PD233: Design of Biomedical Devices and Systems

(Lecture-8 Medical Imaging Systems)
(Imaging Systems Basics, X-ray and CT)

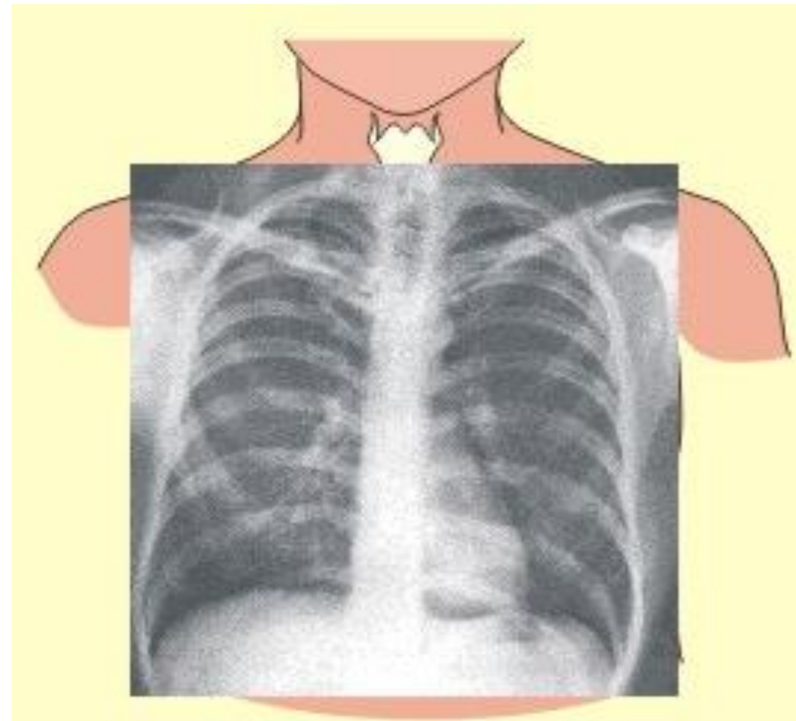
Dr. Manish Arora

CPDM, IISc

Course Website: http://cpdm.iisc.ac.in/utsaah/courses/

Medical Imaging Systems

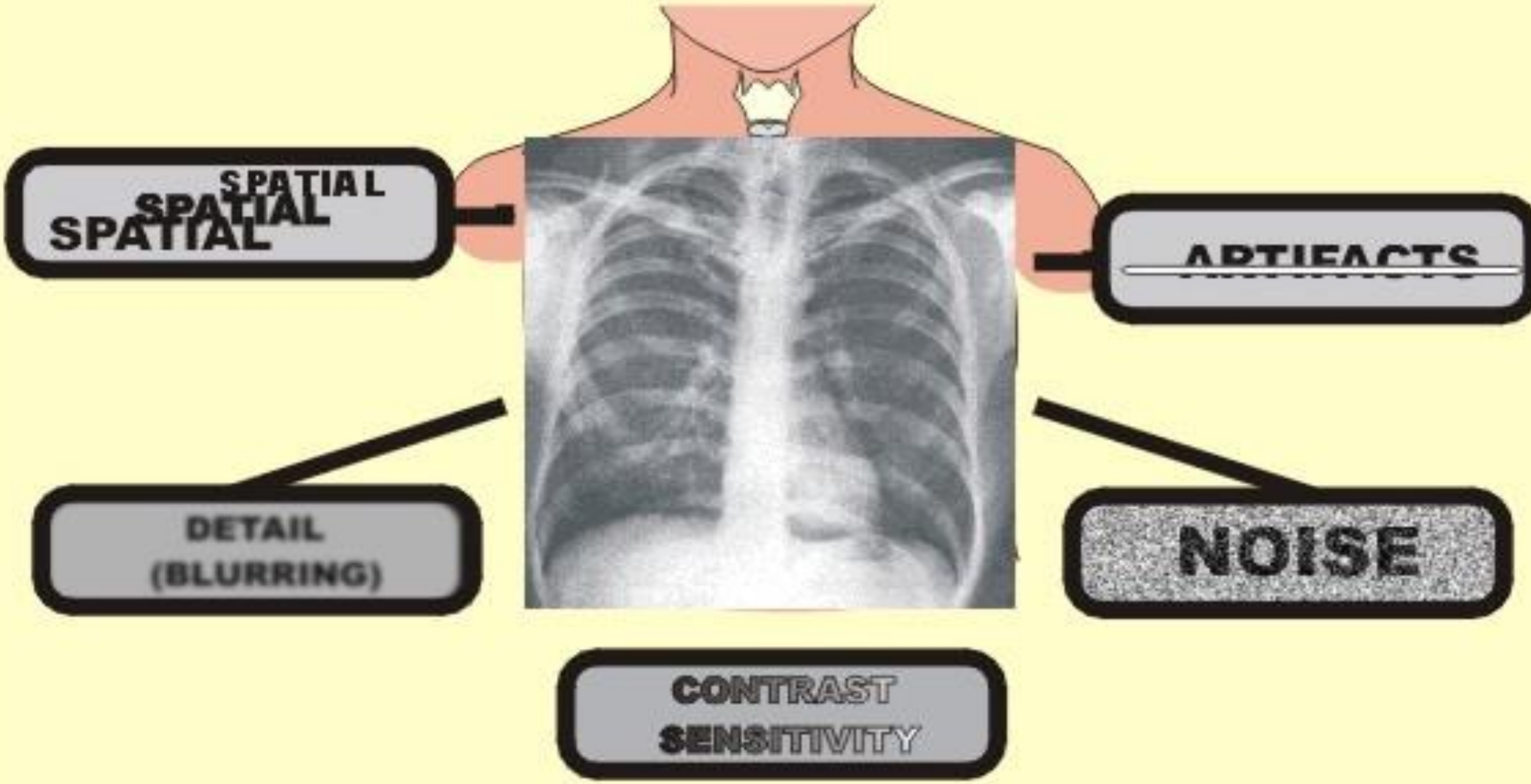
- X- ray
- Computed Tomography (CT)
- Magnetic Resonance Imaging (MRI)
- Ultrasound (US)
- Photoacoustics (PA)
- Optical Coherence Tomography (OCT)



- Provide a window into the body to see ***anatomy*** and ***signs of pathology***
- No window is perfect

Image credit http://www.sprawls.org/resources/

IMAGE QUALITY CHARACTERISTICS

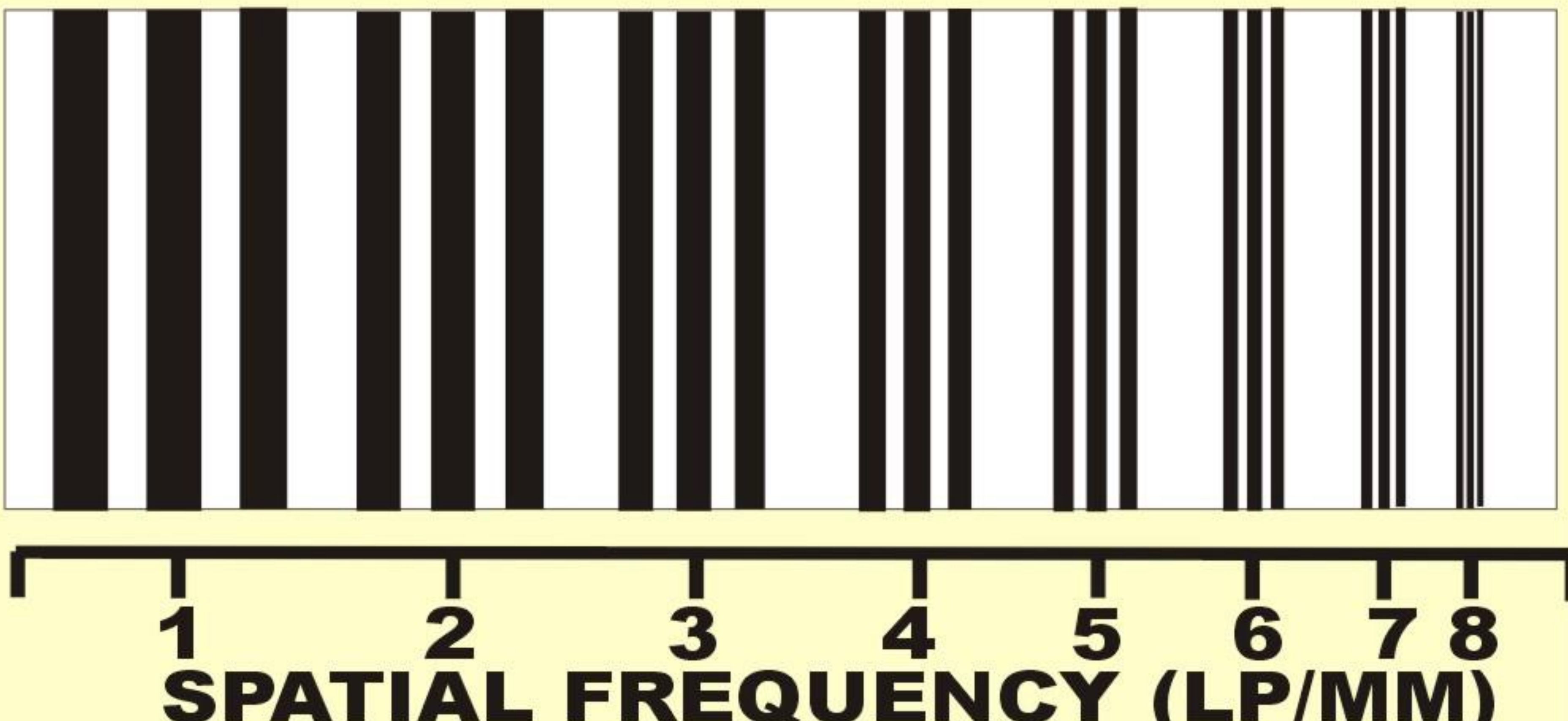


THAT AFFECT VISIBILITY

Image credit http://www.sprawls.org/resources/

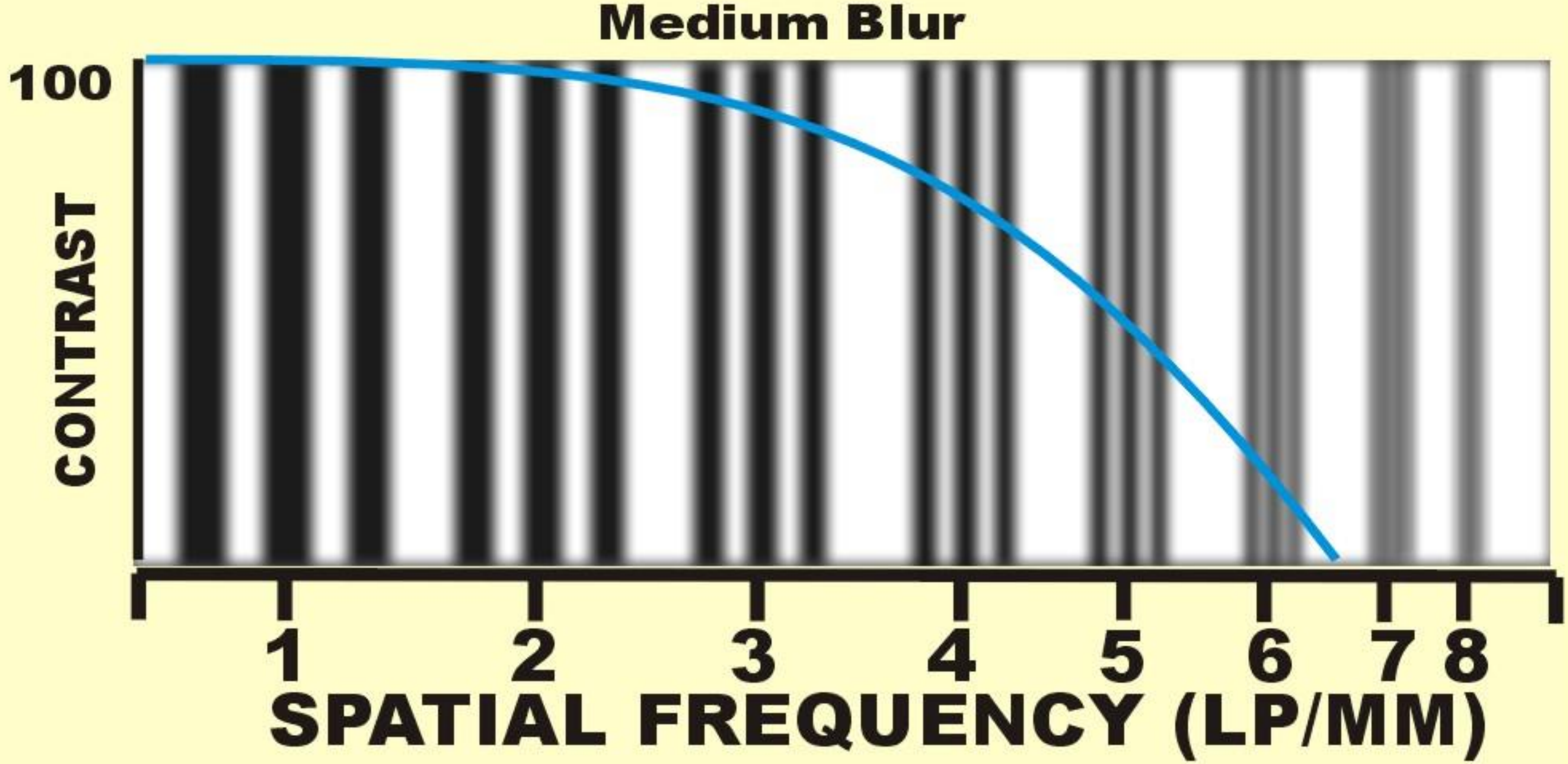
Sprawls

RESOLUTION TEST PATTERN



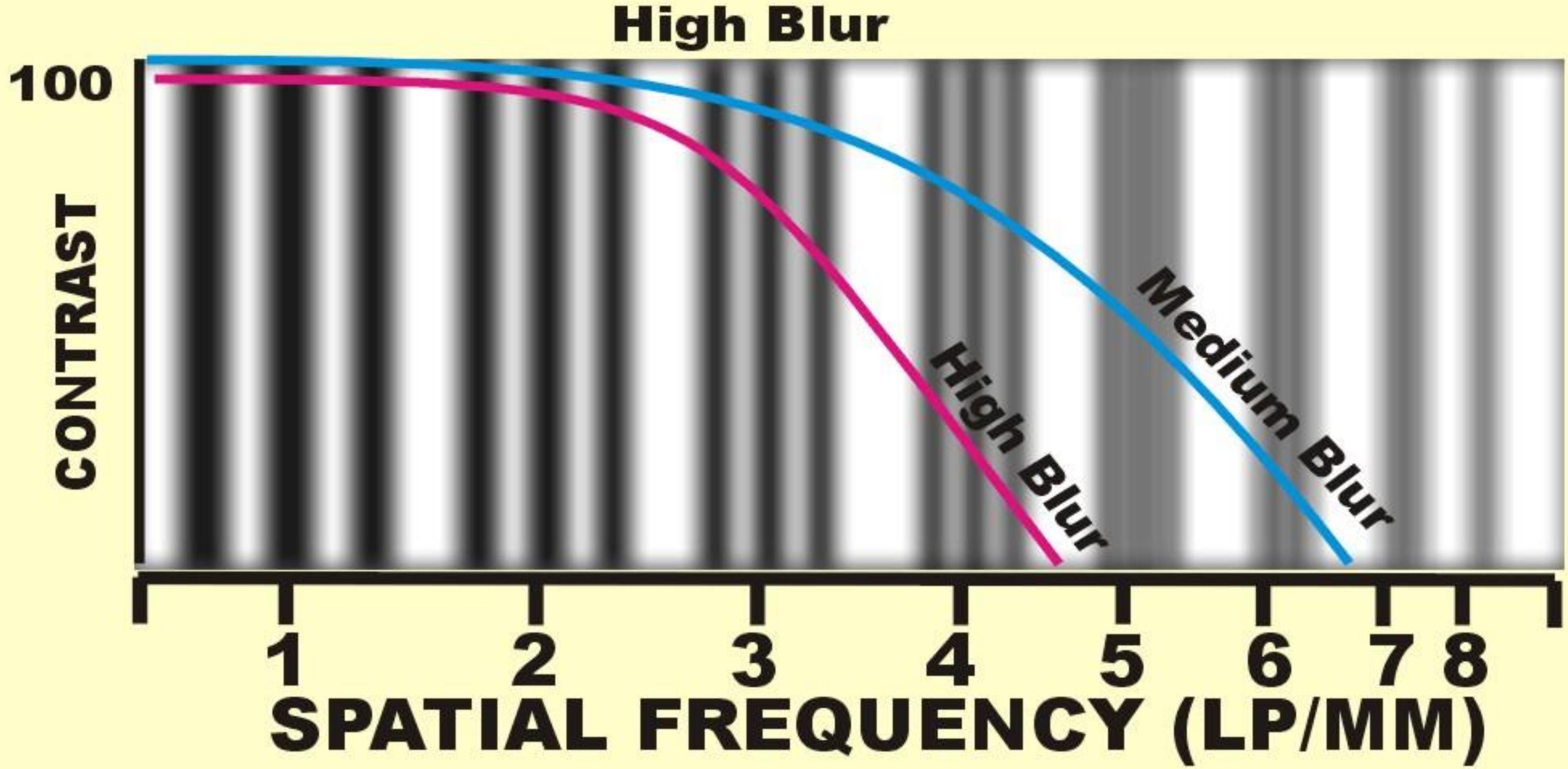
Sprawls

CONTRAST TRANSFER FUNCTION



Sprawls

CONTRAST TRANSFER FUNCTION



Sprawls

Accuracy of Diagnostic System

Clinical questions:

- Is the bone fractured?
- Is a kidney stone present?
- Is their a blockage in the artery?

Disease Present

Diagnostic Test Result	+	-
+	a True Positive	b False Positive
-	c False Negative	d True Negative

Sensitivity ➔

Probability of positive test given patient is sick

TP/ (TP+FN)

city ➔ the extent to which a diagnostic test is specific for a particular condition,

Probability of negative test given patient is well

TN/ (TN+FP)

accuracy?

Accuracy of Diagnostic System

Positive Predictive Value:

If the test is positive what is the probability what is the probability that the disease is present.

Negative Predictive Value:

If the test is negative what is the probability what is the probability that the disease is absent.

Imaging Test Result	Disease Present +	Disease Present -
+	a	b
-	c	d

Prevalence: Fraction of population with diseases present in a given population at a given time

X-Ray Imaging

"First medical X-ray by Wilhelm Röntgen of his wife Anna Bertha Ludwig's hand " by Wilhelm Röntgen.

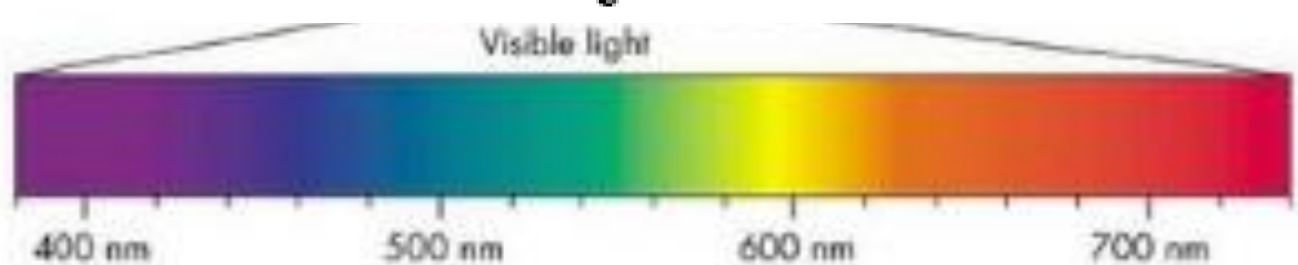
Reading material: Chapter 1, Kirk Shung

Electromagnetic (EM) wave Spectrum

$$\frac{\partial^2 E}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} \quad \text{and} \quad \frac{\partial^2 B}{\partial x^2} = \frac{1}{c^2}\frac{\partial^2 B}{\partial t^2}$$

for the electric Field for the magnetic Field

$$\text{where } \frac{1}{c^2} = \varepsilon_o \mu_o$$



X-Ray as Particle

Energy of a single photon

$E = hf$

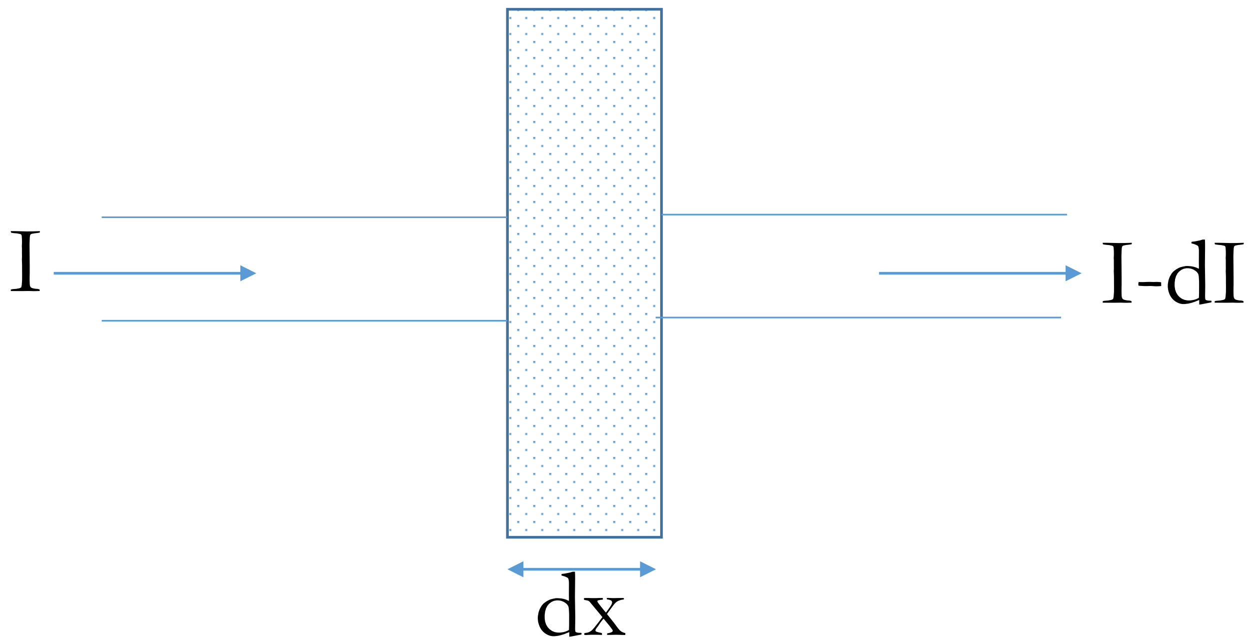
h = Plancks Constant

= 4.13×10^{-18} keV-sec

What is eV?

Calculate energy of single 1nm X-ray Photon

Attenuation of X-Ray beam



Beam of intensity **I** and cross-sectional area **A**

$$\mathbf{dI = -\beta I dx}$$

β = Linear attenuation coefficient

At what distance will the Intensity become half?

What will happen is material changes state/density?

Attenuation of X-Ray beam

Half Layer Value = 0.693/β

Material	*HVL (mm)*		
	30 keV	***60 keV***	***120 keV***
Tissue	20.0	35.0	45.0
Aluminum	2.3	9.3	16.6
Lead	0.02	0.13	0.15

Mass-attenuation coefficient = β/ρ

ρ =density

$$\beta = n\sigma$$

Material has **n** atoms per unit volume each with cross section σ

Intensity of X-ray beam

$$\text{Intensity} \propto \text{energy of the photons}$$
$$\propto \text{number of photons}$$

X-Ray Dose –should also account for time of exposure

Roentgen (R): total number of ions produced in 1cc of air at (760mm Hg and 0^oC)

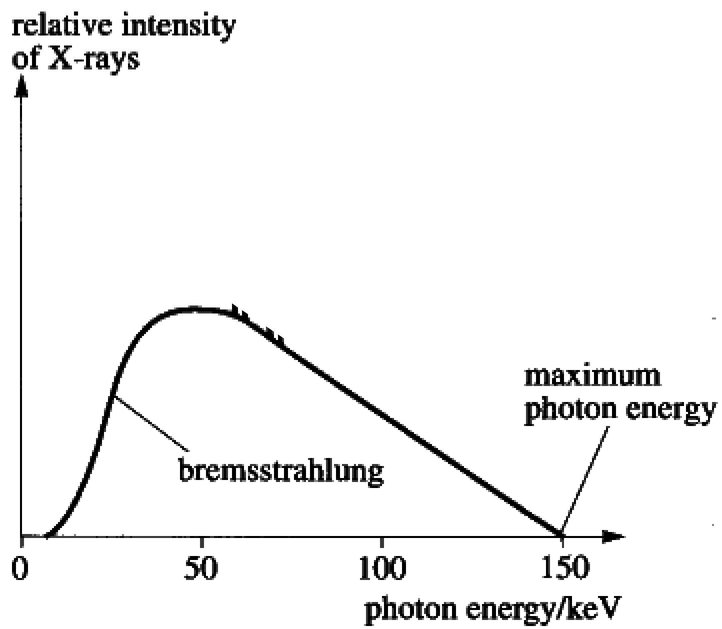
Radiation Absorbed Dose(rad): X-Ray energy absorbed per kg of material

$$1\text{rad} = 0.01 \text{ Joules absorbed per kg}$$
$$1 \text{ gray (Gy)} = 100 \text{ rad}$$

X-ray Generation

X –Rays can be generated by bombarding metal targets with high energy electron

White Radiation:
Energy lost by striking electron interact with the positivity charged metal targets inelastically
Also know as Bremsstrahlung or stopping radiation

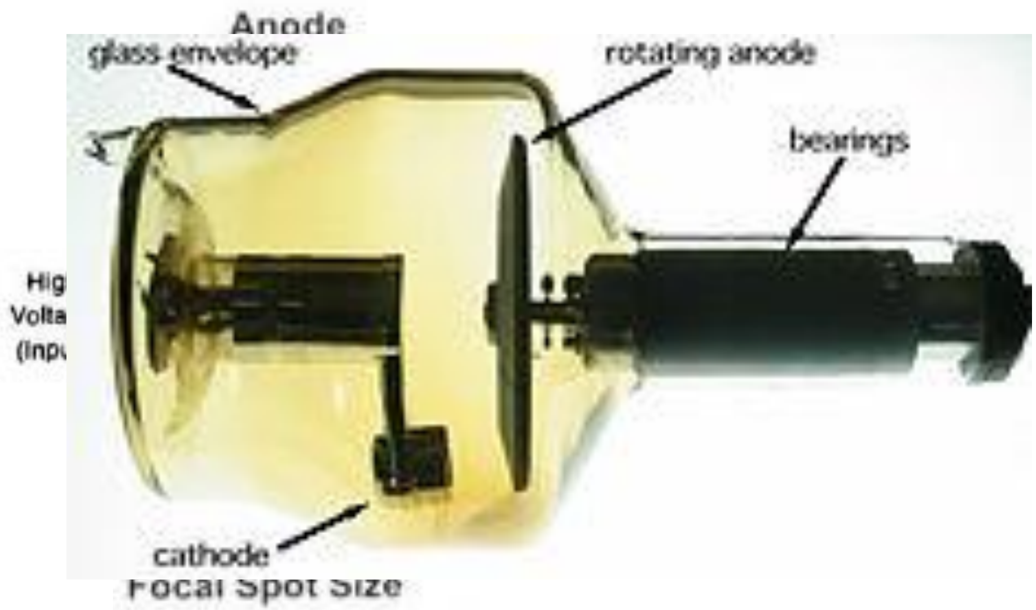


Characteristic Radiation:
When inner shell electrons are removed by interaction striking electrons

This phenomenon similar to photoelectric effect

X-ray Generators

X –Rays can be generated by bombarding metal targets with high energy electron



X ray Tube Characteristics
- Target material
- Tube voltage
- Tube current
- Filament current

Striking electrons heat up the metal target

Line Focus Principle

Large focal spot on the surface but small effective spot

$$F = f \sin(\theta)$$

Rotating Anode

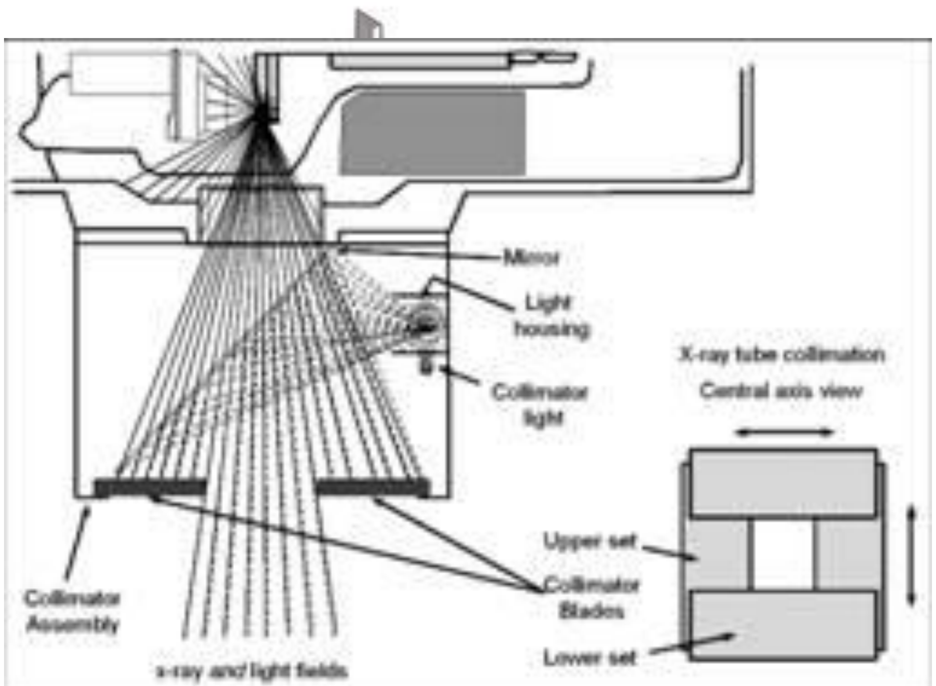
3000 to 10000 rpm

Beam Restrictors

Needed to regulate size and shape of the x-ray beam

Beam Restrictors:

- Aperture diaphragms
- Cone and cylinders
- Collimators

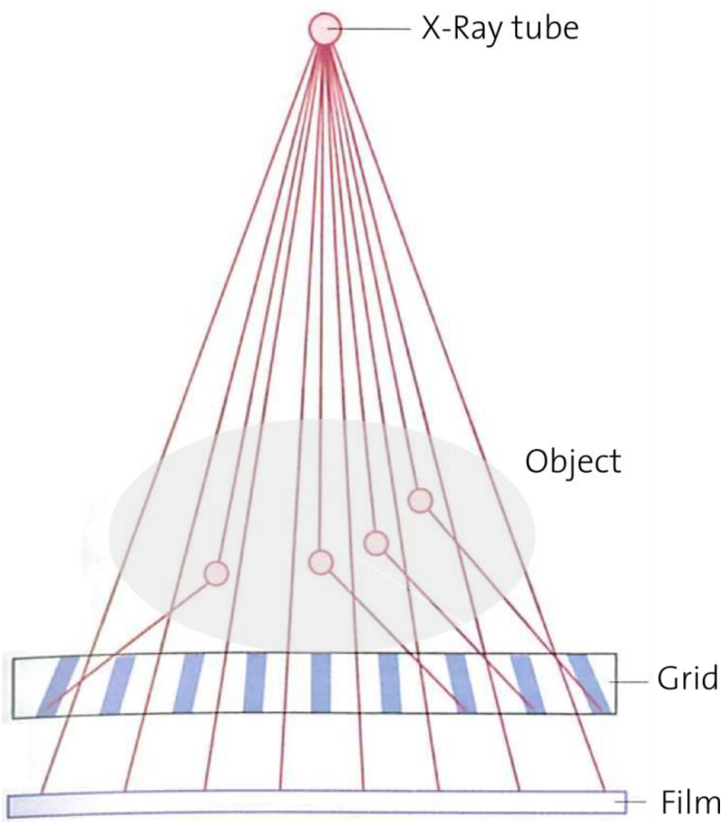


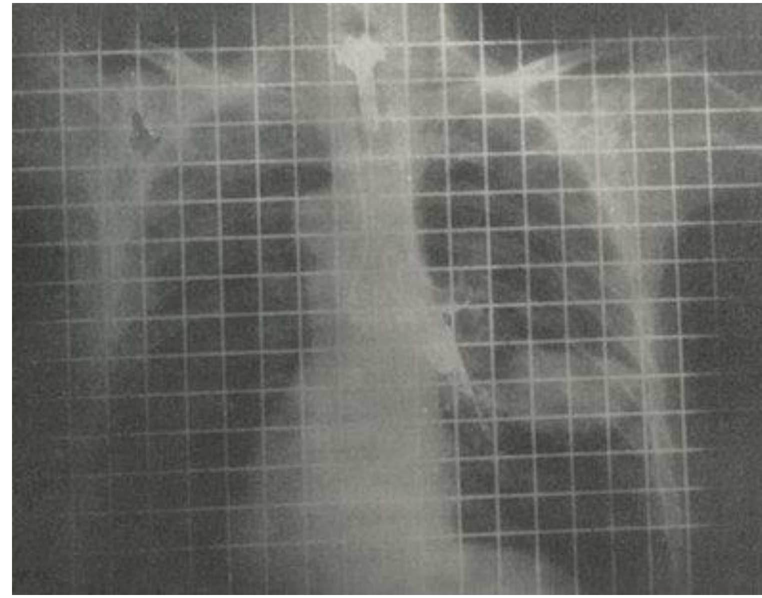
Cllimators provide moveable opening
Light used a guide to see the region to be exposed by x-ray

Note Finite focal spot leads to penumbra along edges

Grids

Used to remove effect scattered emissions





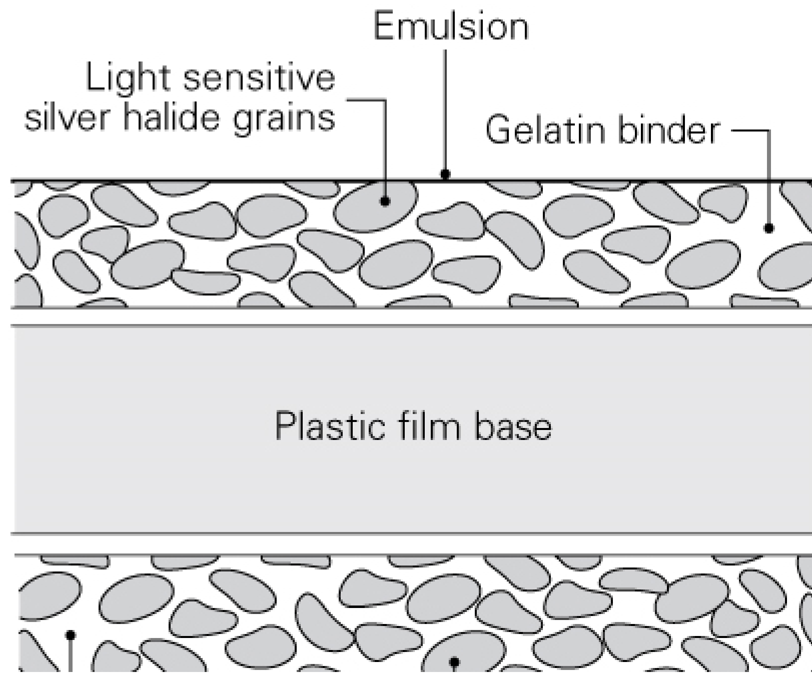
Early image of x-ray with grid

Snap on grid, attaches to the x-ray film cassette

X-ray Detectors

X-Ray (Photographic) films

X-Ray produces free electrons, which reduces silver halide in the exposed region
Silver halide is black, hence region less exposed appear bright

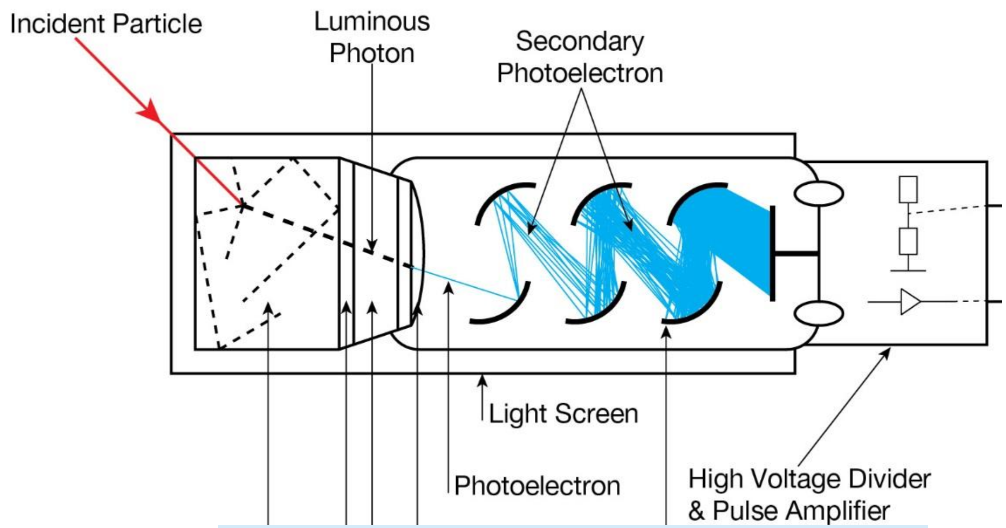


Digital Radiography (DR)
Uses reversible chemistry
Exposed film is scanned by variety of means
-camera, drum scanner, laser scanning

Alternatively, x ray detectors can be electronics/digitals

Self study!
X Ray film characteristics
response curve, speed, fog, speed

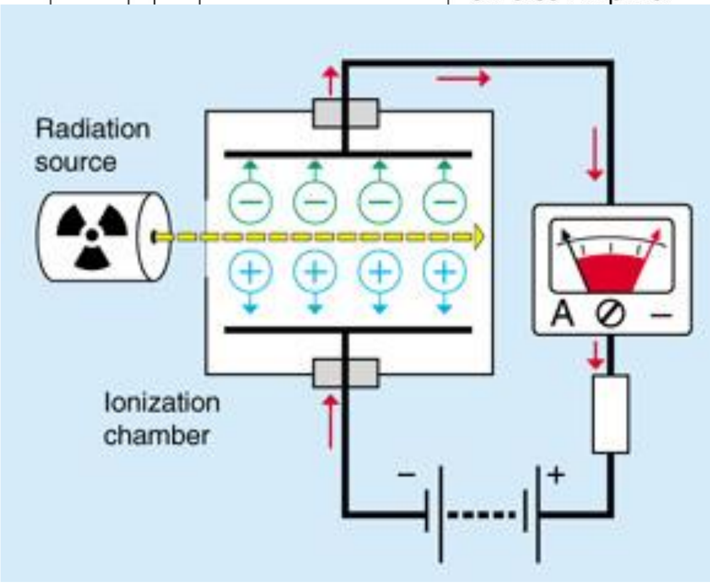
X-ray Detectors



Scintillation Detectors

X-Ray photon can produce visible photon in scintillation material (NaI, Th)
Visible photons and amplified by photomultiplier tube (PMT)
-85% efficient

Ionization Chamber Detectors
X Ray ionizes inert gases in confined chamber place between charged electrodes.
Amount of ions produced result in a current which digitized



Limitation of Conventional X-ray imaging

1) 2d Projection of 3D object – i.e. multiple planes are mapped on to one plane – depth information is lost
2) Limited use to distinguish soft tissue
3) Conventional X ray is not quantitative
   -Image intensity/size depend on source-object-detectors distance

Biological Effects of X-Ray

Factors effecting biological effects:

Threshold:
Quantitative level above which there is an tissue damage happens

Exposure Time:
Exposure Area:

Biological Variation:
Response varies from varies from species to species, tissue to tissue
Lethal dose vs short term effects

Biological Effects of X-Ray

LD 50/30:

Dose of substance or radiation which will kill 50% of the individual over a 30 day period.

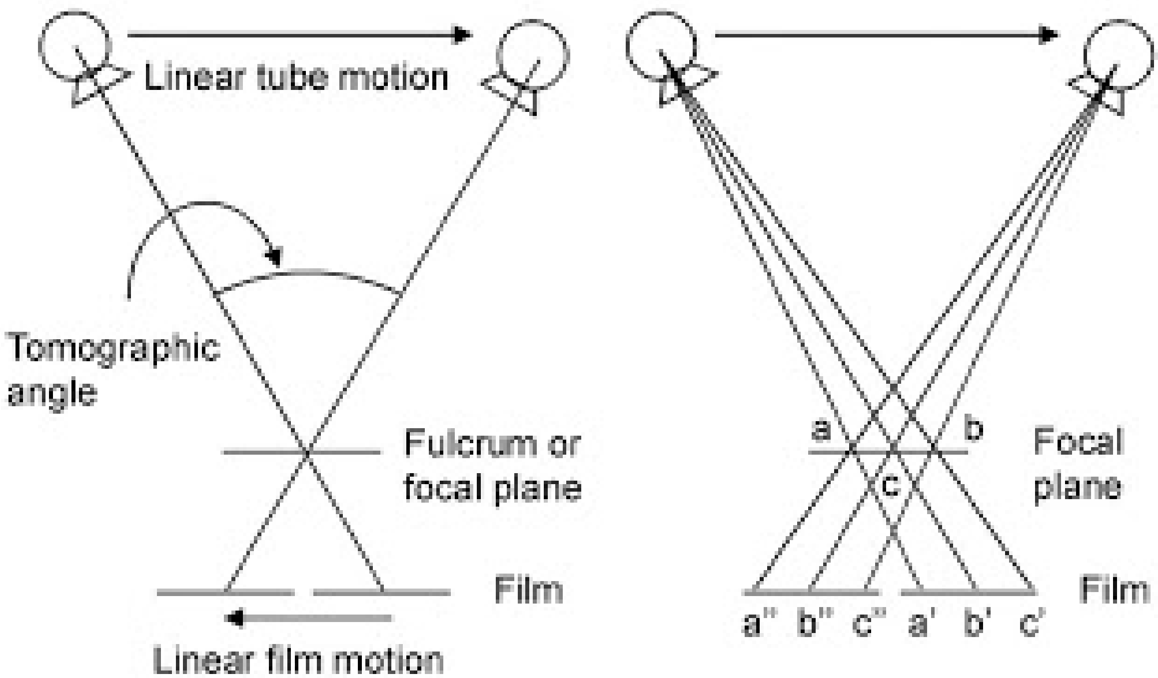
Lethal dose for humans is ~450 rad

Short term effects like nuseua, vomiting can happen at dose of 100rad

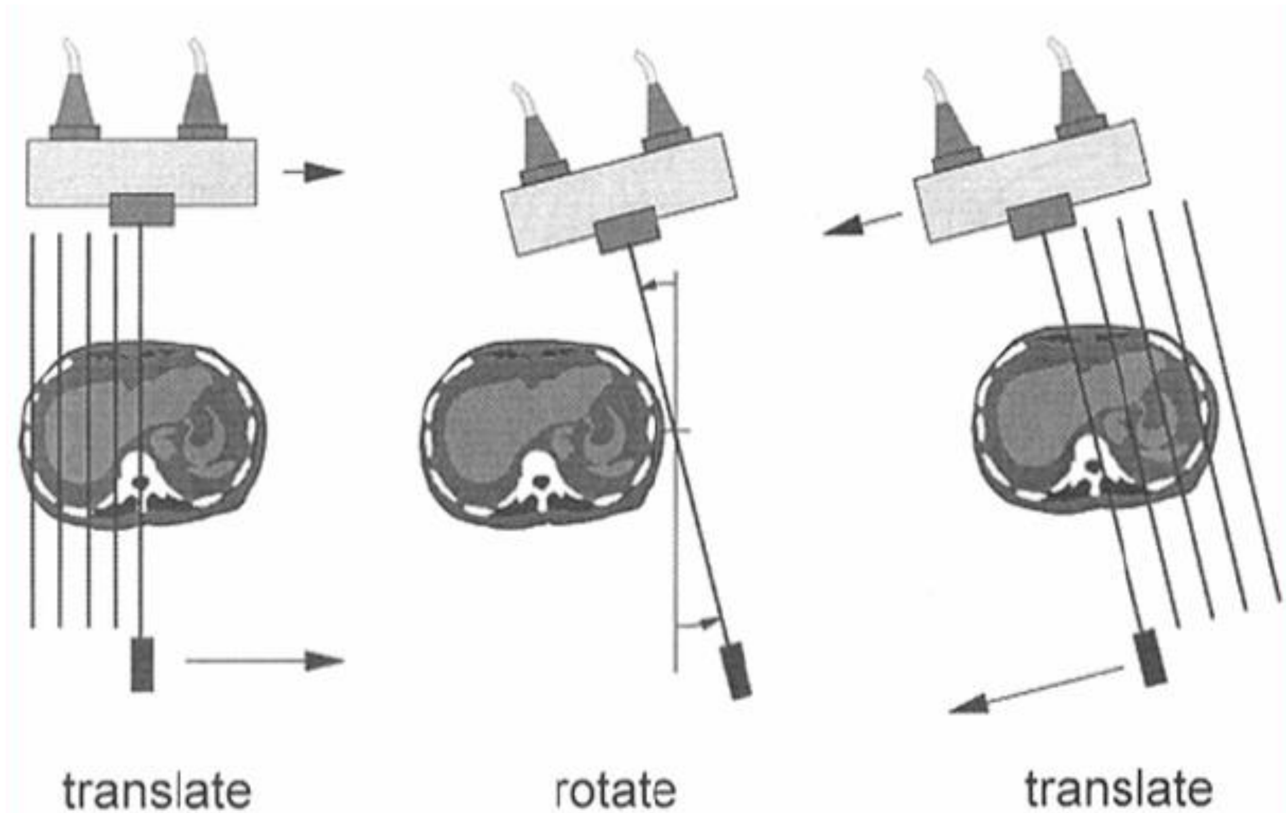
+ carcinogenic effects
+ genetic effects

Even diagnostic X ray is harmful!!

Conventional Tomography



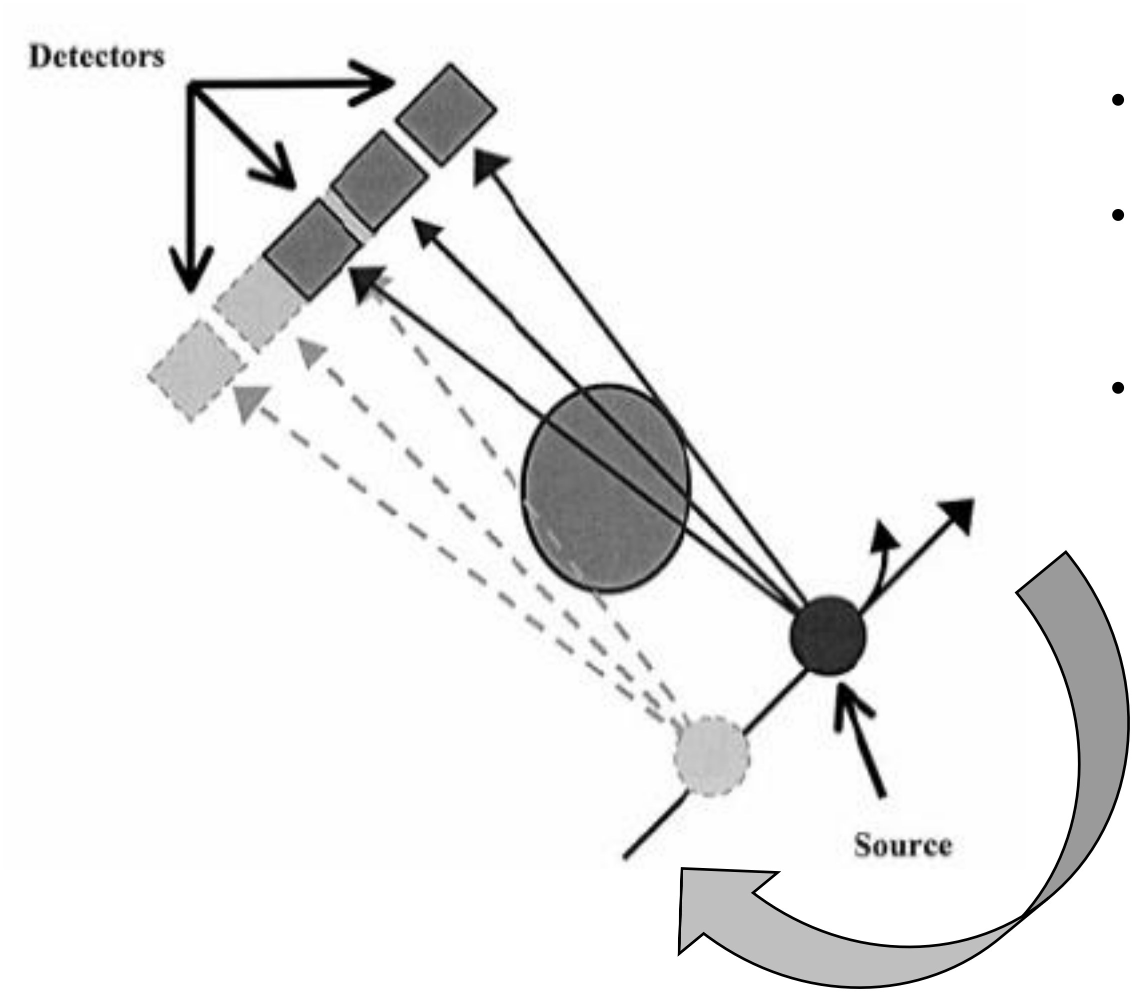
1st Gen. Computed Tomography



-Few minutes for each scan
-Pencil beams
-Motion artifacts
-Translate and Rotate Scanner

Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf

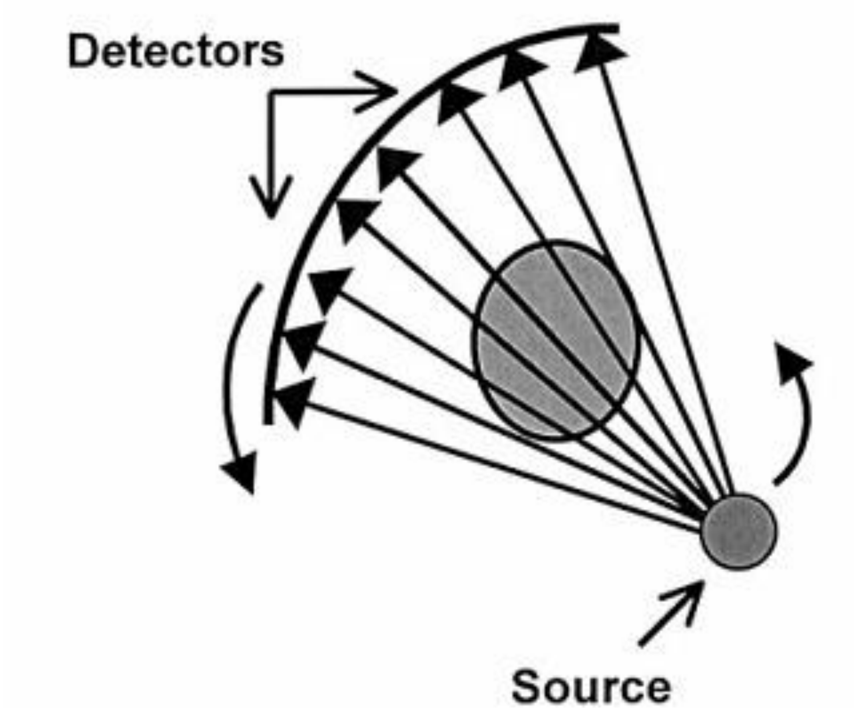
2^{st} Gen. Computed Tomography



- Multiple detector for single beam
- Initial versions with 3 detectors later upto 50+ detectors
- Still uses translate and rotate scanner

Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf

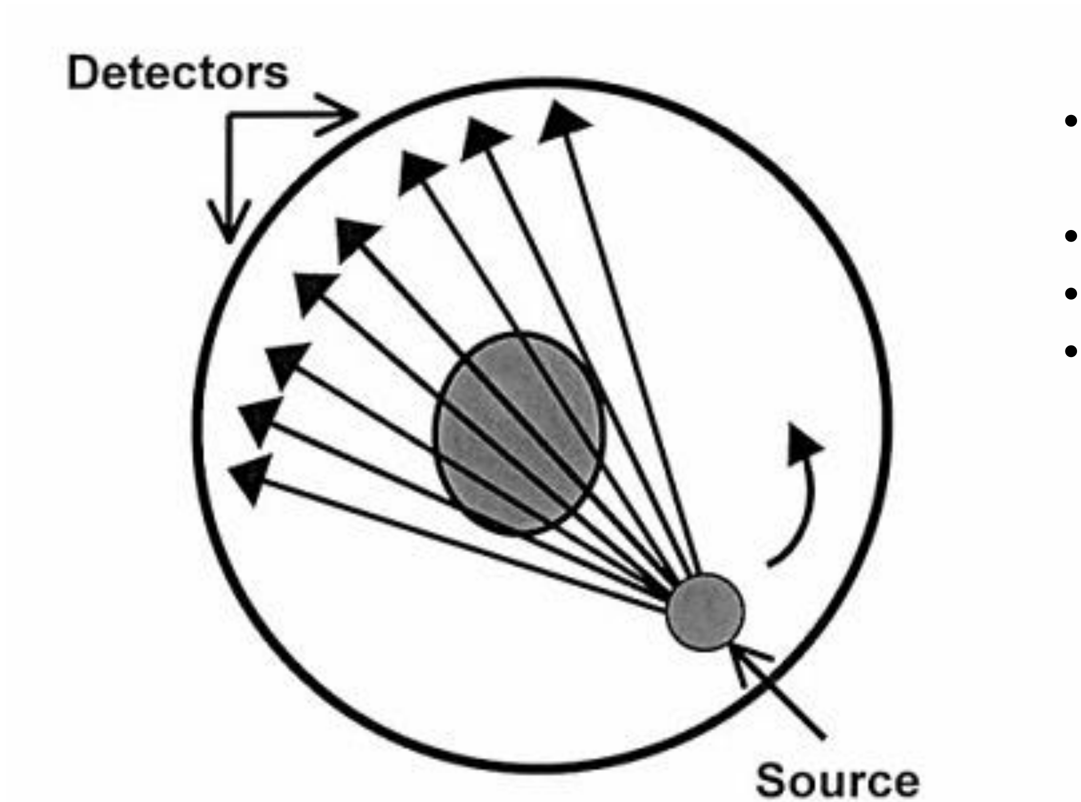
3st Gen. Computed Tomography



- 300-500 detectors
- Designed for pure rotational scanning
- X ray tube collimated for fan-beam
- Scanning time reduced to 2 sec per slice
- Got rid of translate and rotate scanning – even used in most recent configurations

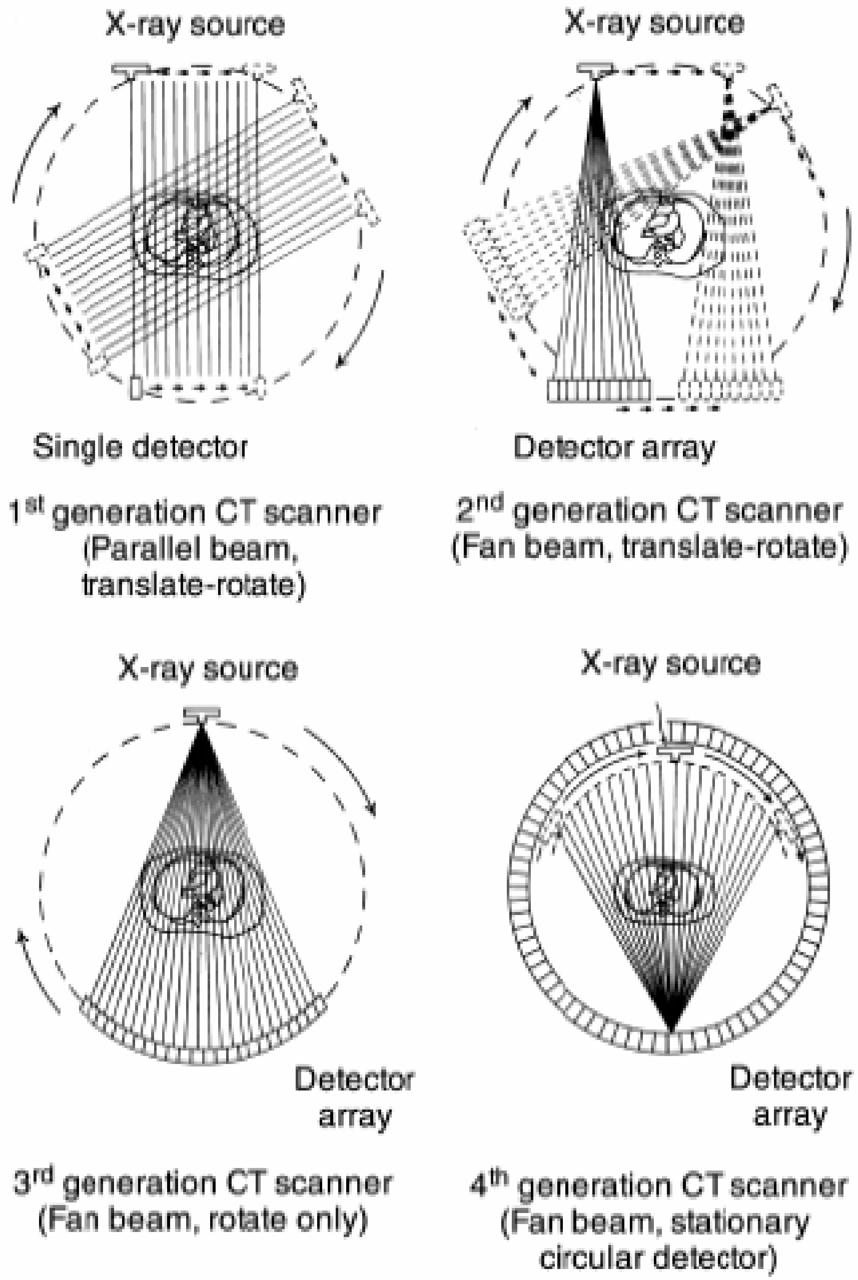
Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf

4^{th} Gen. Computed Tomography



- Circular array of fixed detectors
- Only source rotates
- 600-4800 detectors
- Less efficient as only ¼ of detectors used at any point in time.

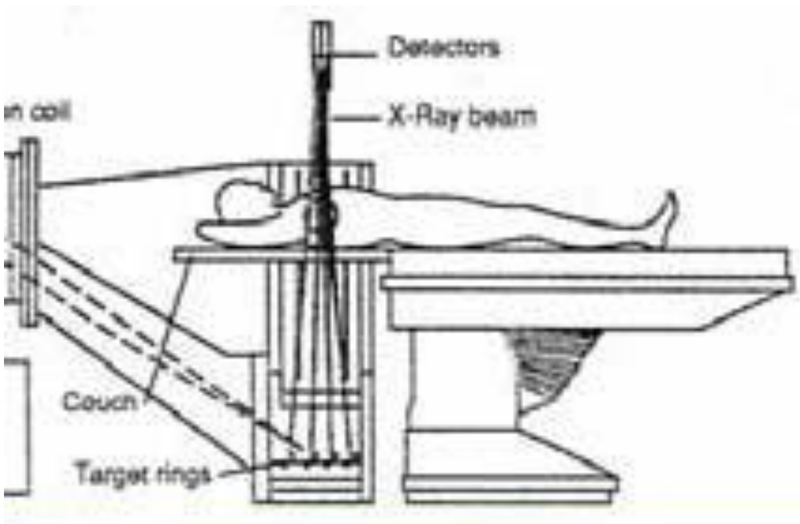
Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf

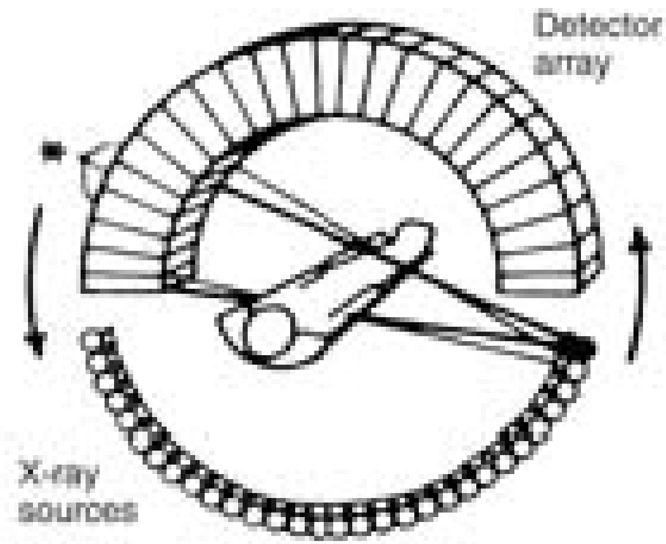


Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf

5^{th} Gen. Computed Tomography

Cine CT/ millisecond CR/ultrafast CT



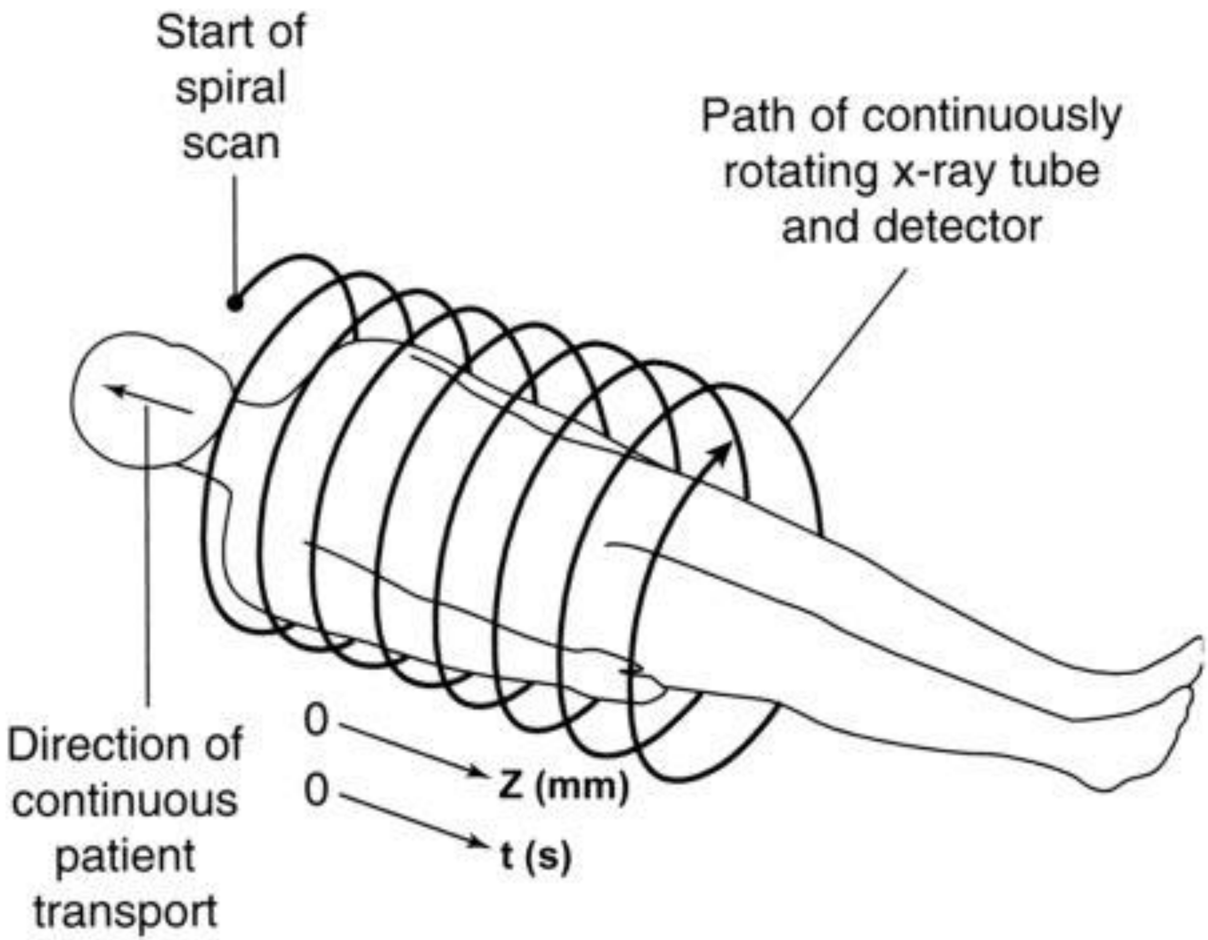


- Stationary-Stationary configuration – no mechanical scanning
- X ray source single tube with array of tungsten targets
- Reduced scanning time to 50ms, cardiac scanning made possible

Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf

6^{th} Gen. Computed Tomography

Spiral/Helical CT

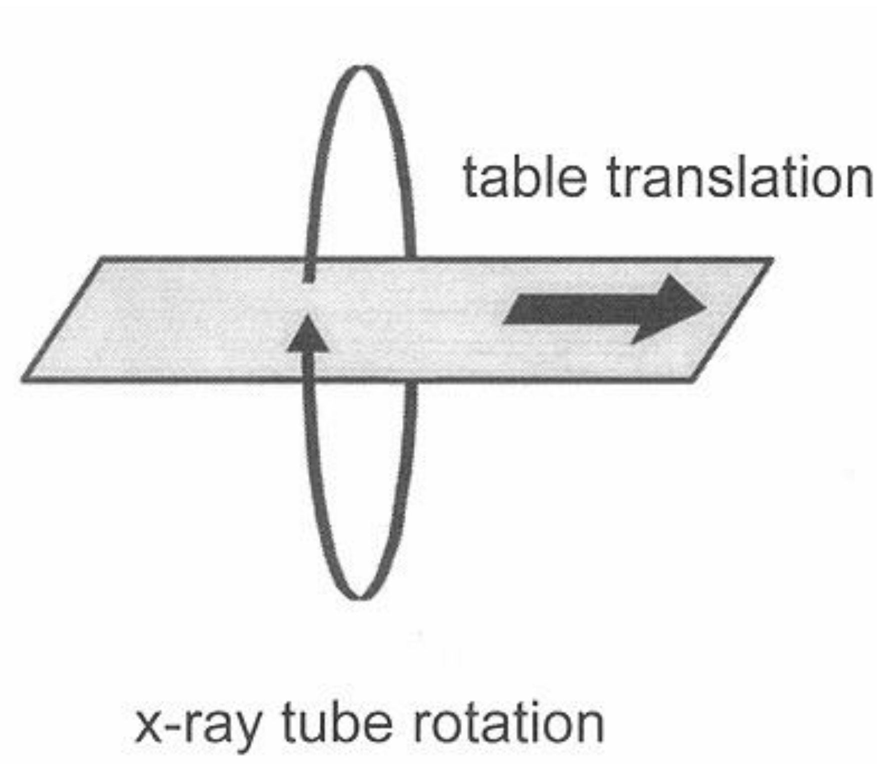


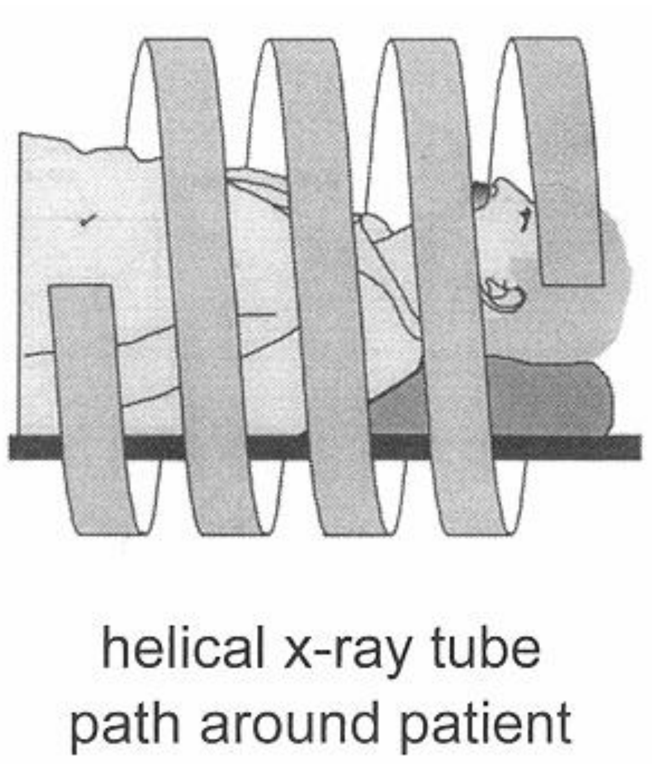
- Table translation with source rotation
- Slip ring technology X ray source continuously
- Volume data interpolation algorithms developed
- Whole abdomen in 30sec

Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf

6th Gen. Computed Tomography

Spiral/Helical CT

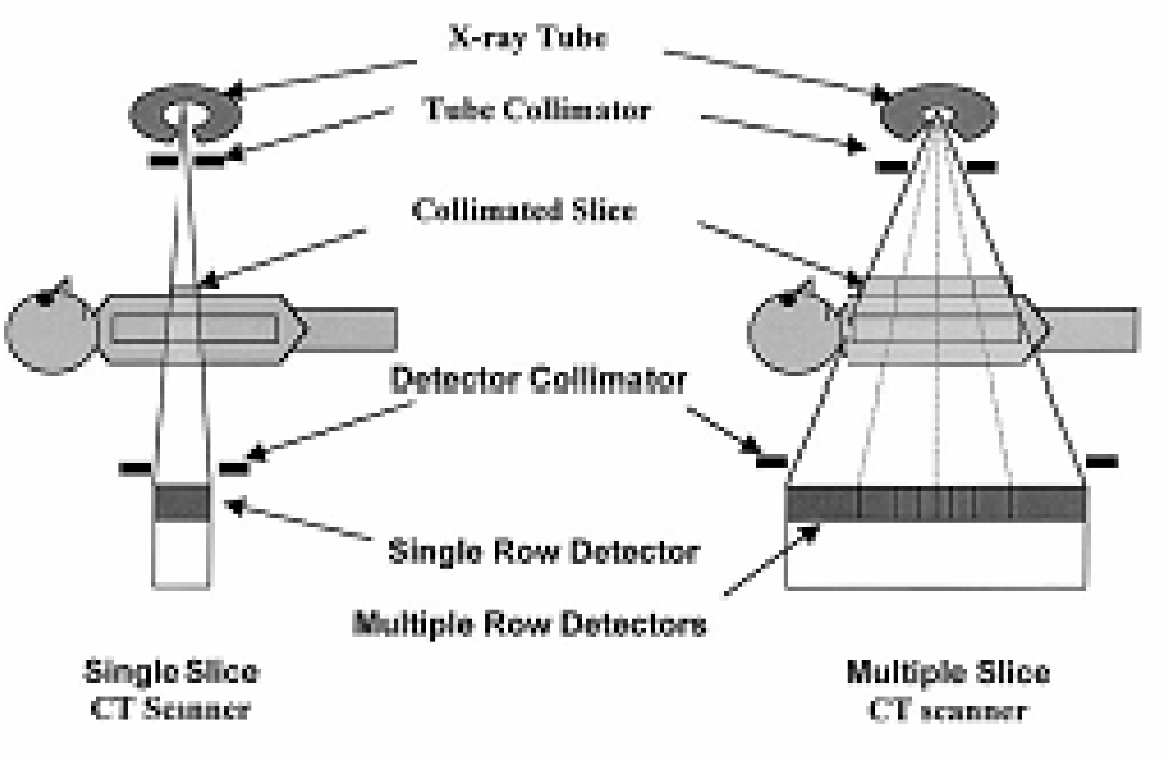




Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf

7th Gen. Computed Tomography

MDCT/ Cone beam CT

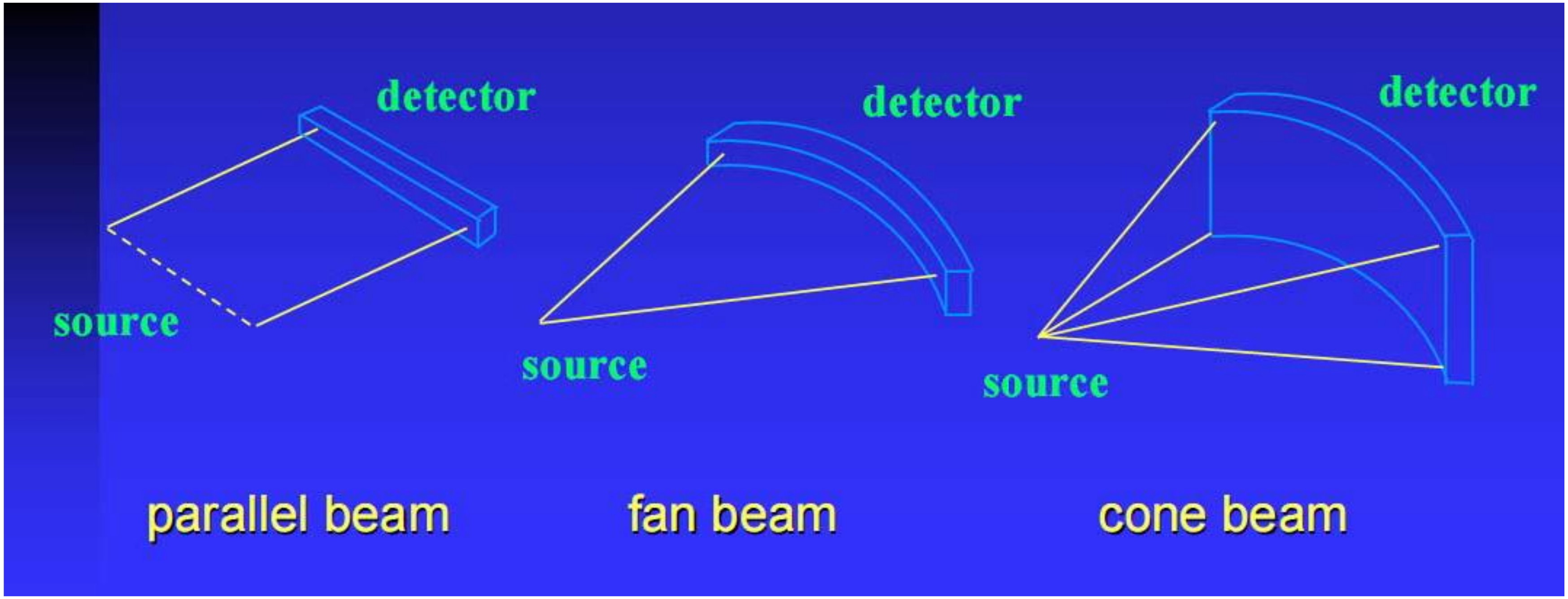


Multi-row Detector CT
Collimator opened even more
Key advance in detector technology – 2D arrays rather then one 1D array

Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf

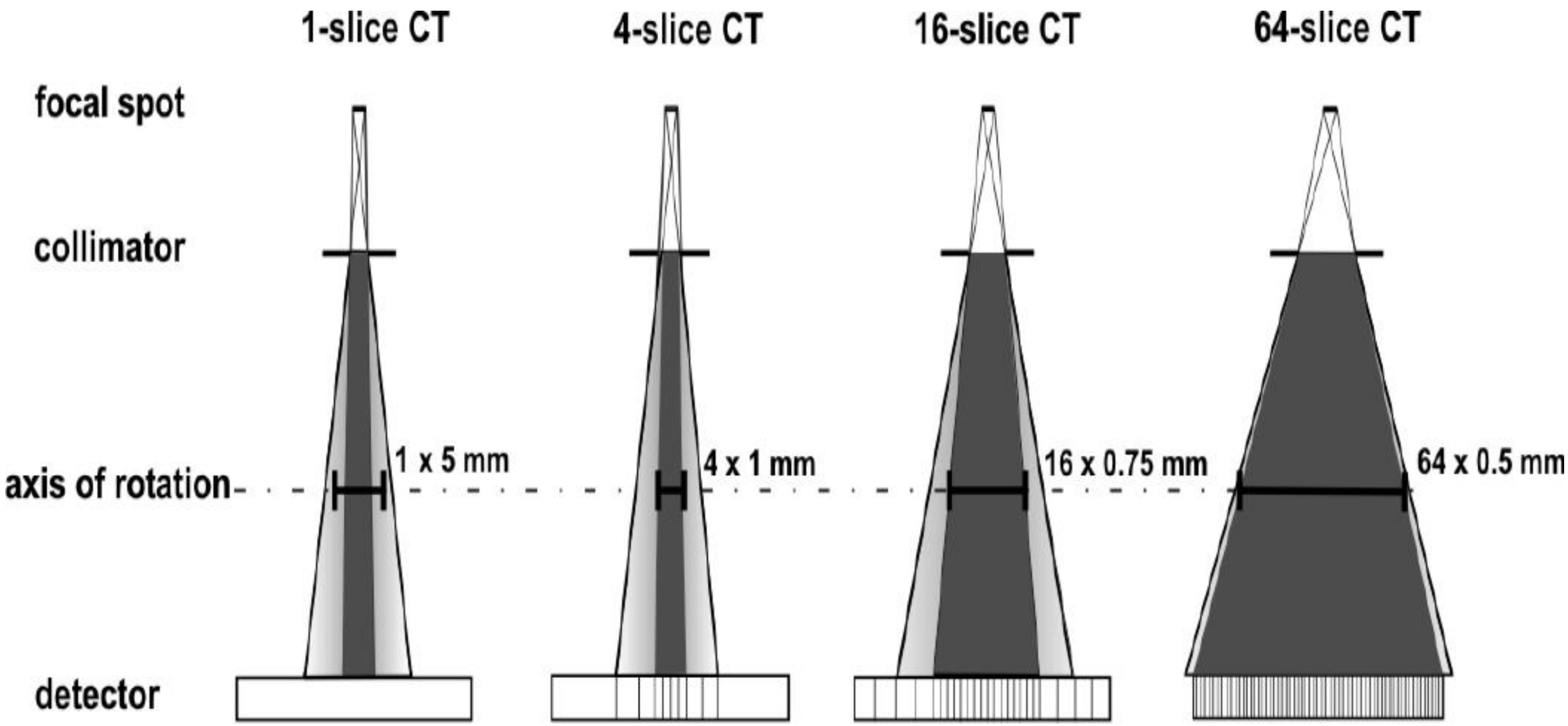
7th Gen. Computed Tomography

MDCT/ Cone beam CT



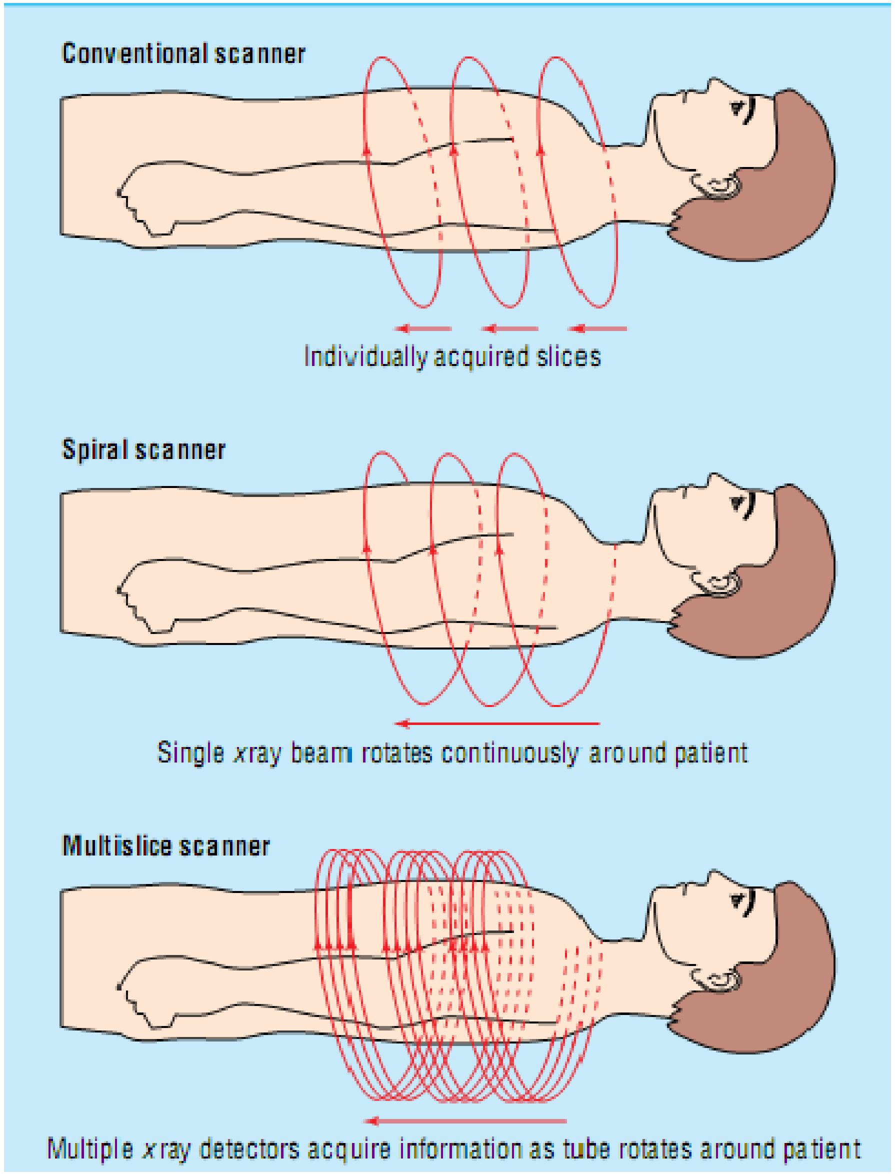
Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf

War on slices!!



Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf

5th,6th,7th Gen. Computed Tomography



Images source: www.kau.edu.sa/Files/0008512/Files/19500_2nd_presentation_final.pdf

Gen.	Source	Source Collimation	Detector
1st	Single X-ray Tube	Pencil Beam	Single
2nd	Single X-ray Tube	Fan Beam (not enough to cover FOV)	Multiple
3rd	Single X-ray Tube	Fan Beam (enough to cover FOV)	Many
4th	Single X-ray Tube	Fan Beam covers FOV	Stationary Ring of Detectors
5th	Many tungsten anodes in single large tube	Fan Beam	Stationary Ring of Detectors
6th	3G/4G	3G/4G	3G/4G
7th	Single X-ray Tube	Cone Beam	Multiple array of detectors