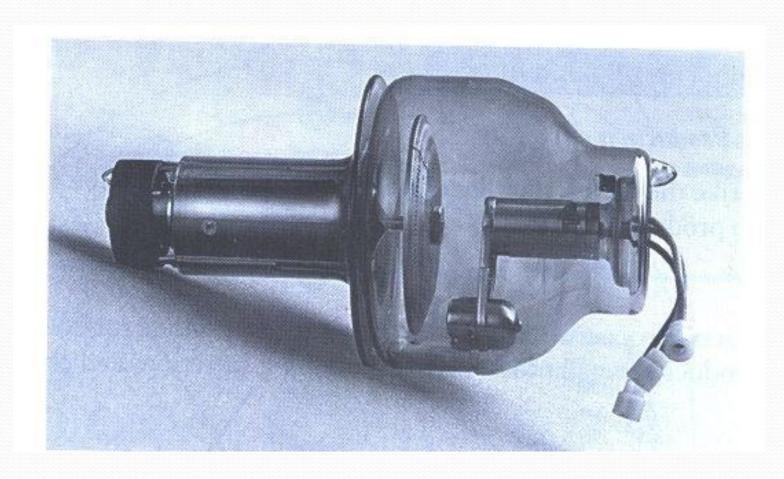
#### • X-ray production:

- To produce photons of x-ray we need:
- 1. A filament (Cathode): This is a source of electrons.
- 2. An evacuated space in which to speed up the electrons.
- 3. A high positive potential to accelerate the negative electrons.
- 4. A target ((anode )): which the electrons strike to produce x-rays.





# The X-ray tube



## The X-ray tube parts:

#### Cathode (-)

Filament made of • tungsten

Anode (+) target

Tungsten disc that • turns on a rotor

#### Stator

motor that turns the rotor

#### Port

Exit for the x-rays •

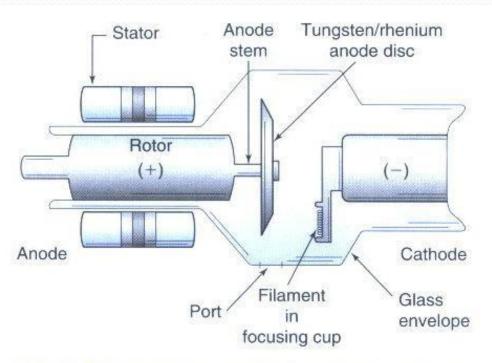
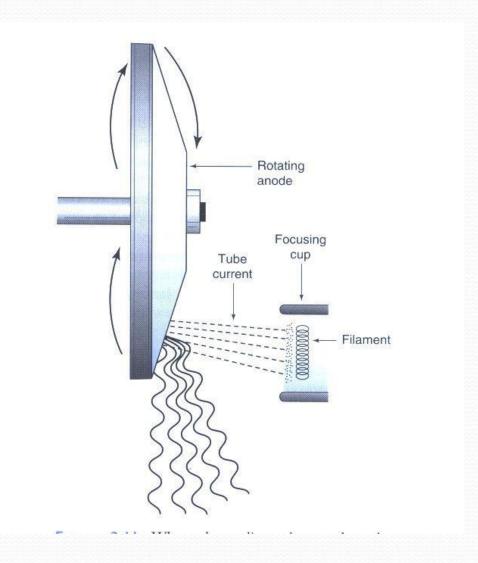


FIGURE 2-5 Structure of a typical x-ray tube, including the major operational parts.

## X-ray production

- Push the "rotor" or "prep" button
- Charges the filament causes thermionic emission (e- cloud)
  - Begins rotating the anode. •
- Push the "exposure" or "x-ray" button
- e-'s move toward anode target to produce x-rays



# Hitting the target



e-'s hitting the target creates x-rays two different ways:

Characteristic x-rays – are due to the material the e-'s hit (tungsten). Only occurs above 70 kVp

Bremsstrahlung (braking) x-rays – due to slowing down of e- beam.

- < 70 kVp 100% of X-rays are of this type
- > 70 kVp 85% of X-rays are of this type

#### Some notes about x-ray generation:

- 1- High speed electron can convert some or all it's energy into an x-ray photons when it strikes an atom, and thus we need to speed up electrons to produce x-rays.
- 2- An x-ray tube that produced electrons by "boiling" them off a red-hot filament.

- 3-The intensity of the x-rays beam produced is highly depend on the anode material, which preferred to has:
  - a. high atomic number. b. high melting point.
- Example: Tungsten is more preferred:
  - I. It's atomic number (z) = 74.
  - II. It's melting point = 3400c.

- 4-The number of electrons accelerated towards the node depend on: Temperature of the filaments.
- 5-The kilovolt peak used for an x-ray study depends on:
  - a- Thickness of the patient.
  - b- Type of study being done.
- 6-The advantage of the rotating of the node is to avoid overheating of the anode, because the overheating produce a damage of the node.

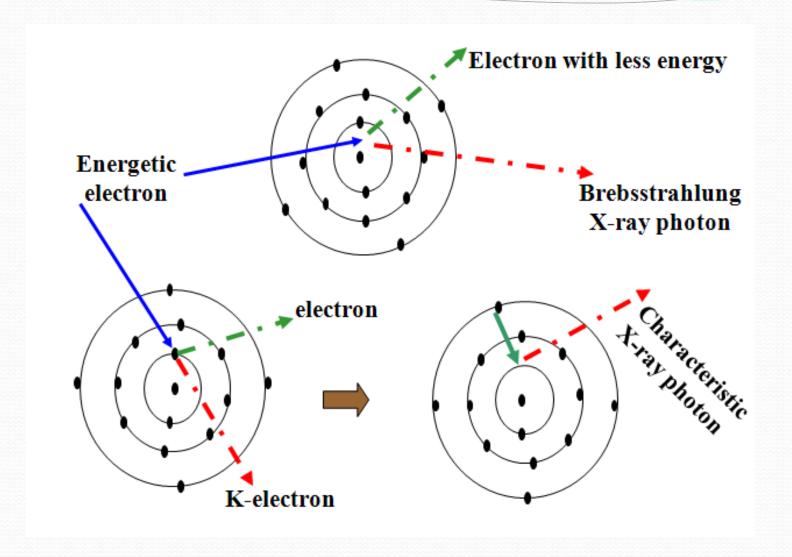
### **Types of x-ray:**

There are two types of x-rays:

- 1-Characteristic x-ray:
- 2- Bremsstrahlung x-ray:

#### 1-Characteristic x-ray:

• A fast electron strikes a K electron in a target atom and knocks its out orbit and free of the atom. The vacancy in the K-shell is filled almost immediately when an electron from an outer shell of the atom falls into it, and in the process. a characteristic K x-ray photon is emitted.



• The emitted photon is named according to the shell of the stroked electron. For example: - K characteristic x-ray or L characteristic x-ray.

#### An x-ray photon emitted when:

- 1. An electron falls from the L-level to the K-level is called  $K\alpha$  characteristic x-ray.
- 2. An electron falls from the M-level to the K-level is called  $K_{\beta}$  characteristic x-ray

• The energy of the emitted photon depends on the energy difference between the shell that have the vacancy and the outer shell (which the electron fills from it).

#### • Bremsstrahlung x-ray:

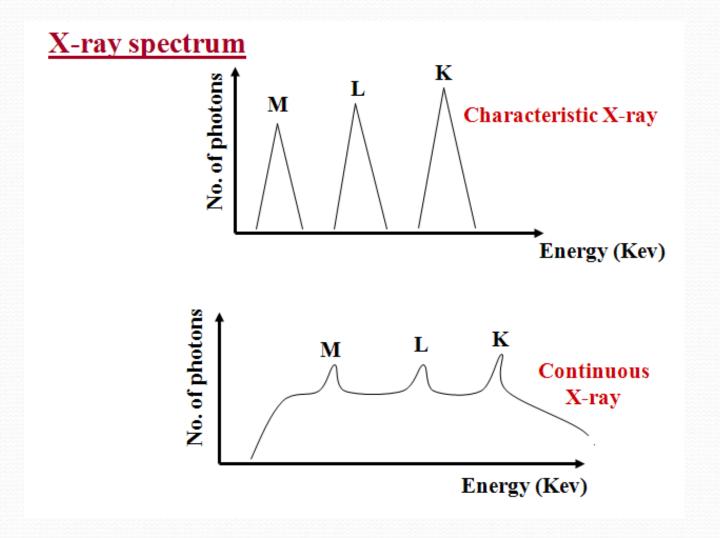
This type of x-ray is produced by the sudden deaccelerating of high energy electron. When the electron gets close enough to the nucleus of the target atom to be diverted from its path.

• This type also called "white radiation" because it's analogous to white light and has a range of wave length.

#### It depend on:

- A: 1- Z of the target.
  - 2- The more protons in the nucleus.
  - 3- The greater acceleration of the electrons.
- B: The kilovolt peak: The faster electrons are more likely to penetrate to the nucleus region.

The spectrum of x-rays produced by x-ray generator is shown in figure 16.8, page: 395. The broad smooth curve is due to the bremsstrahlung, and the spikes represent the characteristic x-rays.



### How x-rays are absorbed:

- X-ray are not absorbed equally well by all materials. Heavy elements such as calcium are much better absorbers of x-rays than light elements such as Carbon.
- To understand the absorption of x-ray, we need to study the properties of the x-ray.

#### 1- The attenuation:

It's the reduction of an x-ray beam due to the absorption and scattering of some of the out the beam. To measure the attenuation beam intensity  $I_0$  we use:

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

where:

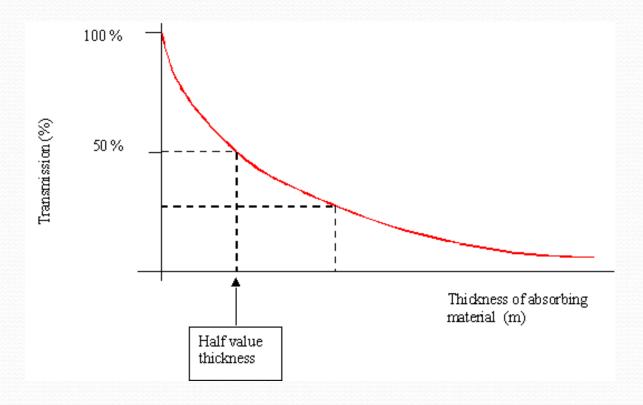
e: Base of natural logarithm = 2.7

I: The final intensity of x-rays beam.

I<sub>o</sub>: attenuated intensity. (original intensity).

x: Thickness of the attenuator (The target).

μ: The linear attenuation coefficient of the attenuator (which is depend on the energy of x-ray photon).



The linear attenuation coefficient of the attenuator  $(\mu)$  was related with half-value layer according to this equation:

$$\mu$$
= 0.693/ HVL

HVL: The thickness of a given material that will reduce the beam intensity by one half.

### 2- Biological effect of an x-rays beam.

• Mass attenuation coefficient: it's used to remove the effect of density when comparing attenuation in several materials.

Mass attenuation coefficient= Linear atten. coeff.
 density of material

$$\mu_m = \mu/\rho$$

•  $\mu_m$  will be in cm<sup>2</sup> /gm

Then

$$I = I_o e^{-(\mu/\rho)\rho x}$$

Therefore

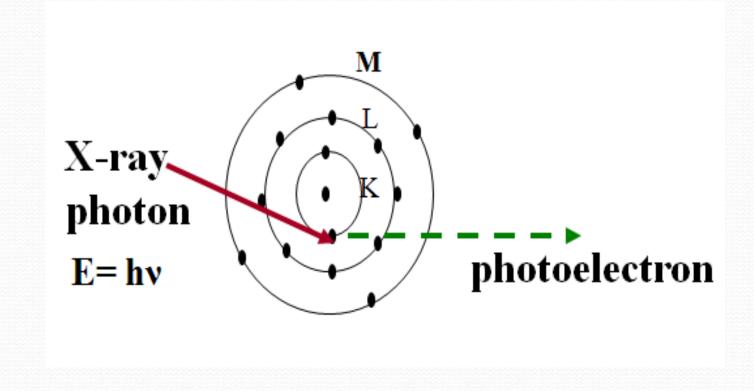
$$I = I_o e^{-\mu m \rho x}$$

### X-ray interaction with matter:

- There are three types of interaction between the x-rays and matter. Or x-rays lose energy in three ways:
- 1-Photoelectric effect
- 2- Compton effect
- 3- Pair-production

## 1- Photoelectric effect

Its occurs when the incoming x-ray photon transfer all of its energy to an electron which then escapes from the atom.



### Characteristics of Photoelectric effect:

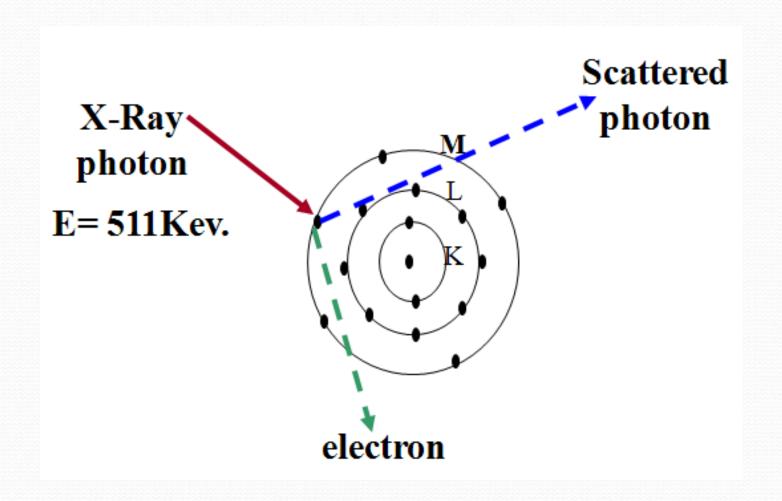
- 1. It's more apt to occur in the intense electric field near the nucleus.
- 2. It's more common in elements with high Z than in those with low Z.
- 3. The photoelectron uses some of its energy (the binding energy) to get away from the positive nucleus and the reminder will be as a kinetic energy for the electron.

4. The energy used about 30 Kev of x-ray photons.

5. Used more than Compton effect in diagnosis. Especially the bones and heavy materials such as bullets in the body.

### 2- Compton effect

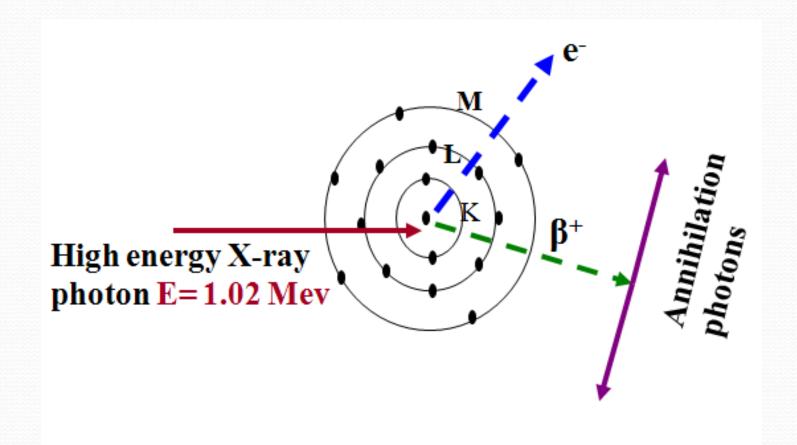
- 1. It occurs by collision of an x-ray photon with an loosely bounded electron.
- 2. More apt to occurs at the outer electrons.
- 3. The energy used usually more than 100 Kev.
- 4. It usually done at low atomic number (Z) materials.
- 5. Used also in diagnosis especially the soft tissue.



### 3- Pair-production

#### Its occur when:

- 1. A very energetic photon enters the intense field of the nucleus, and converted into two particles: an electron and a positron ( $\beta$ +), or positive electron.
- 2. This energetic photon providing the mass for the two particles requires a photon with energy of at least 1.02 Mev and the remainder of the energy over 1.02 Mev is given to the particles as a kinetic energy.



- 3. The positron is a piece of antimatter. After it has spent its kinetic energy in ionization it does death dance with an electron.
- 4. Both then vanish, and their mass energy usually appears as two photons of 511 kev each called (annihilation radiation).
- 5. Pair-production is more apt to occur in high Z elements than in low Z elements.

#### Contrasting:

This technique is made to make further use of the photoelectric effect. This done by injected high Z material into different parts of the body which are called (Contrasting media).

#### Examples:

- 1. Compound containing iodine is injected into a blood stream to show the arteries.
- 2. Oily mist containing iodine is sometimes sprayed into the lungs to make the airways visible.
- 3. Barium enemas to view lower GI system.
- 4. Barium compound is given orally to see parts of the upper gastrointestinal tract.

#### X-ray slices of the body

- On an ordinary x-ray image the shadows of all the objects in the path of x-ray beam are superimposed, and thus the shadows of normal structures may mask or interface with the shadows that indicate disease.
- In order to distinguish the shadows indicating disease (so, avoid problem above) the radiologist often takes x-ray images from different directions, such as from the back, the side, and an intermediate angle.

- The ways that used for taking x-ray image of slices are:
- **1- Tomography:** x-ray images of slices of the body, or body section radiography.
- **2- Axil tomograph:-** is an image of slice across the body and is taken by rotating the x-ray tube and film around the patient.
- **3- Computerized axil tomography (CAT)** or Computerized tomography (CT): It is use of a technique for analyzing data by computer.

The technique for (CAT) is:

1. The original CAT unit designed to be used on the head.

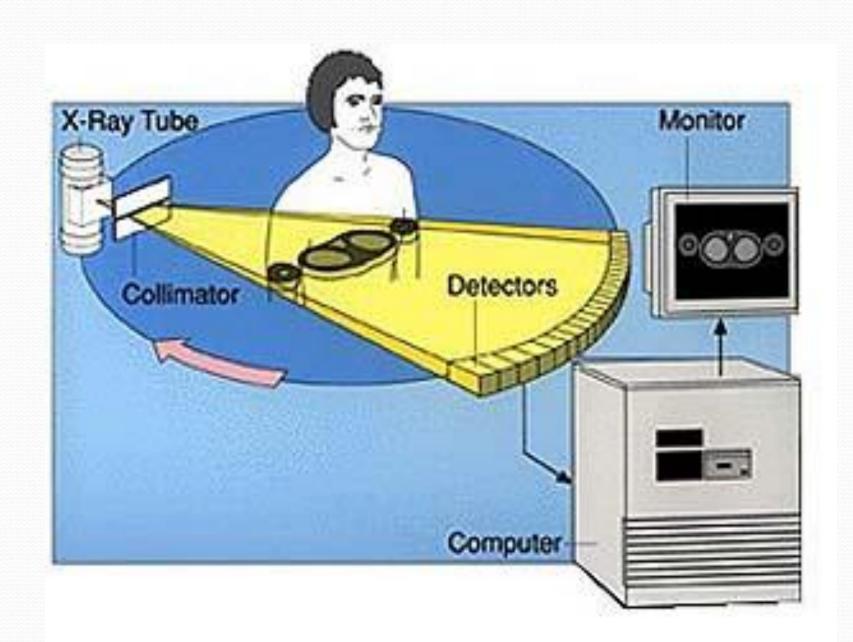
2. An x-ray tube is collimated to produce 2-narrow x-ray beams that scan across the head, and the intensities of the transmitted beams are measured by 2 detectors moving with the beam.

- 3. The data from the scan are stored in the memory of the computer.
- 4. The tube and the detector are then rotated 1° and the process repeated.
- 5. This process is repeated until. 180 scan have been obtained, which require about 4 min.

- 6. The computer analyzes the data to determine the distribution of densities in the slice.
- 7. The operator have these densities that represented by shades of gray to produce an image.

#### Note1:

*CAT* scanners that could be used on any portion of the body were developed.



#### *Note2*: When the scan is made for the thorax:

The patient should not breathe during the test in order to eliminate blurring on scan, and it's difficult for the patient for holding the breath for more than 30 sec. therefore:

The time of the test must be reduced from 4 min. to 20 sec. by using x-rays beam collimated in a fan shape and many detectors to measure the transmitted segments of the beam.

#### **Fluorescence:**

The production of light by bombarding certain materials with other form of radiation. Its property of x-ray.

X-ray image images could be viewed directly on a sheet coated with fluorescent material, or a fluorescent screen. Fluoroscopic techniques are useful where motion, such as the movement of contrast media in the digestive tract.

# **Computed Tomography**

Basic principles Geometry and historical development

## Basic principles

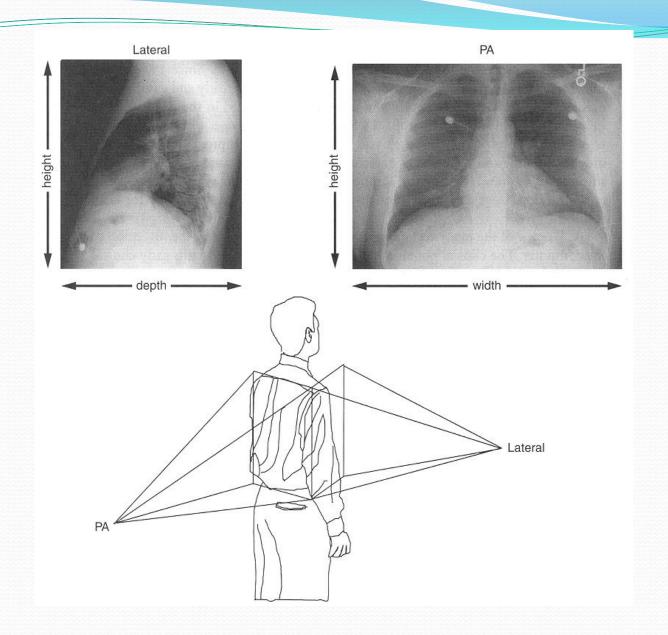
- Mathematical principles of CT were first developed in 1917 by Radon •
- Proved that an image of an unknown object could be produced if one had an infinite number of projections through the object

## Basic principles (cont.)

- Plain film imaging reduces the 3D patient anatomy to a 2D projection image
- Density at a given point on an image represents the x-ray attenuation properties within the patient along a line between the x-ray focal spot and the point on the detector corresponding to the point on the image

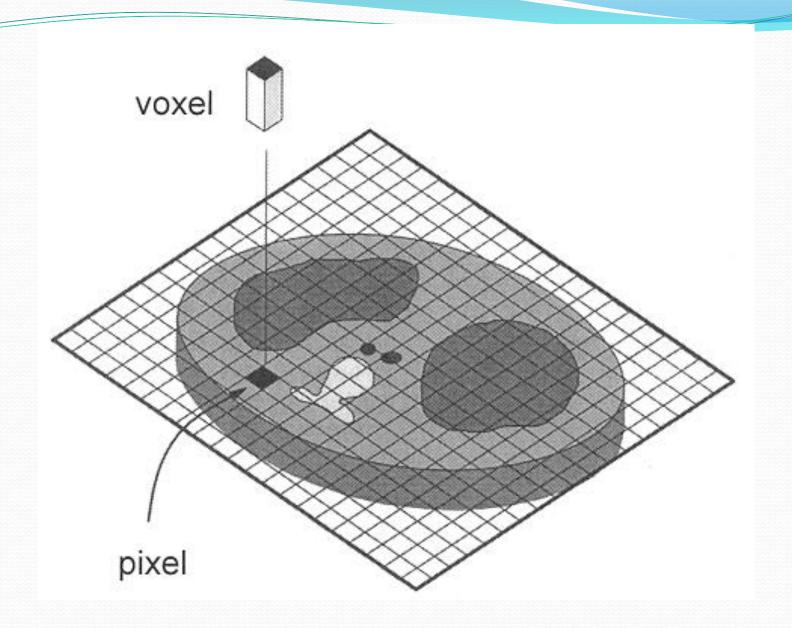
### Basic principles (cont.)

- With a conventional radiograph, information with respect to the dimension parallel to the x-ray beam is lost
  - Limitation can be overcome, to some degree, by acquiring two images at an angle of 90 degrees to one another
  - For objects that can be identified in both images, the two films provide location information



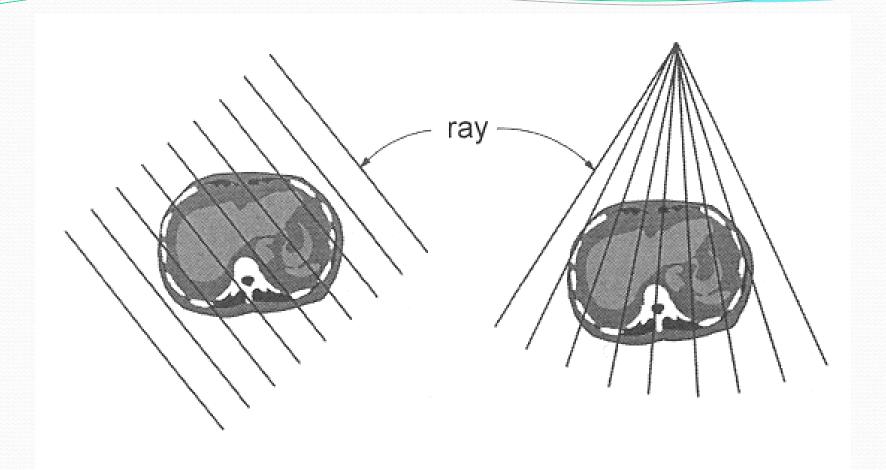
### Tomographic images

- The tomographic image is a picture of a slab of the patient's anatomy
  - The 2D CT image corresponds to a 3D section of the patient •
- CT slice thickness is very thin (1 to 10 mm) and is approximately uniform •
- The 2D array of pixels in the CT image corresponds to an equal number of 3D voxels (volume elements) in the patient
- Each pixel on the CT image displays the average x-ray attenuation properties of the tissue in the corrsponding voxel



### Tomographic acquisition

- Single transmission measurement through the patient made by a single detector at a given moment in time is called a *ray*
- A series of rays that pass through the patient at the same orientation is called a *projection* or *view* 
  - Two projection geometries have been used in CT imaging: •
  - Parallel beam geometry with all rays in a projection parallel to one another
    - Fan beam geometry, in which the rays at a given projection angle diverge •



parallel beam projection

fan beam projection

## Acquisition (cont.)

- Purpose of CT scanner hardware is to acquire a large number of transmission measurements through the patient at different positions
- Single CT image may involve approximately 800 rays taken at 1,000 different projection angles
- Before the acquisition of the next slice, the table that the patient lies on is moved slightly in the cranial-caudal direction (the "z-axis" of the scanner)

### Tomographic reconstruction

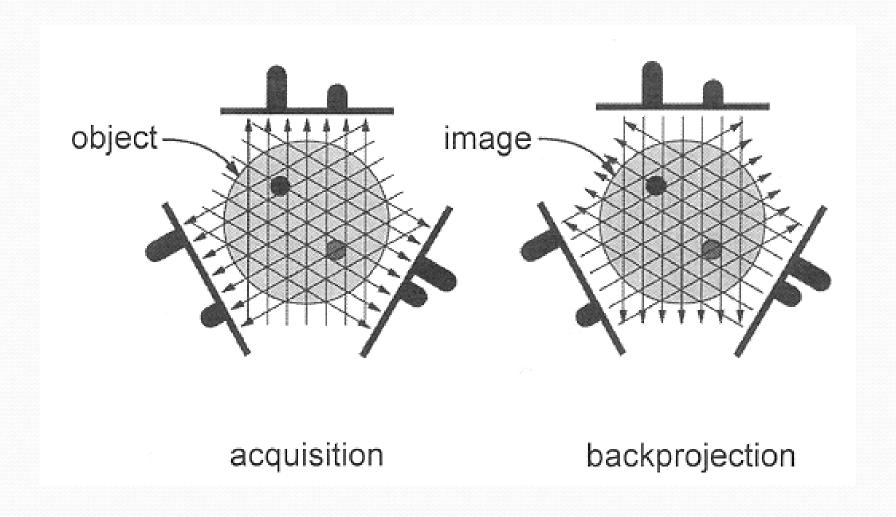
- Each ray acquired in CT is a transmission measurement through the patient along a line
  - The unattenuated intensity of the x-ray beam is also measured during the scan by a reference detector

$$I_{t} = I_{0}e^{-\mu t}$$

$$\ln(I_{0}/I_{t}) = \mu t$$

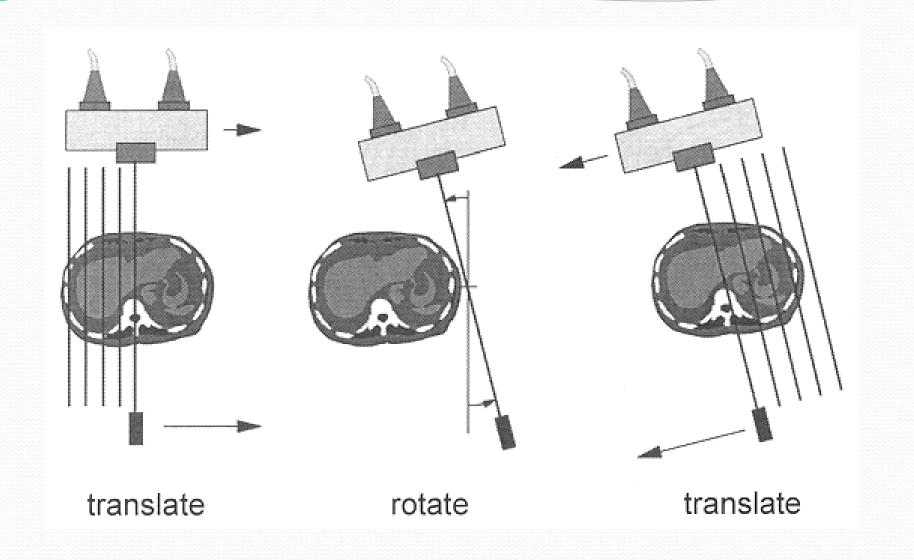
#### Reconstruction (cont.)

- There are numerous reconstruction algorithms •
- Filtered backprojection reconstruction is most widely used in clinical CT scanners
  - Builds up the CT image by essentially reversing the acquistion steps •
- The  $\mu$  value for each ray is smeared along this same path in the image of the patient
  - As data from a large number of rays are backprojected onto the image matrix, areas of high attenutation tend to reinforce one another, as do areas of low attenuation, building up the image



# 1<sup>st</sup> generation: rotate/translate, pencil beam

- Only 2 x-ray detectors used (two different slices)
  - Parallel ray geometry •
- Translated linearly to acquire 160 rays across a 24 cm FOV •
- Rotated slightly between translations to acquire 180 projections at 1- degree intervals
  - About 4.5 minutes/scan with 1.5 minutes to reconstruct slice •

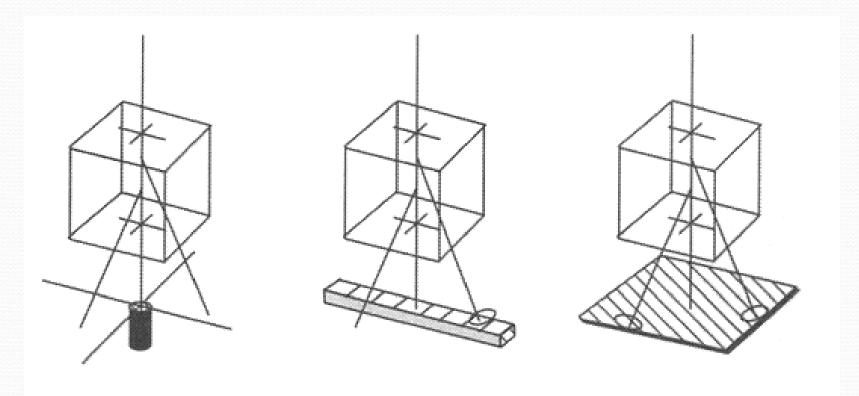


## 1<sup>st</sup> generation (cont.)

- Large change in signal due to increased x-ray flux outside of head •
- Solved by pressing patient's head into a flexible membrane surrounded by a water bath
  - NaI detector signal decayed slowly, affecting measurements made temporally too close together
- Pencil beam geometry allowed very efficient scatter reduction, best of all scanner generations

# 2<sup>nd</sup> generation: rotate/translate, narrow fan beam

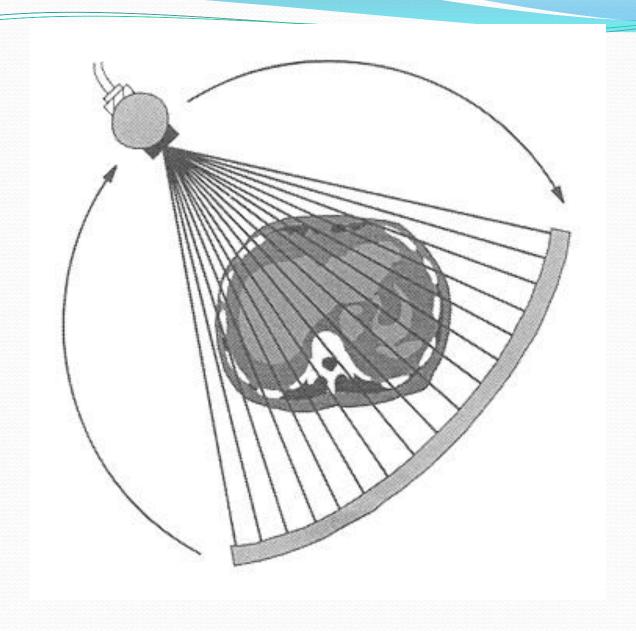
- Incorporated linear array of 30 detectors •
- More data acquired to improve image quality (600 rays x 540 views)
  - Shortest scan time was 18 seconds/slice •
  - Narrow fan beam allows more scattered radiation to be detected •



Pencil Beam Geometry Fan Beam Geometry Open Beam Geometry

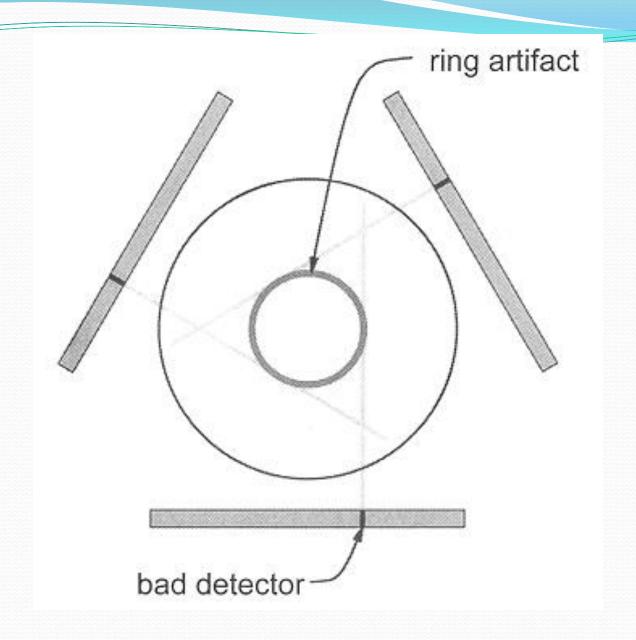
# 3<sup>rd</sup> generation: rotate/rotate, wide fan beam

- Number of detectors increased substantially (to more than 800 detectors)
  - Angle of fan beam increased to cover entire patient
    - Eliminated need for translational motion •
  - Mechanically joined x-ray tube and detector array rotate together
    - Newer systems have scan times of ½ second •



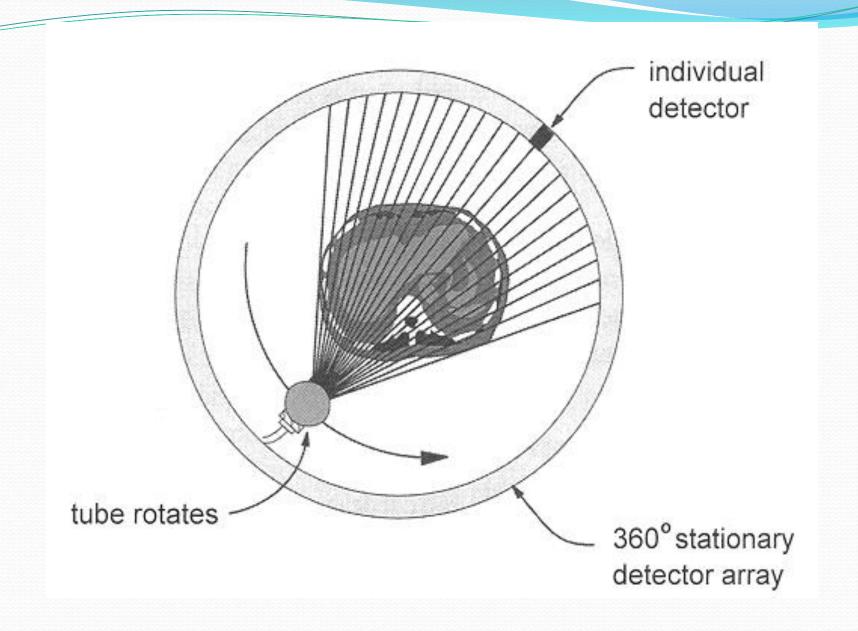
### Ring artifacts

- The rotate/rotate geometry of 3<sup>rd</sup> generation scanners leads to a situation in which each detector is responsible for the data corresponding to a ring in the image
  - Drift in the signal levels of the detectors over time affects the  $\mu$ t values that are backprojected to produce the CT image, causing ring artifacts



## 4<sup>th</sup> generation: rotate/stationary

- Designed to overcome the problem of ring artifacts
  - Stationary ring of about 4,800 detectors •

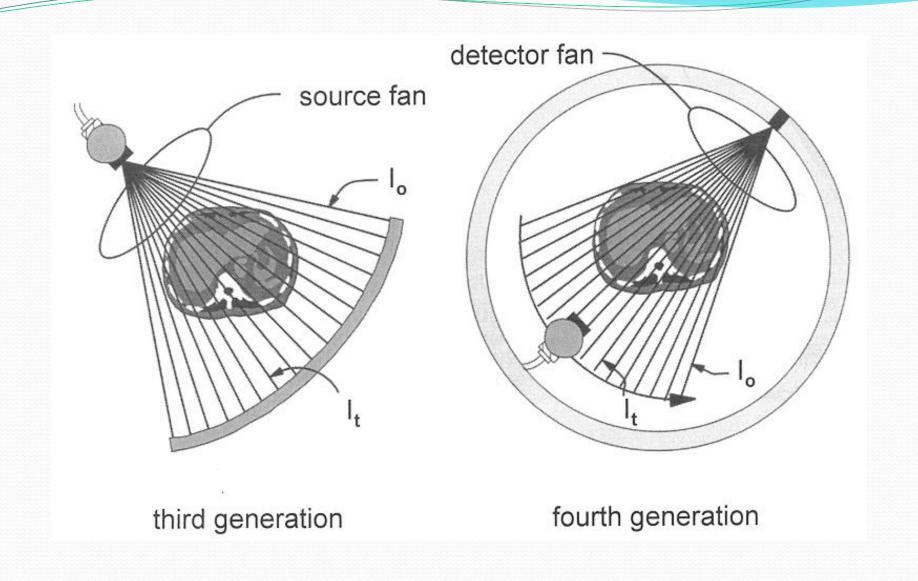


# 3<sup>rd</sup> vs. 4<sup>th</sup> generation

3<sup>rd</sup> generation fan beam geometry has the x-ray tube as the apex of • the fan; 4<sup>th</sup> generation has the individual detector as the apex

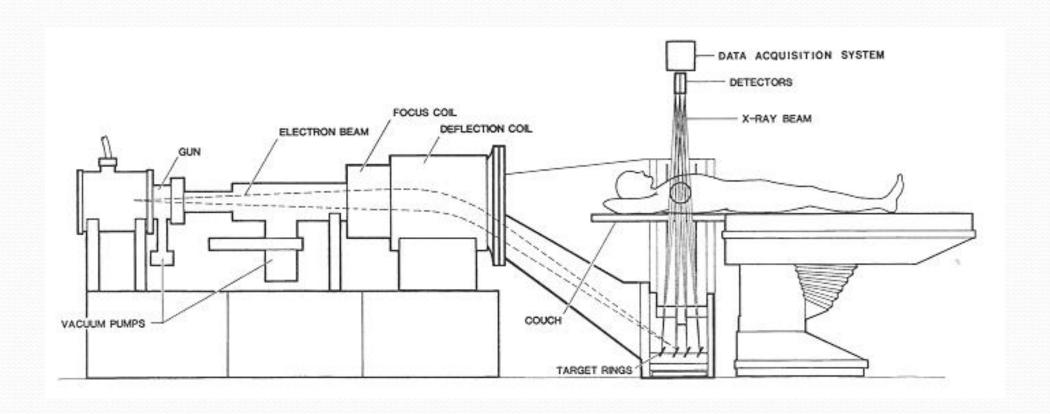
$$3^{\text{rd}} \text{ gen} : \ln(g_1 I_0 / g_2 I_t) = \mu t$$

$$4^{\text{th}} \text{ gen } : \ln(gI_0 / gI_t) = \mu t$$



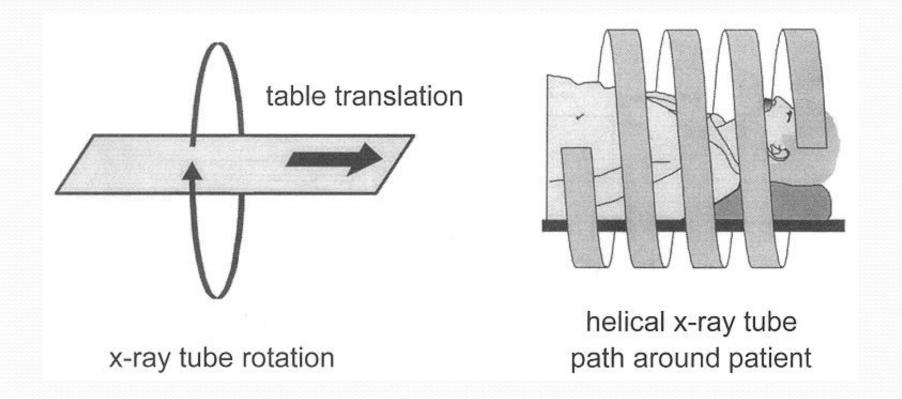
# 5<sup>th</sup> generation: stationary/stationary

- Developed specifically for cardiac tomographic imaging •
- No conventional x-ray tube; large arc of tungsten encircles patient and lies directly opposite to the detector ring
  - Electron beam steered around the patient to strike the annular tungsten target
  - Capable of 50-msec scan times; can produce fast-frame-rate CT movies of the beating heart



## 6<sup>th</sup> generation: helical

- Helical CT scanners acquire data while the table is moving •
- By avoiding the time required to translate the patient table, the total scan time required to image the patient can be much shorter
  - Allows the use of less contrast agent and increases patient throughput
  - In some instances the entire scan be done within a single breath- hold of the patient



# 7<sup>th</sup> generation: multiple detector array

- When using multiple detector arrays, the collimator spacing is wider and more of the x-rays that are produced by the tube are used in producing image data
  - Opening up the collimator in a single array scanner increases the slice thickness, reducing spatial resolution in the slice thickness dimension
  - With multiple detector array scanners, slice thickness is determined by detector size, not by the collimator

