

Biophysics I

12. X-ray

2. basics of X-ray diagnostics

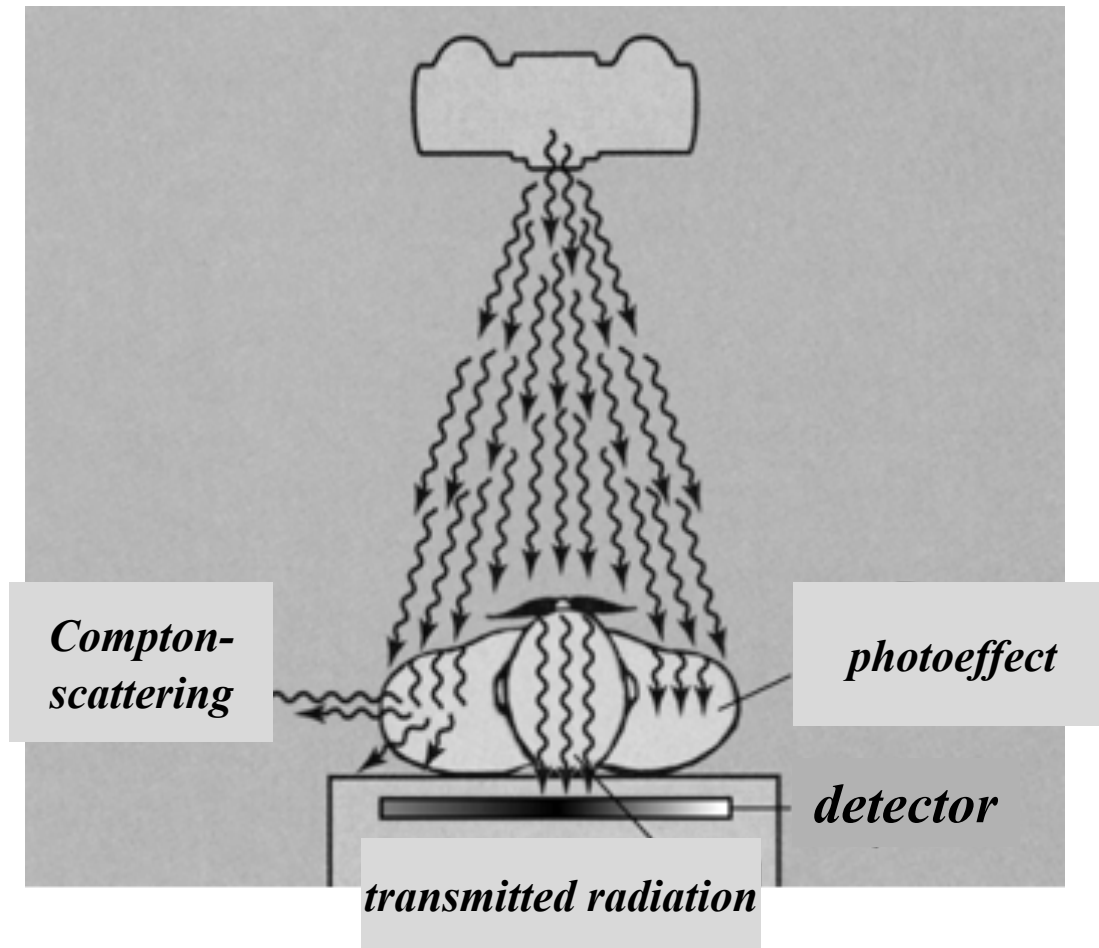
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26. 11. 2021.

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The basis of X ray diagnostics: absorption



Interactions of photon:

elastic scattering

photoeffect

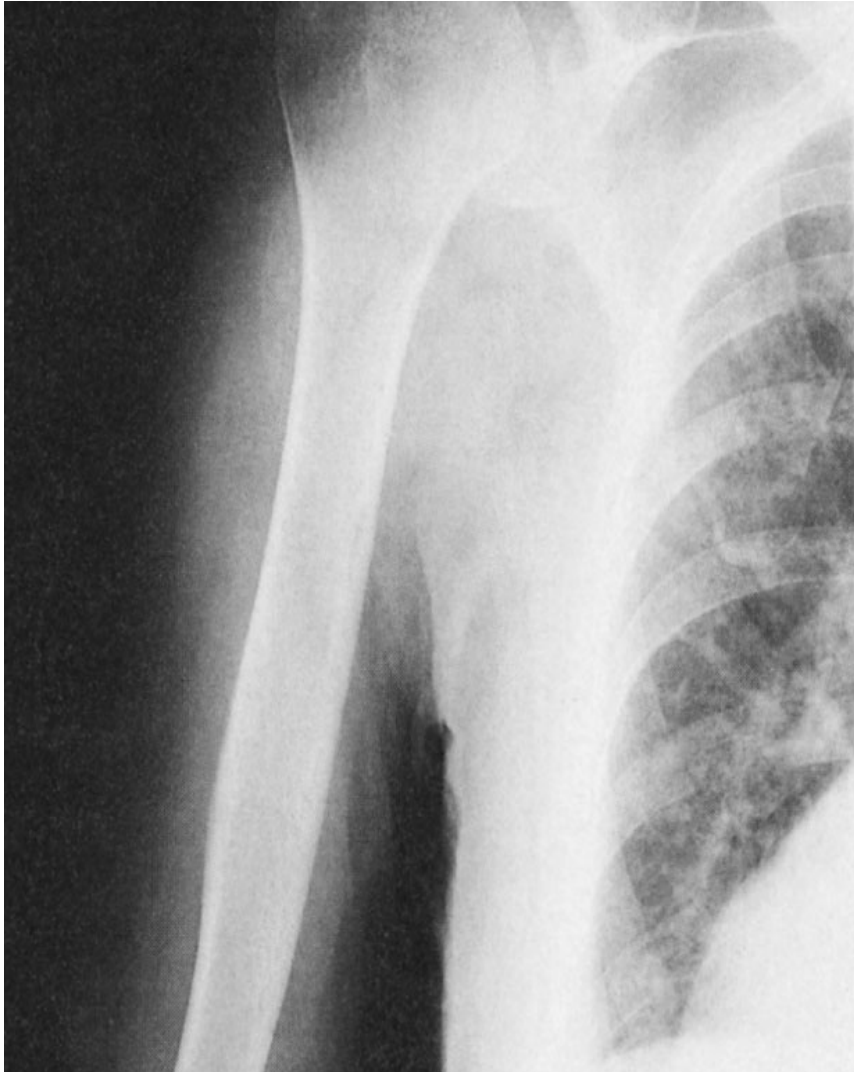
Compton scattering

pair production

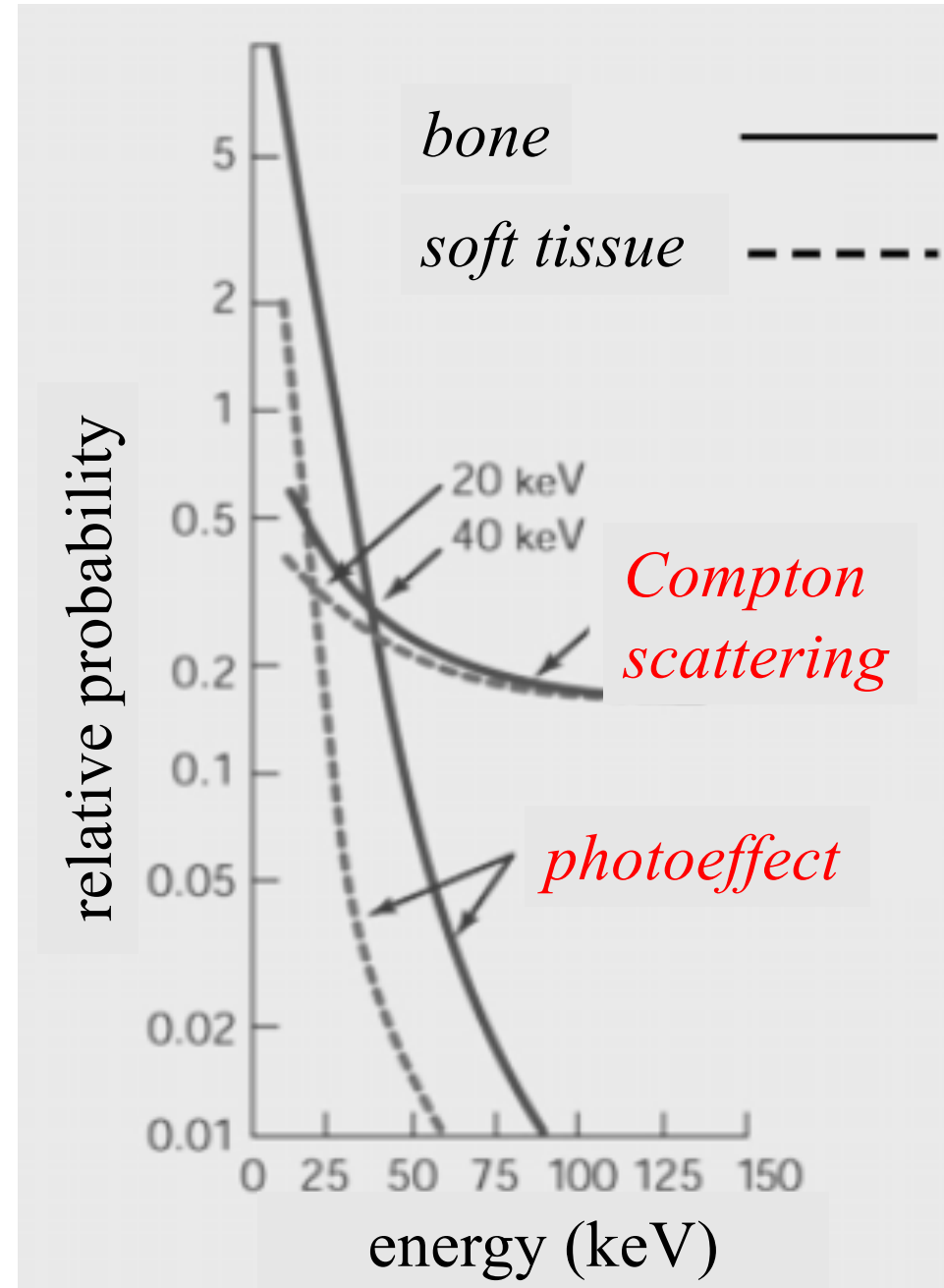
(no interaction)

Individual interactions' contributions depend on the photon energy and the atomic number

	Dependence on E	Dependence on Z	Energy range in soft tissue
τ_m	$\sim 1/E^3$	$\sim Z^3$	10 – 100 keV
σ_m	Slowly decreases with increasing E	$\sim Z/M$	0.5 – 5 MeV
κ_m	Slowly increases with increasing E	$\sim Z^2$	> 5 MeV
Elastic scattering	$\sim 1/E^2$	$\sim Z^2$	< 10 keV



Photoeffect and Compton scattering are the main contributors to image formation.

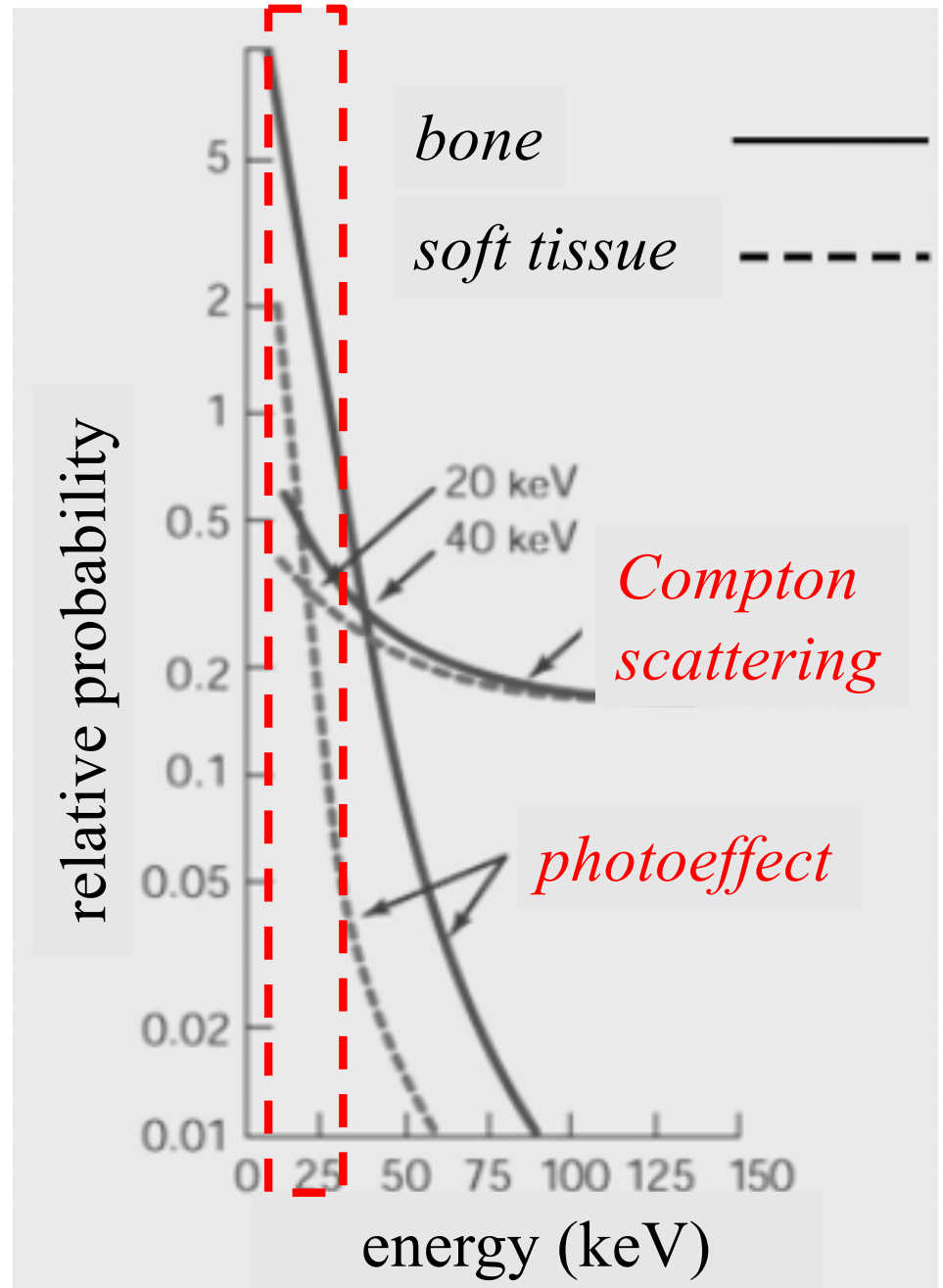


Increasing photon energy decreases attenuation by decreasing the photoeffect. In the low energy regime τ_m is dominating the attenuation process.

τ_m depends strongly on the atomic number:

$$\tau_m \approx \lambda^3 Z^3$$

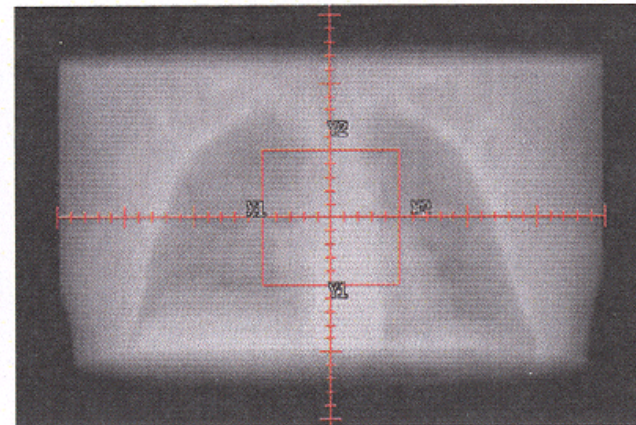
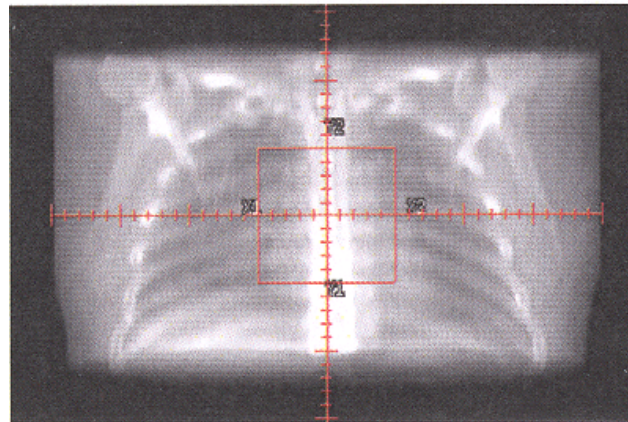
Change in photon energy can have a profound effect on the absorption process.



Photonenergy - picture quality

$$U_1 < U_2$$

(30 keV) *(2 MeV)*



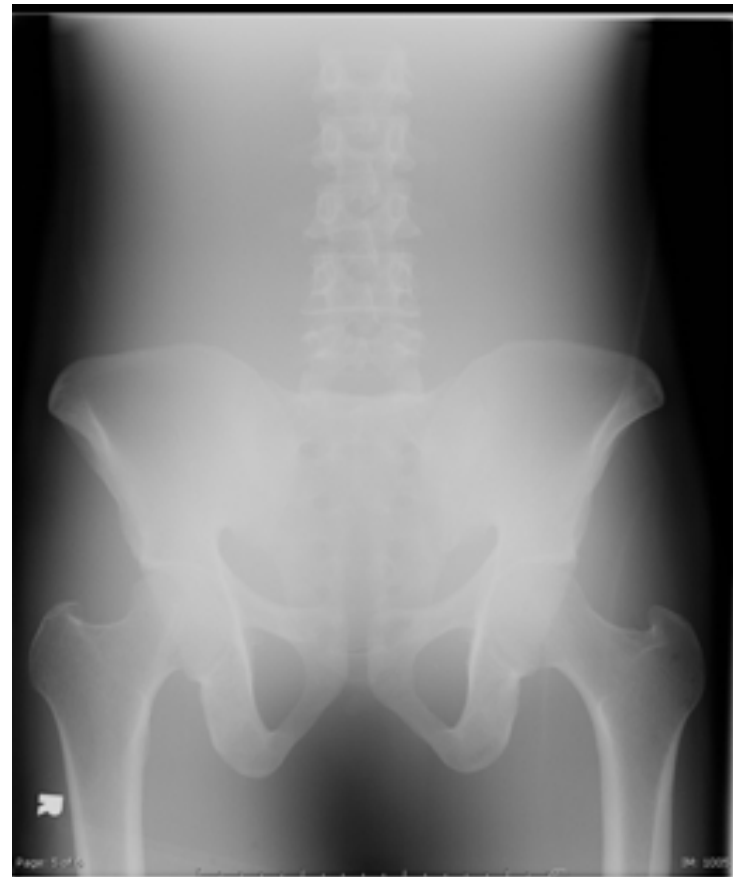
<i>Photoeffect*</i>	<i>36%</i>	<i>0%</i>
<i>Compton scattering*</i>	<i>51%</i>	<i>99%</i>
<i>Pair production*</i>	<i>0%</i>	<i>1%</i>

*Mean values

Photonenergy - picture quality

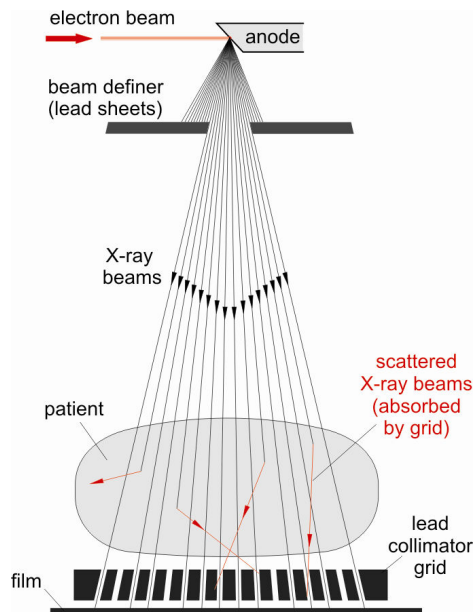


photonenergy: 60 keV
contrast ratio: 200:1
exposition: 141 mAs
dose: 7,6 mGy

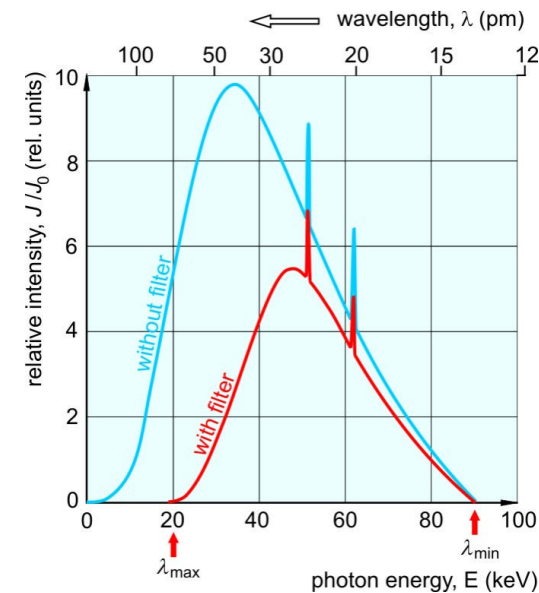


120 keV
60:1
6 mAs
1,4 mGy

Improving picture quality



with collimators

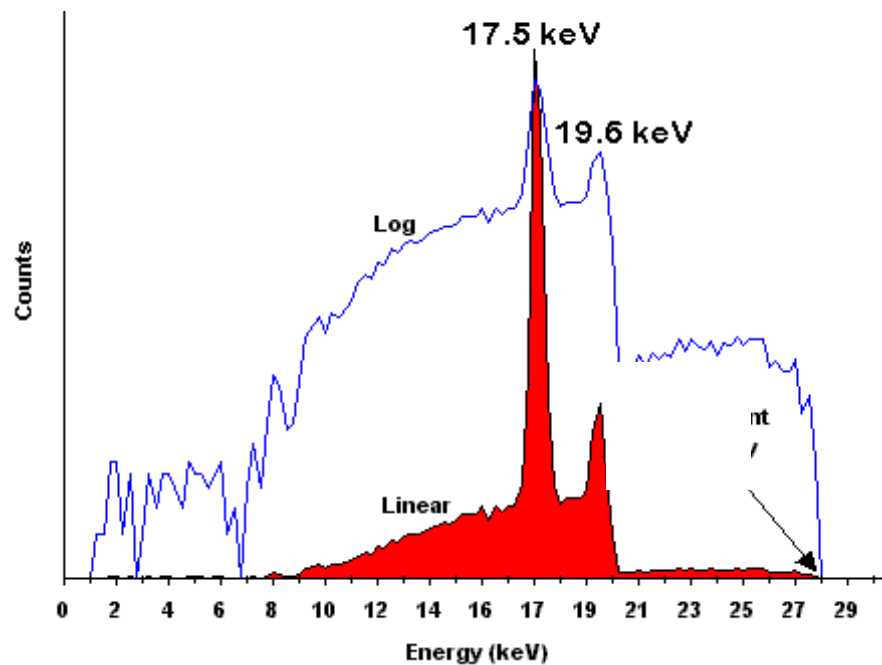


with filtering out soft X ray

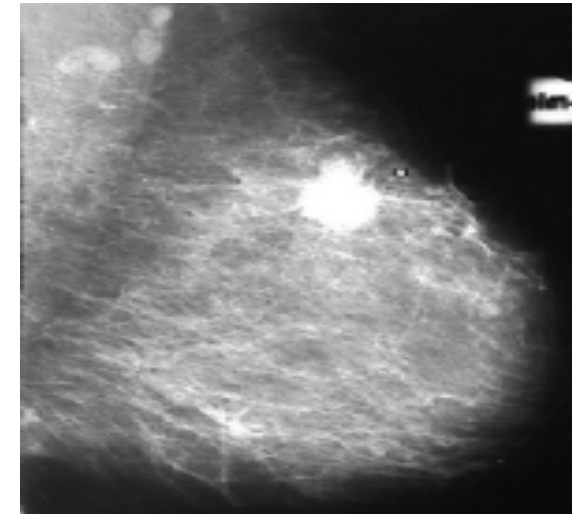
to reduce scattered radiation

– short exposure time to reduce unsharpness due to patient move

Spectrum of X ray used in mammography



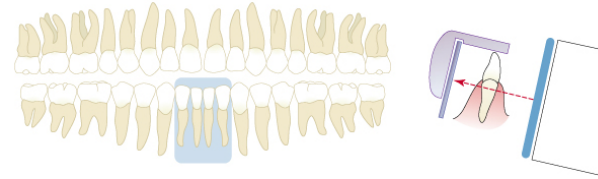
Characteristic lines of
Molybdenum



*Mammogram showing
malignant tissue*

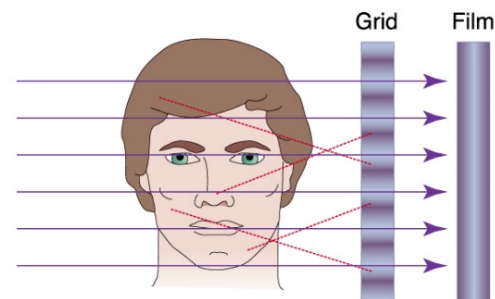


Intraoral radiography



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Extraoral radiography



----- Scatter radiation
→ Primary x-rays

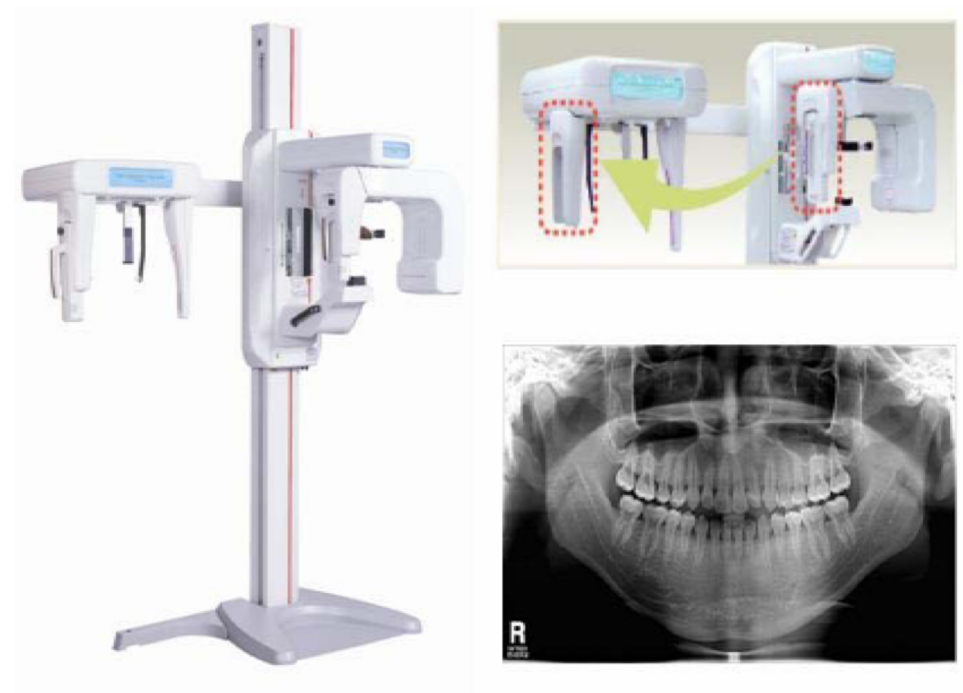
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Panoramic dentistry imaging

In panoramic imaging, the film and the source are rotated around the patient's head, taking several individual images. Combining these overlapping images results in a panoramic image of the maxilla and the mandible.

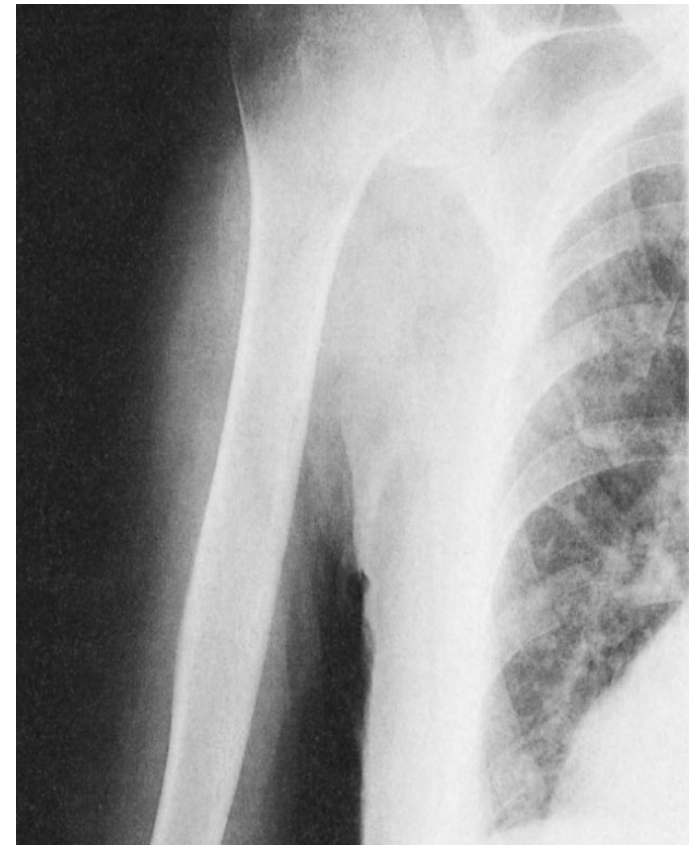


Effective atomic number

$$Z_{eff} = \sqrt[3]{\sum_{i=1}^n w_i Z_i^3}$$

$$\tau_m = C \lambda^3 Z_{eff}^3$$

material	Z_{eff}
air	7,3
water	7,7
soft tissue	7,4
bone	13,8



Applying contrast materials

Soft tissues hardly show differences based on photoeffect

$$\tau_m = C\lambda^3 Z_{eff}^3$$

but Z_{eff} or the density can be changed!

	Z_{eff}	$\rho \text{ (g/cm}^3\text{)}$
H ₂ O	7.7	1
Soft tissue	7.4	1
Bone	13.8	1.7 - 2.0
Air	7.3	$1.29 \cdot 10^{-3}$

Positive contrast \rightarrow *higher attenuation to surroundings*

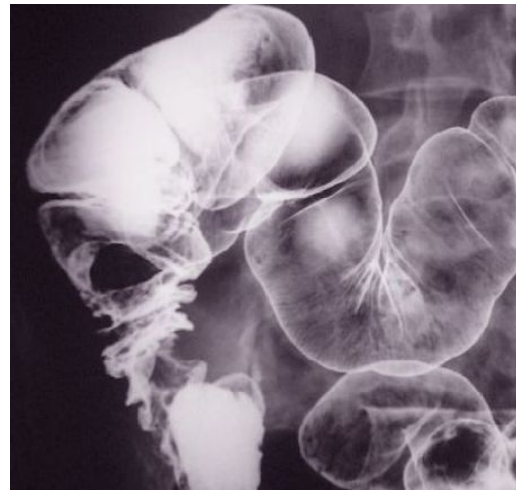
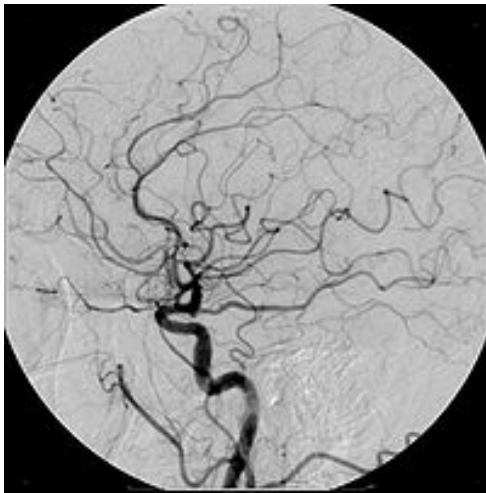
$$Z_{eff} > Z_{environment} \rightarrow \mu > \mu_{environment}$$

Negative contrast \rightarrow *lower attenuation to surroundings*

$$Z_{eff} < Z_{environment} \rightarrow \mu < \mu_{environment}$$

Applying contrast materials

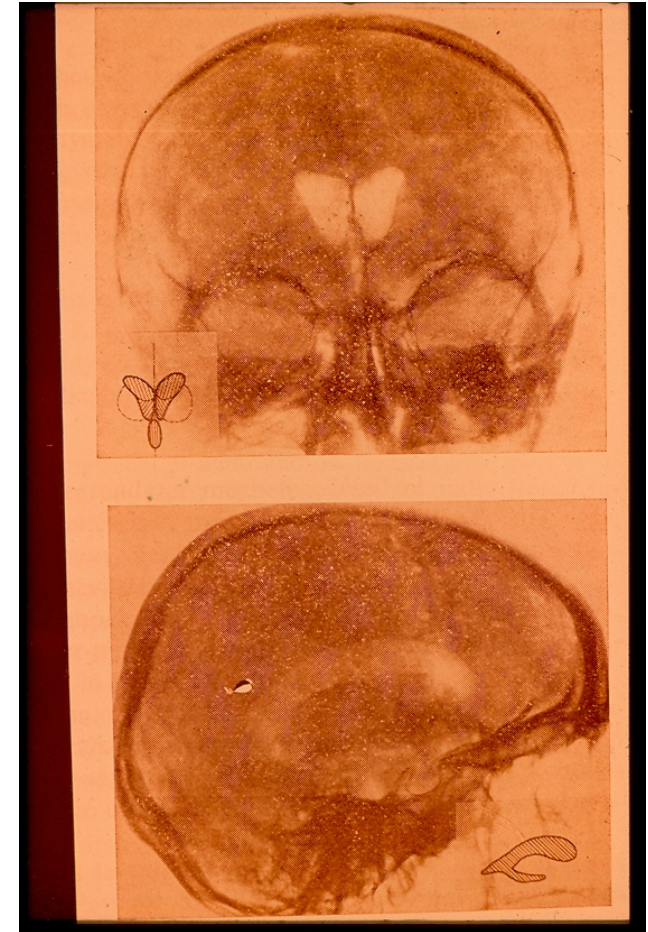
higher Z_{eff}



Iodine or barium compounds

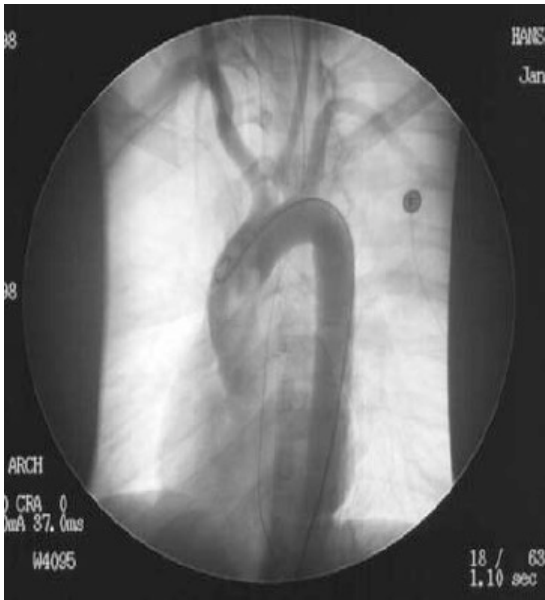


lower density



air, CO_2

Digital Subtraction Angiography (DSA)



*with contrast
material*



native



contrast - native

X ray image formation:

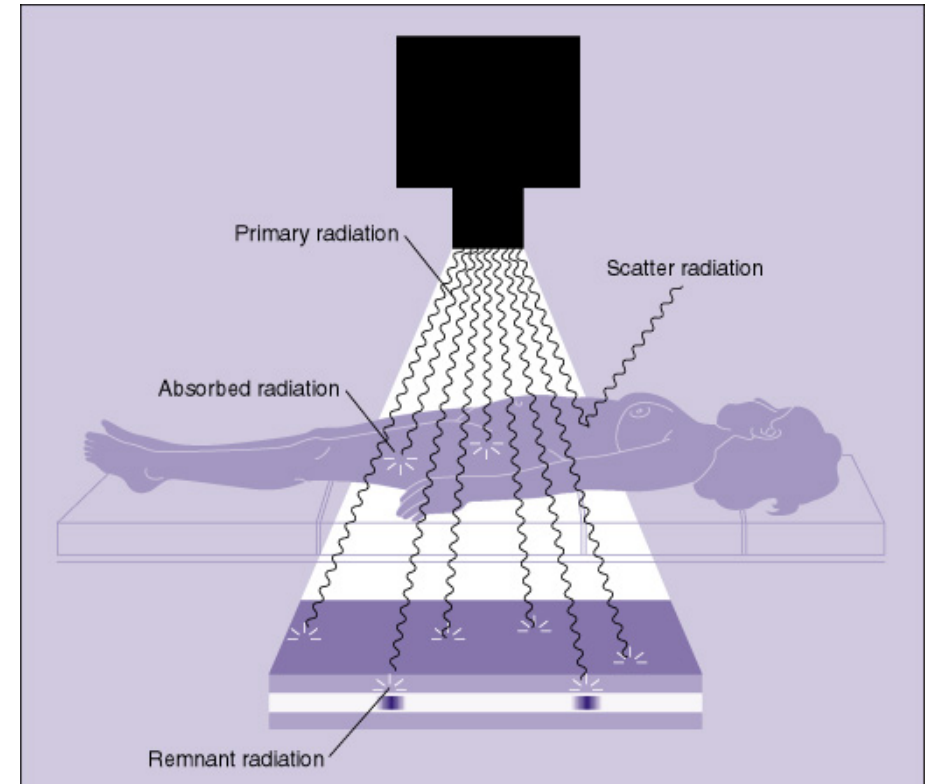
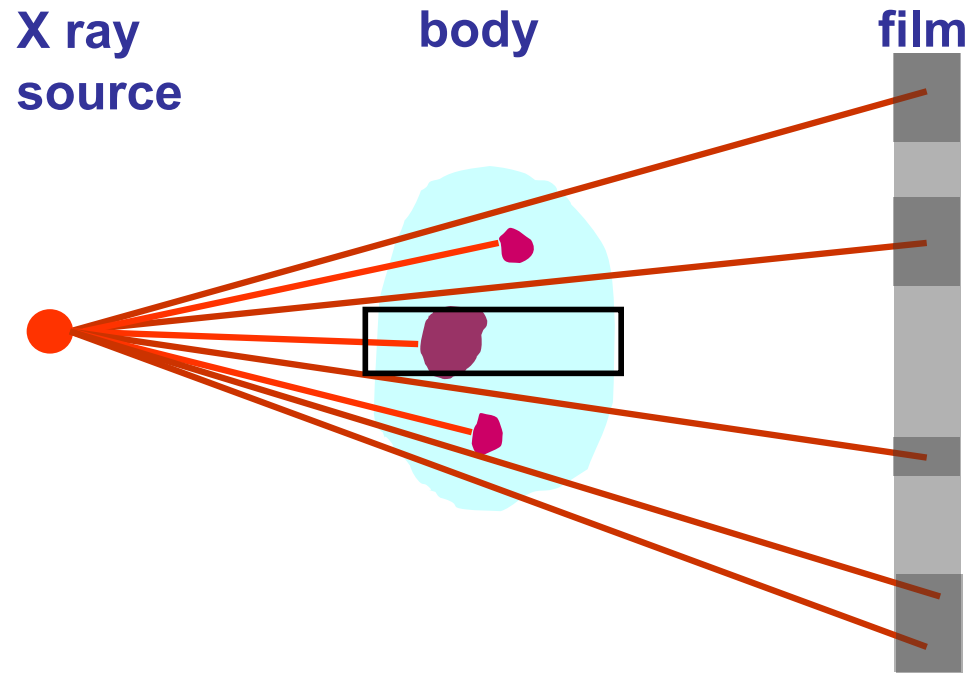
*Depicting intensity differences
of radioation travelled through
the specimen*

Visualize image with

- X ray film
- luminescence screen
- a digitized image



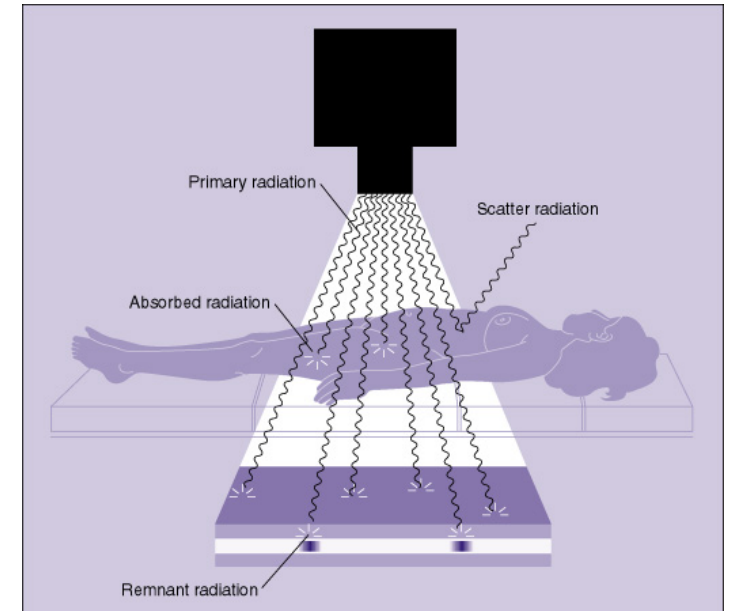
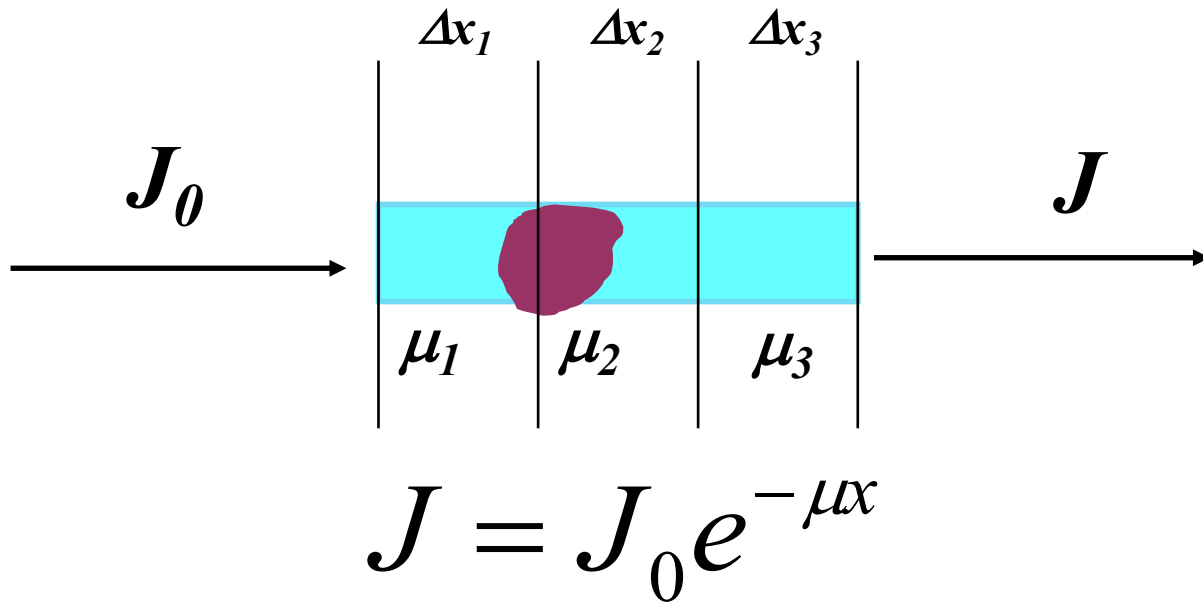
Summation image



A diagram showing a beam of radiation with initial intensity J_0 entering a body (represented by a light blue rectangle with a dark purple irregular shape inside). The radiation exits the body with a final intensity J . Below the diagram, the equation for the attenuation of radiation is given:

$$J = J_0 e^{-\mu x}$$

Intensity changes are proportional with the total attenuation across the body!



$$J = J_0 e^{-(\mu_1 + \mu_2 + \mu_3) \Delta x}$$

This information is missing!

$$D = \lg \frac{J_0}{J}$$

$$D = \sum_i D_i$$

Solution:

CT - computed tomography



Godfrey Hounsfield



Allan Cormack

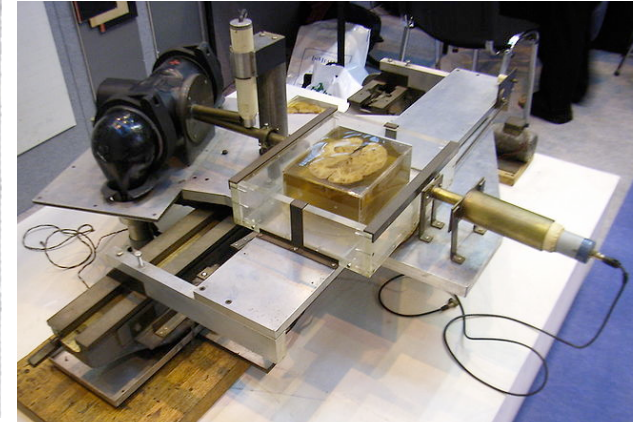
1979 – Nobel price in medicine

Brief history:

- 1967: first CT image
- 1972: prototype of CT
- 1974: first clinical CT image
- 1976: whole body CT
- 1979: Nobel price
- 1990: spiral CT
- 1992: multislice CT
- 2006: 64 slices
- multiplex and hybrid CT:
SPECT-CT, PET-CT,
“Dual-source” CT



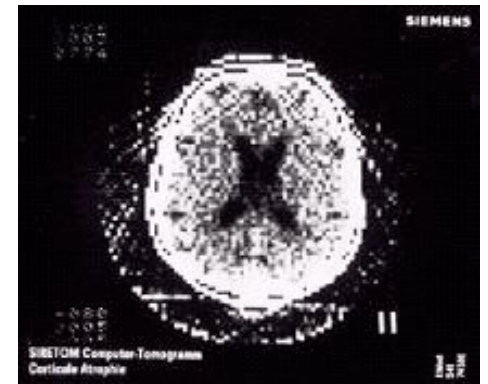
First lab CT of brain slice



Prototype CT (EMI)



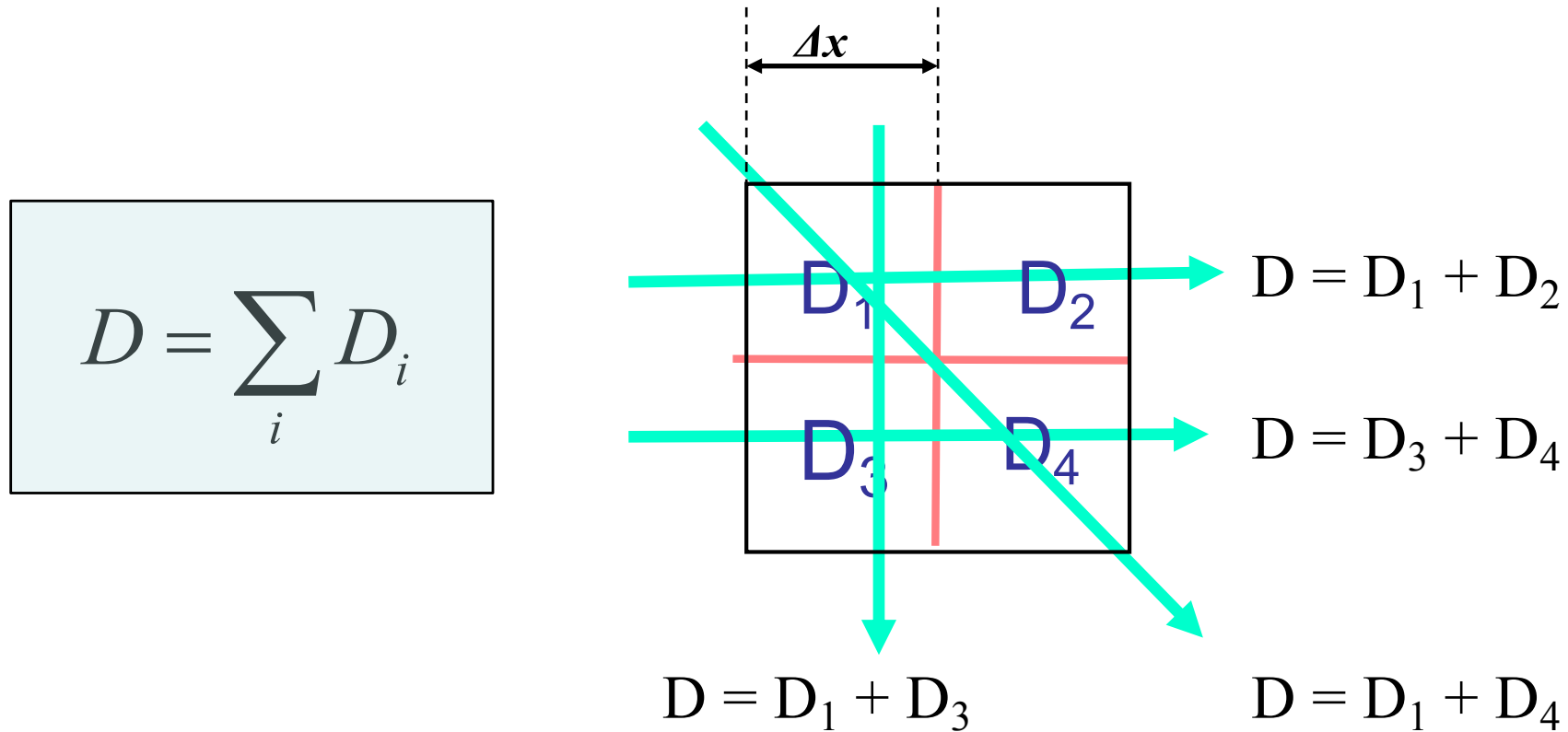
„Siretom” head scanner (1974)



128x128 pixel image (1975)



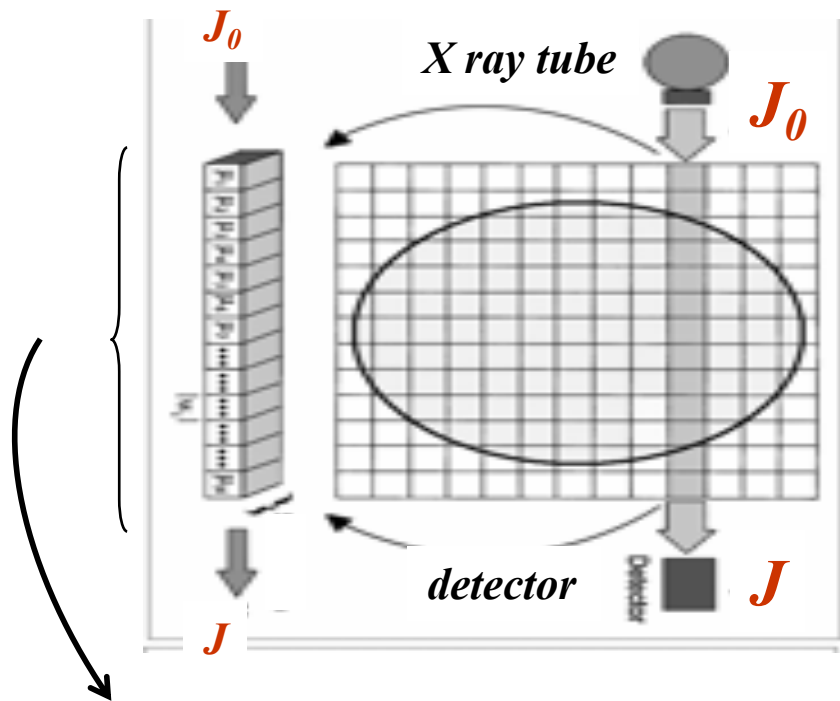
Illustration of math principle:



“n” independent equation for „n” unknowns
→ unambiguous solution exists!

object

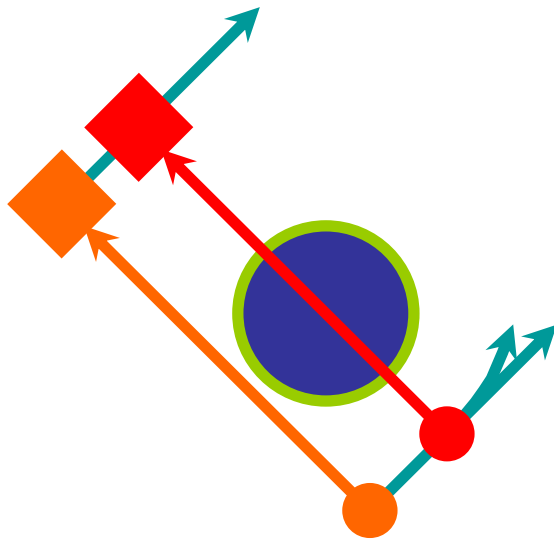
digital image



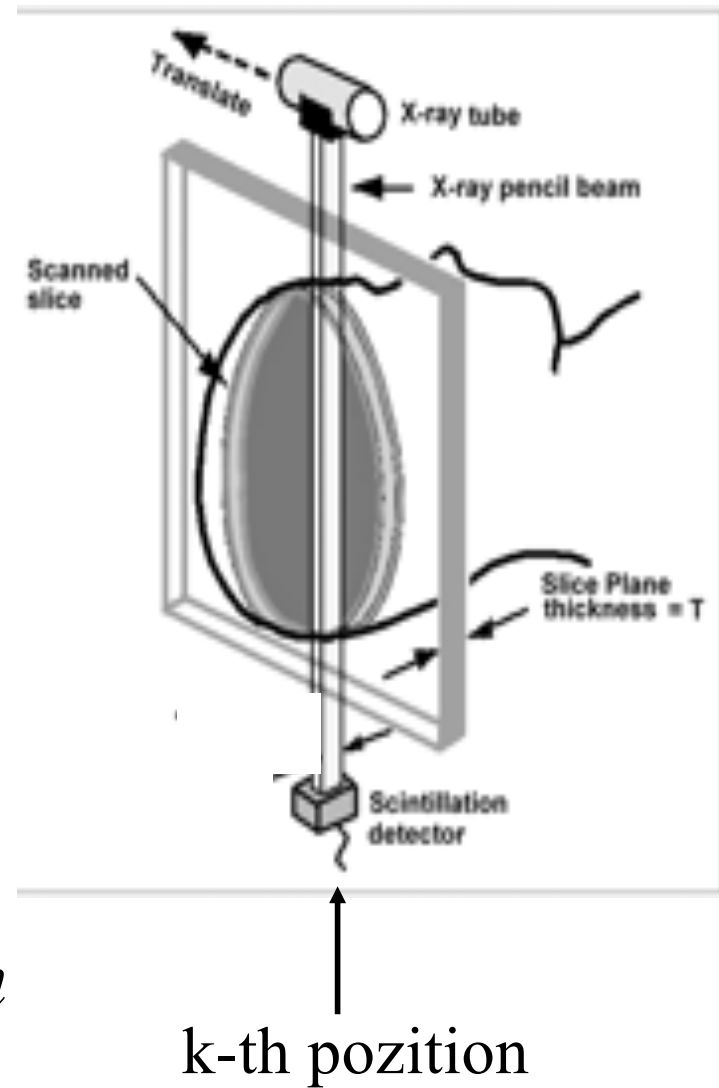
Voxel :
volume element

Pixel :
picture element

First generation CT



Single detector
Translation and rotation
Parallel beams



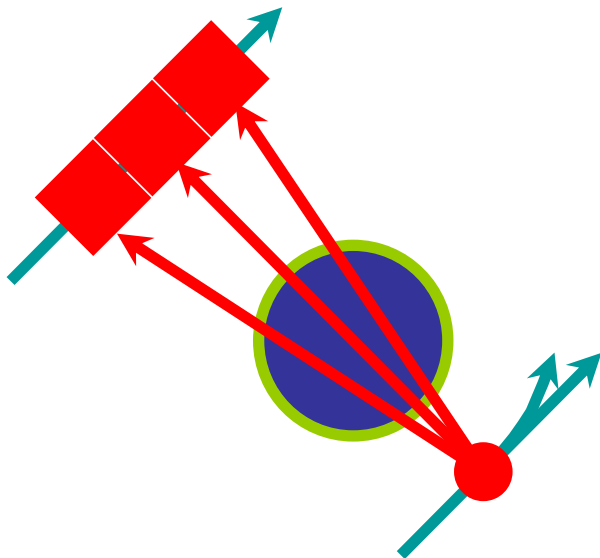
First generation CT

1st Gen Rotating CT



Second generation CT

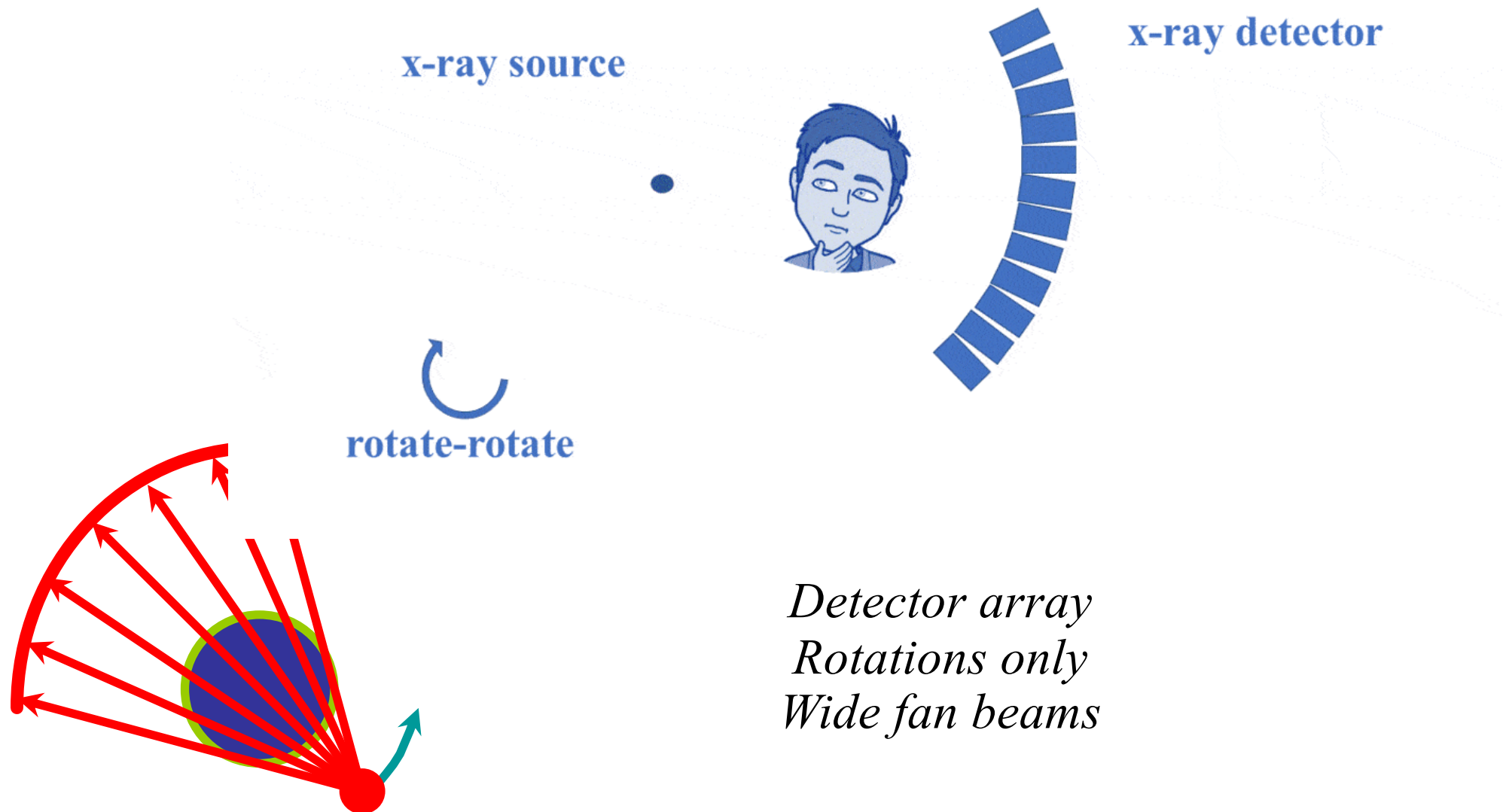
2nd Gen CT



*Multiple detectors
Translation and rotation
narrow fan beams*

Third generation CT

3rd Gen CT



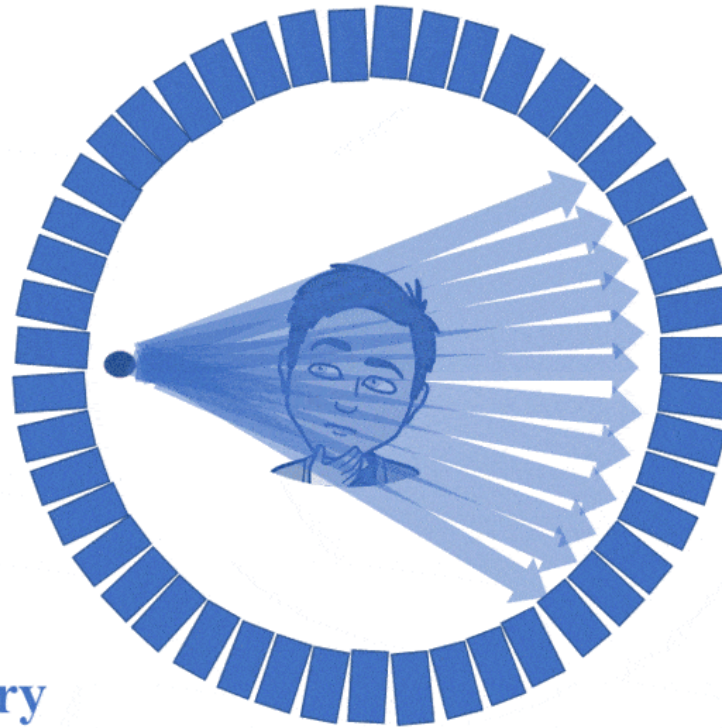
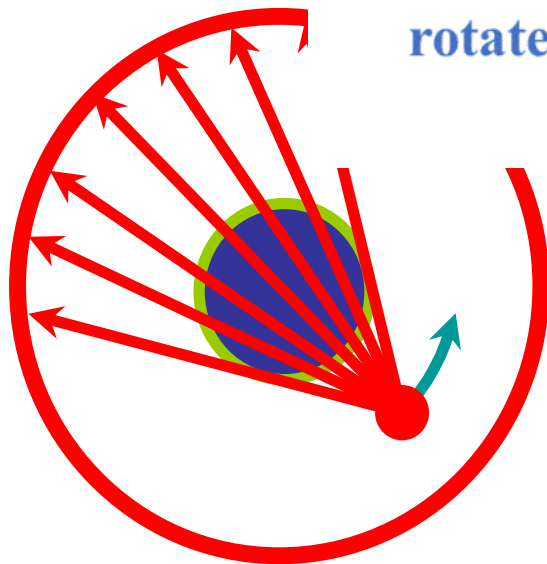
Fourth generation CT

4th Gen CT

x-ray source

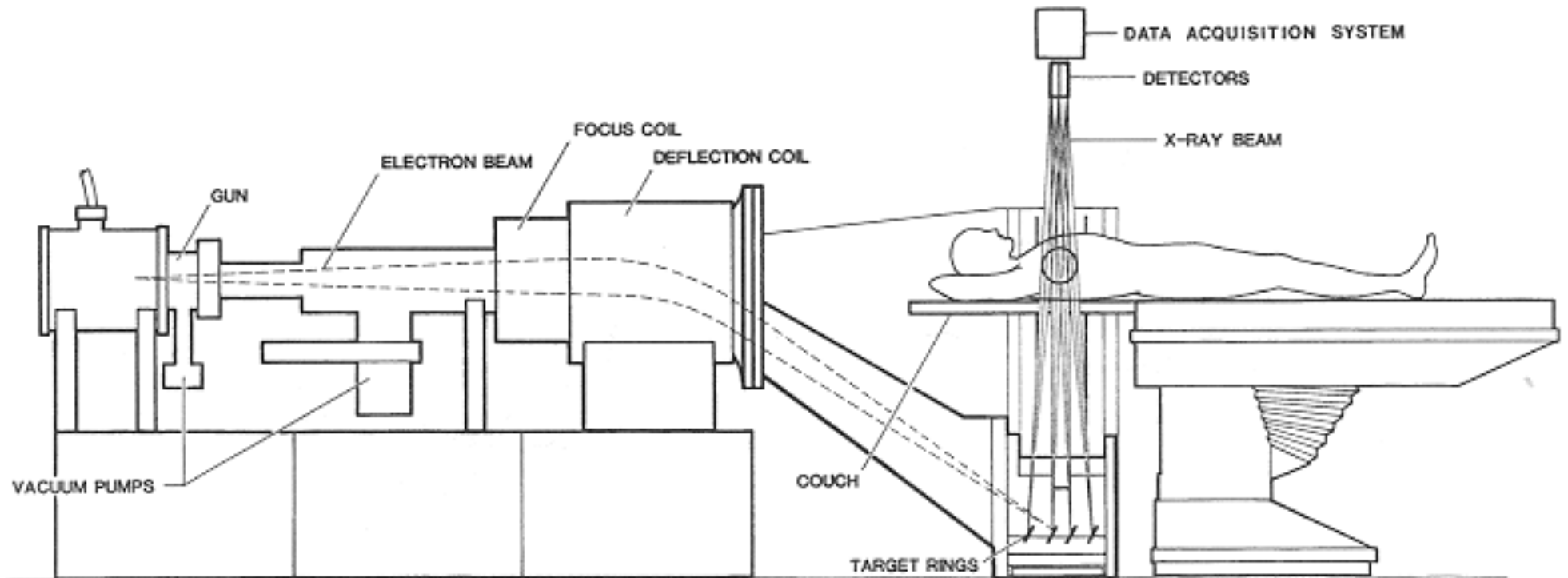
x-ray detector

rotate-stationary



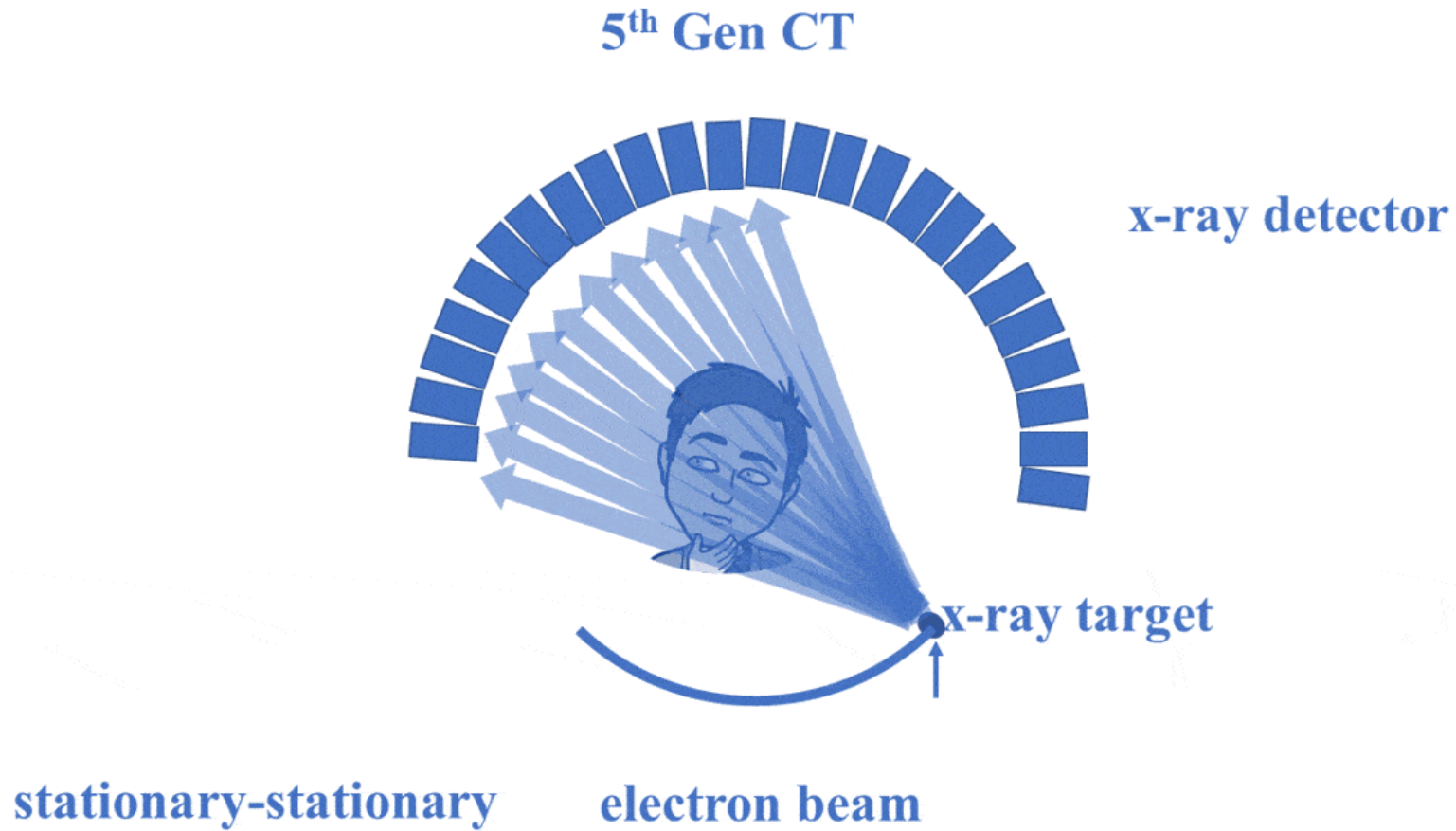
*Detector ring fixed
Rotation of X ray source only
Wide fan beams*

Fifth generation CT



Electron gun instead of X ray tube. Electron beam directed on fixed W-target.

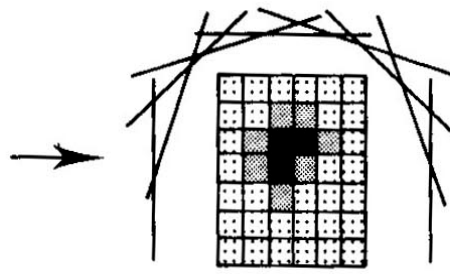
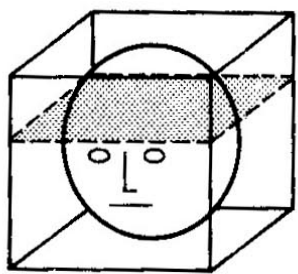
Fifth generation CT



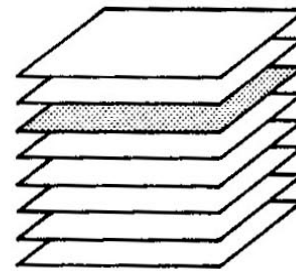
Comparison of CT generations

Generation	Year	Why Developed	Anatomy	Source-Detector Movement	Time to acquire 1 image	Why it died?
1 st Gen	1971	To show CT works	Head Only	Translate-Rotate	~5 min	Slow
2nd Gen	1974	Image Faster	Head Only	Translate-Rotate	20sec-2min	Slow
3rd Gen	1975	Image Faster	All Anatomy	Rotate-Rotate	1 sec	This Geometry won.
4th Gen	1976	Make images without rings	All Anatomy	Rotate-Stationary	1 sec	Expensive, not good for scatter.
5th Gen	1980s	Fast Cardiac CT	Cardiac Only	Stationary-Stationary	50 ms	Cardiac specific, low x-ray flux.

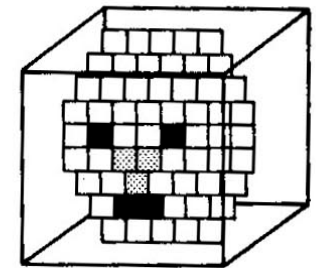
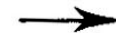
3D reconstructions



Many 1D projections
are used to reconstruct
a single slice of data

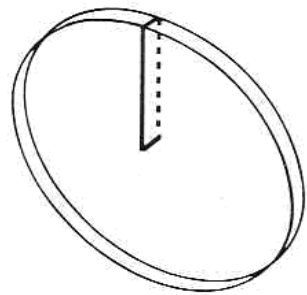


Many 2D slices

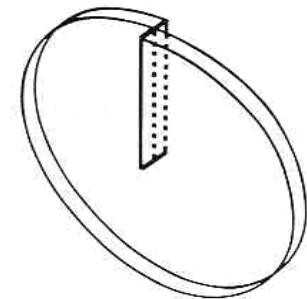
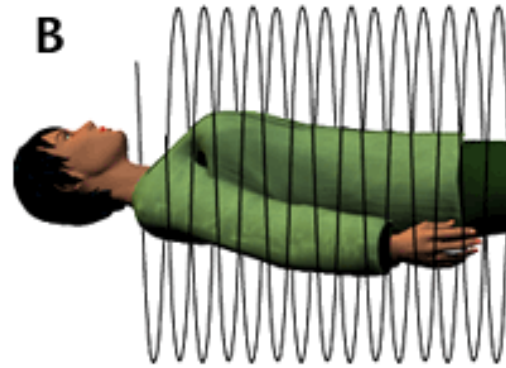
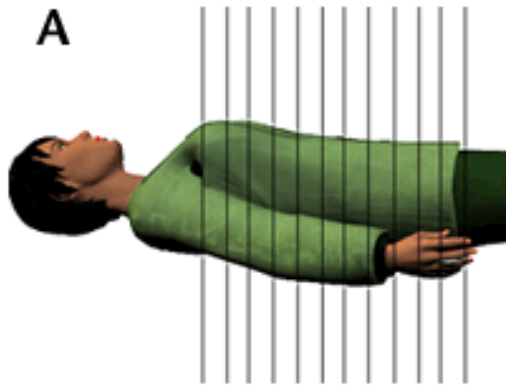


One 3D voxel model

Spiral CT

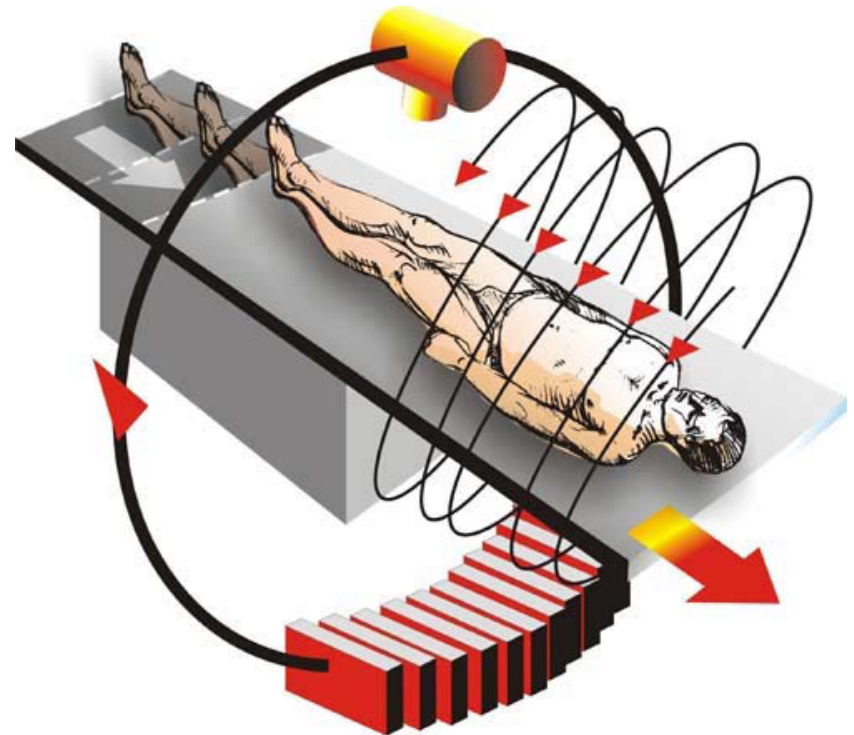
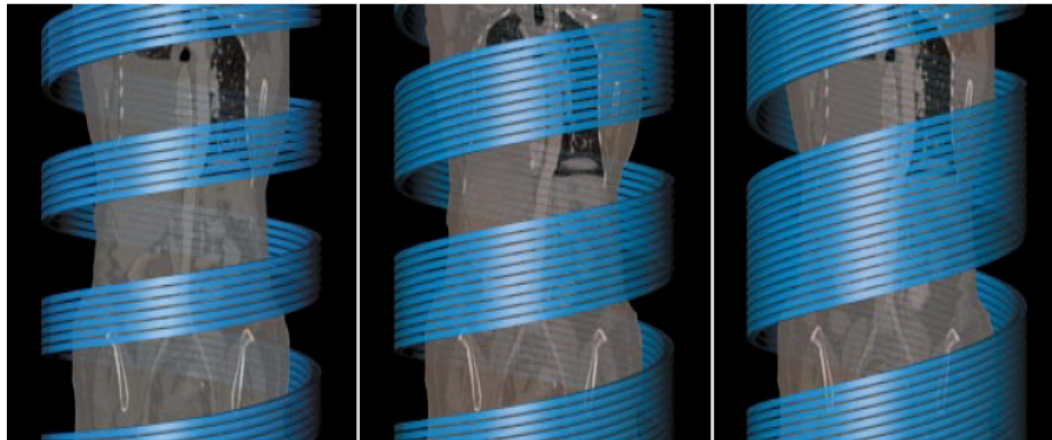


Conventional
CT slice



Spiral CT
slice

Precise 3D reconstruction
faster data acquisition



Dentistry: Cone beam CT

- *Cone-beam computed tomography (CBCT), C-arm CT, cone beam volume CT, flat panel CT*
- *Conical X ray beams*
- *Volumetric data produced, needs digital image reconstruction*
- *Dentistry, interventional radiology, radiotherapy*

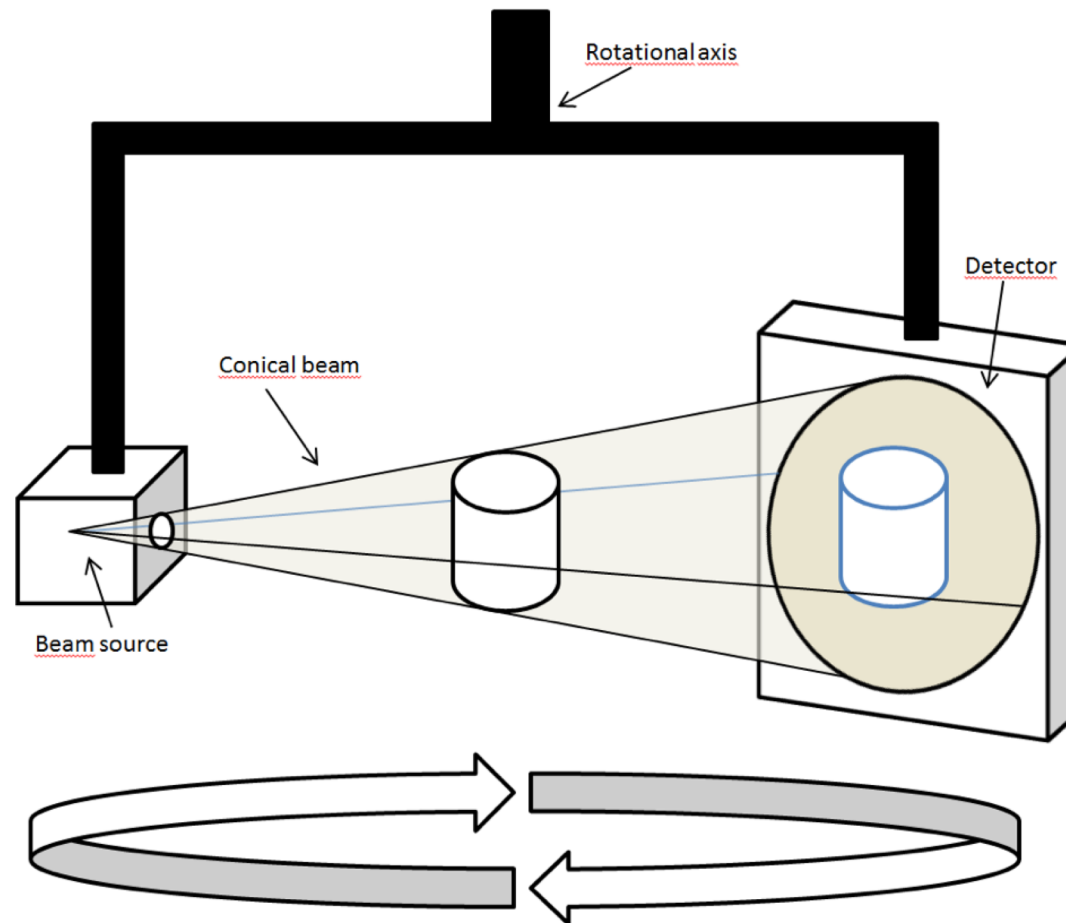


Image reconstruction

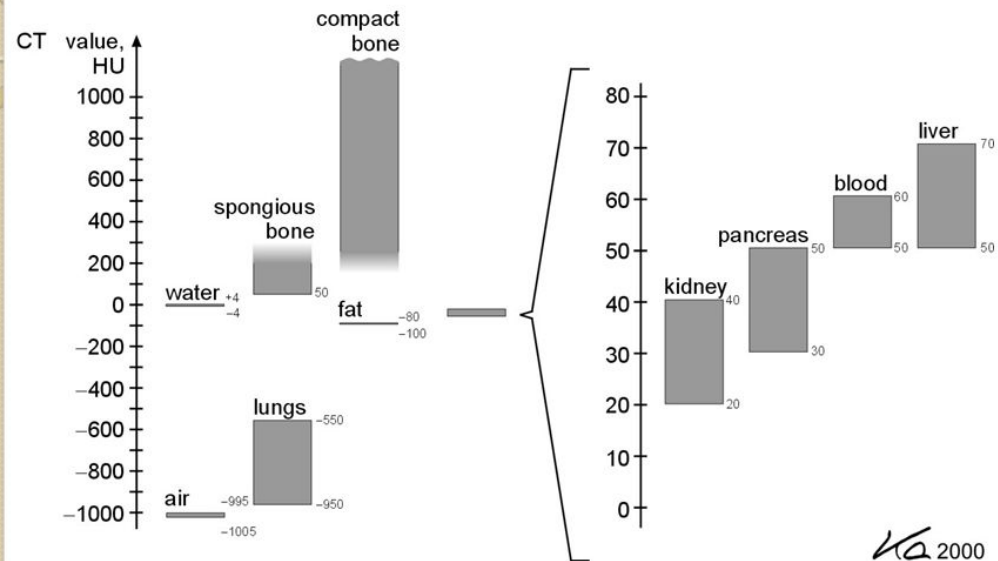
– density matrices

– *Hounsfield units*

$$H_{CT} = 1000 \frac{\mu - \mu_{\text{water}}}{\mu_{\text{water}}}$$

Hounsfield scale

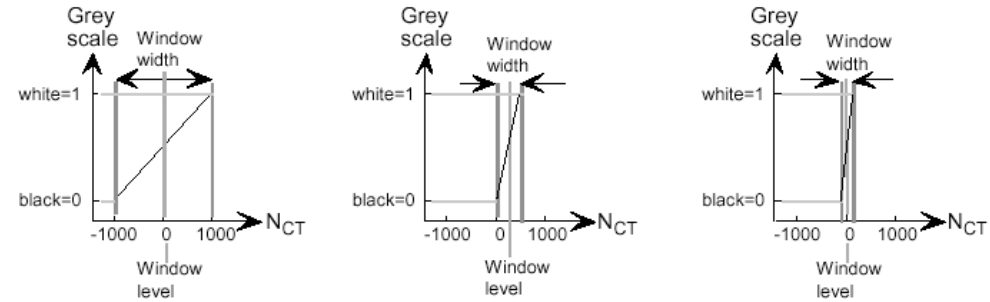
Hounsfield units of tissues



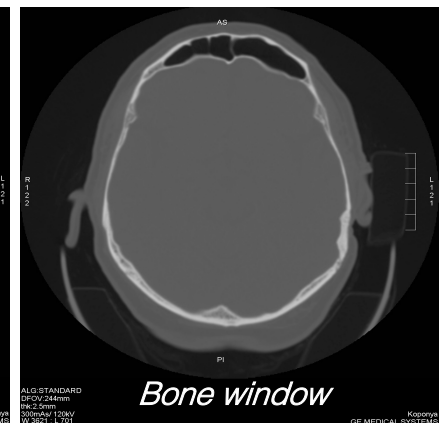
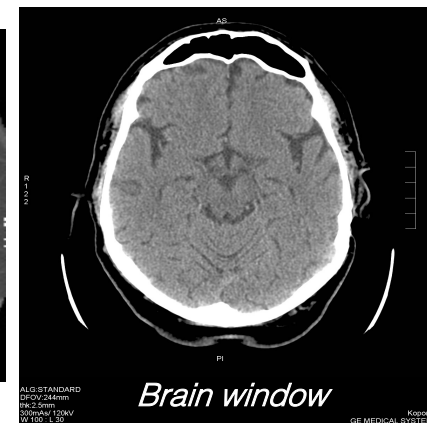
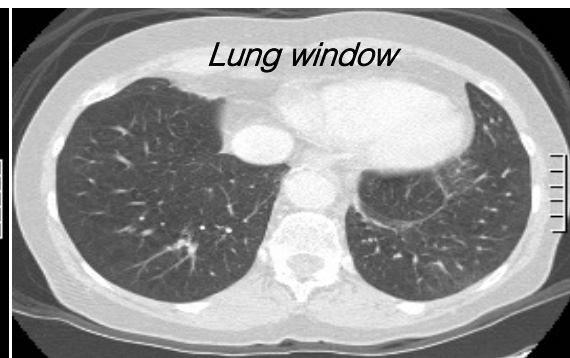
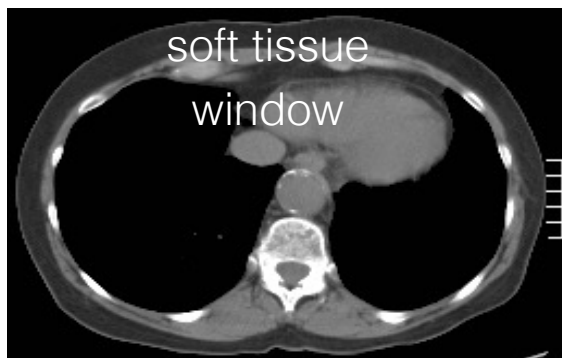
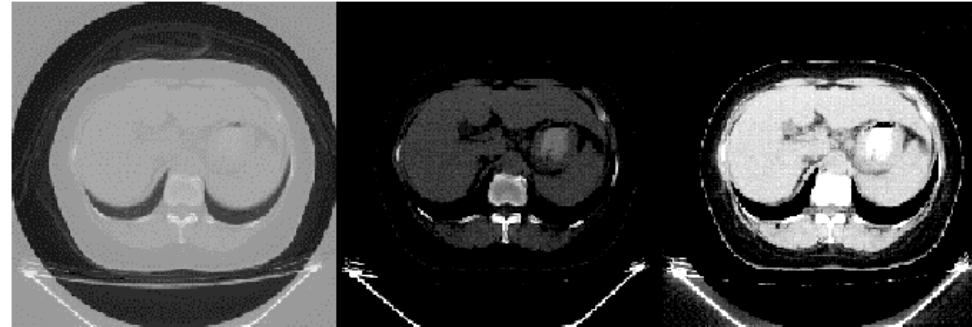
Taken from [1]

KA 2000

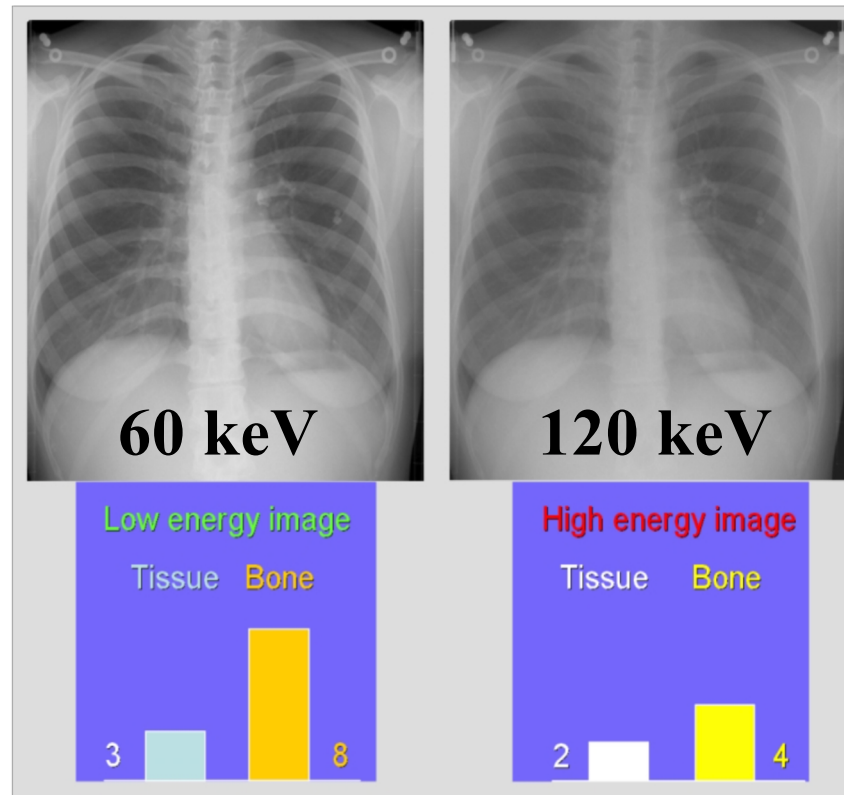
CT contrast enhancement „windowing”



Same thoracic image
with different windowing



Contrast enhancement with dual source CT



Weighted subtraction and scaling

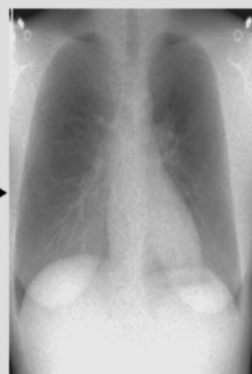
Tissue only: remove bone signal

Choose constants to remove bone:

$$(\text{high} * 2 - \text{low} * 1) * k_t \xrightarrow{\text{Tissue signal scaling factor, } k_t}$$

$$(4 * 2 - 8 * 1) = 0 \text{ (bone residual)}$$

$$(2 * 2 - 3 * 1) = 1 \text{ (soft tissue residual)}$$



Bone only: remove tissue signal

Choose constants to remove tissue:

$$(\text{low} * 2 - \text{high} * 3) * k_b \xrightarrow{\text{Bone signal scaling factor, } k_b}$$

$$(8 * 2 - 4 * 3) = 4 \text{ (bone residual)}$$

$$(3 * 2 - 2 * 3) = 0 \text{ (soft tissue residual)}$$



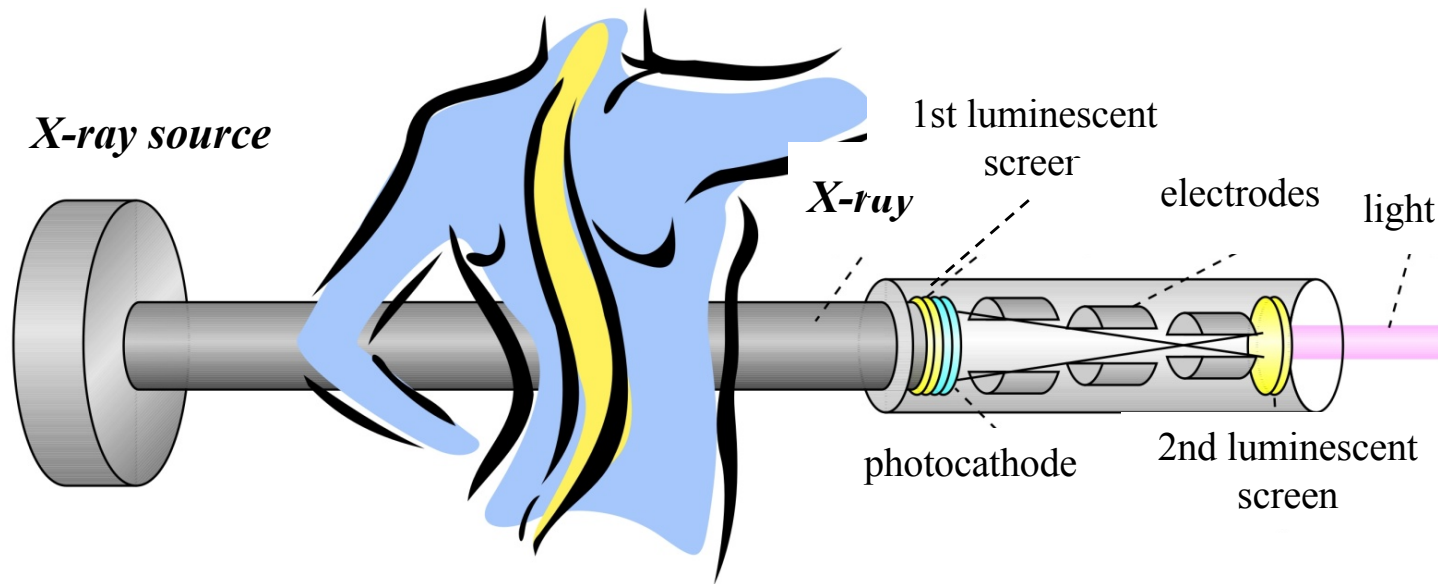
Brief summary of *CT*

- Imaging is based on the differences in X ray absorption / attenuation
- 3D image that can viewed and manipulated, and combined with other imaging techniques
- Spiral CT: one slice – 1 - 1.5 s, total time: 30 - 60 s
- Multislice spiral CT (4-64 detectors): one slice – 0.4 - 1 s, total: 5 - 15 s

limitations of *CT*

- Ionizing radiation
- Dose can be as high as 50-100-times the conventional X ray!
- Indirect exposition due to scattered radiation

X-ray image intensifier



Possibility of image digitization

Smaller patient exposure

Manipulation under X-ray control

Checklist

Absorption of X-ray

Mass-attenuation coefficient

Basic concept of X-ray imaging

Optimal setting of X-ray tube

Summation image – role of the atomic number

Contrast materials

Panoramic X-ray

X-ray image amplifier

Concept of CT

Hounsfield unit

Generations of CT

Damjanovich, Fidy, Szöllősi: Medical Biophysics

VIII. 3.1

3.1.1

3.1.2

VIII.4.3