Biophysics I

12. X-ray diagnostics

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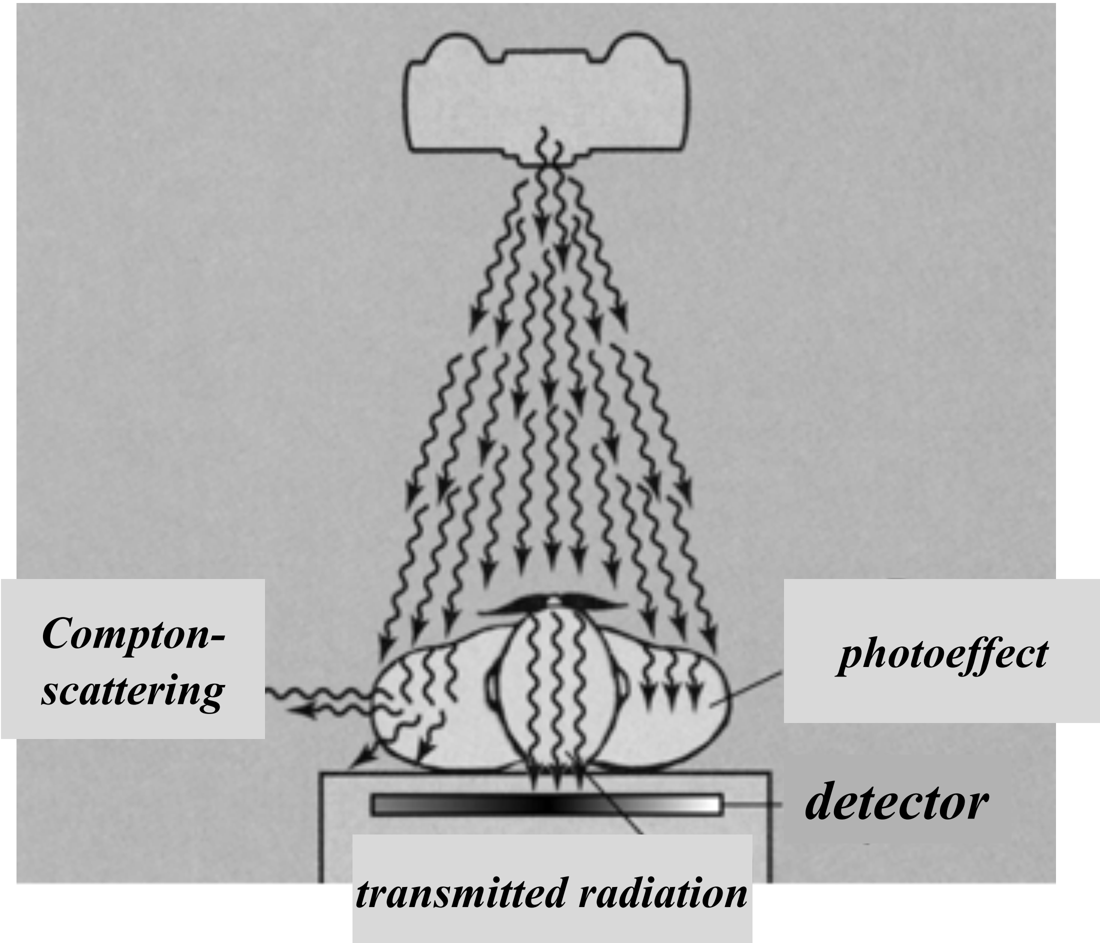
The basis of X ray diagnostics: absorption



Interactions of photon:

elastic scattering

photoeffect

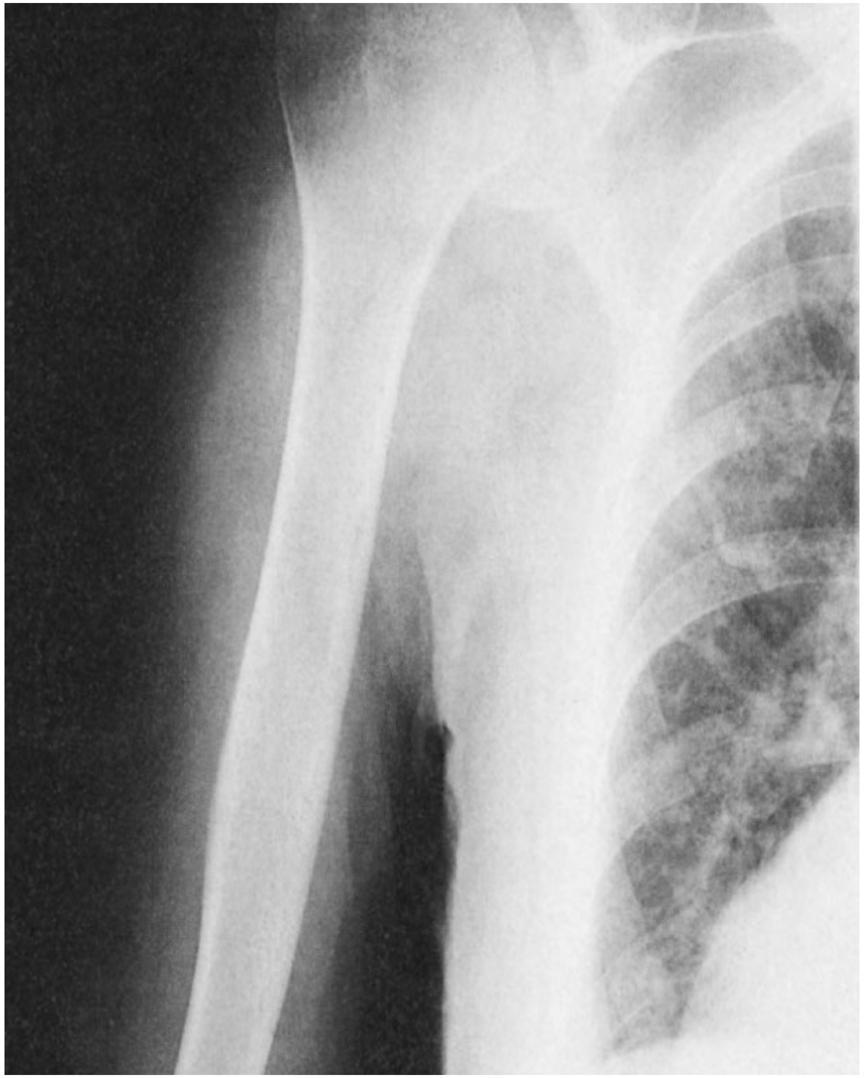
Compton scattering

pair production

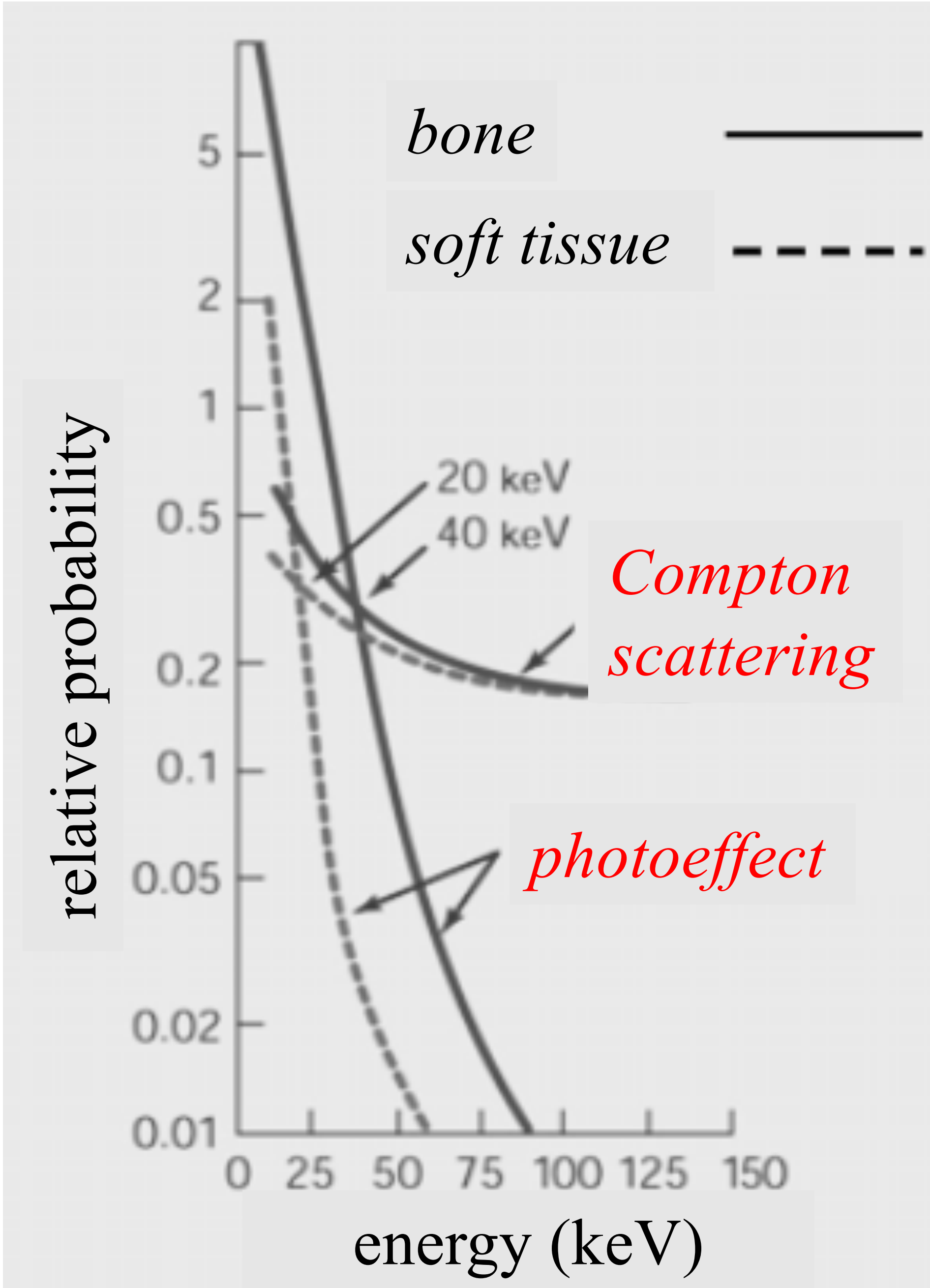
(no interaction)

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.

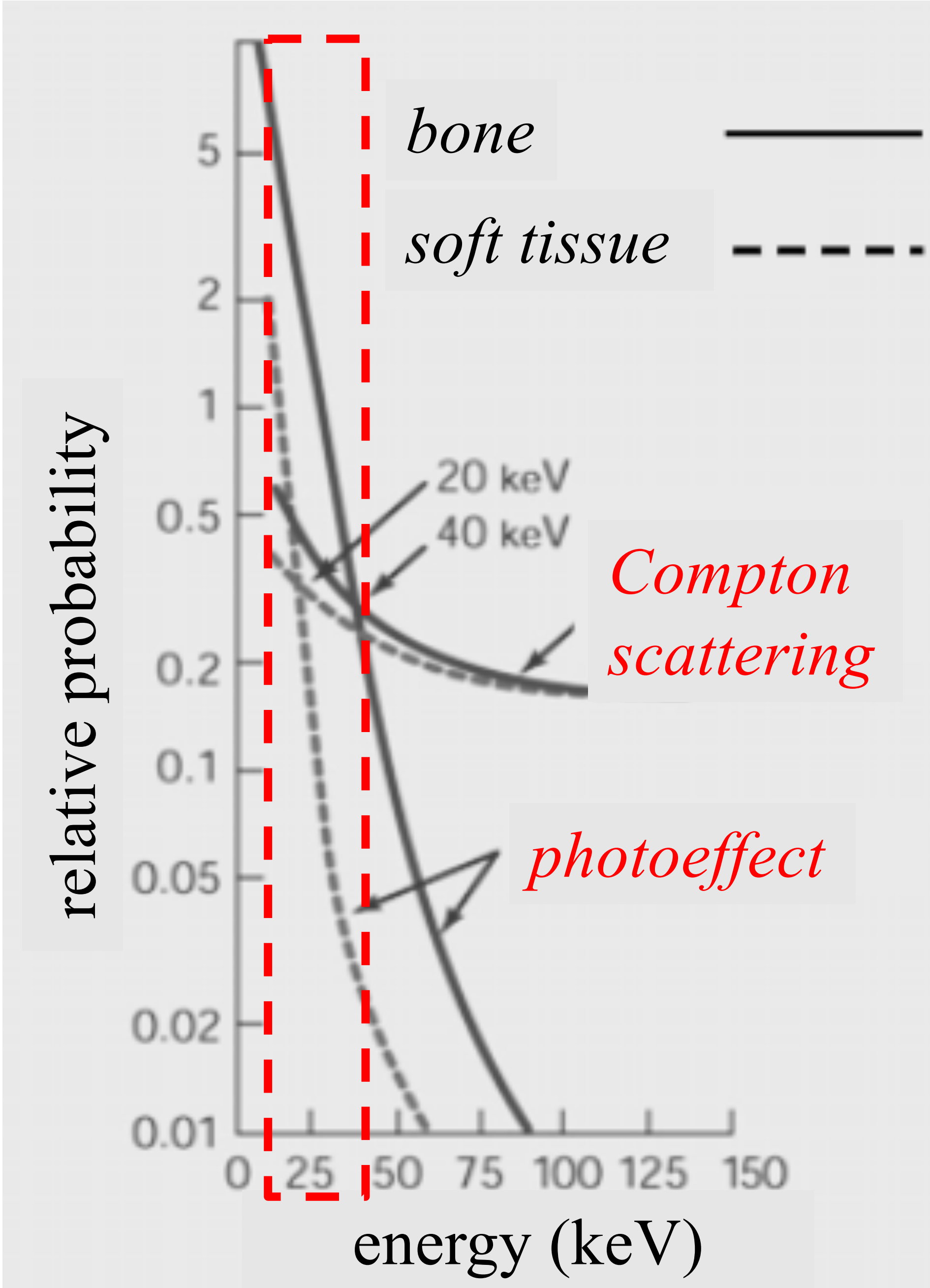


Increasing photon energy decreases attenuation by decreasing the photoeffect. In the low energy regime τ_m is dominating the attenuation process.

τ_m depends strongly on the atomic number:

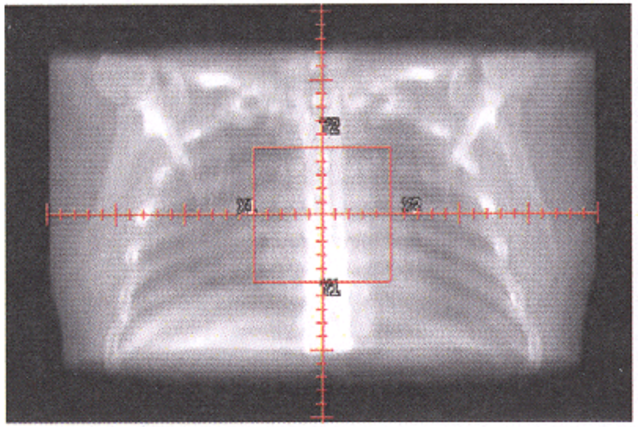
$$\tau_m \approx \lambda^3 Z^3$$

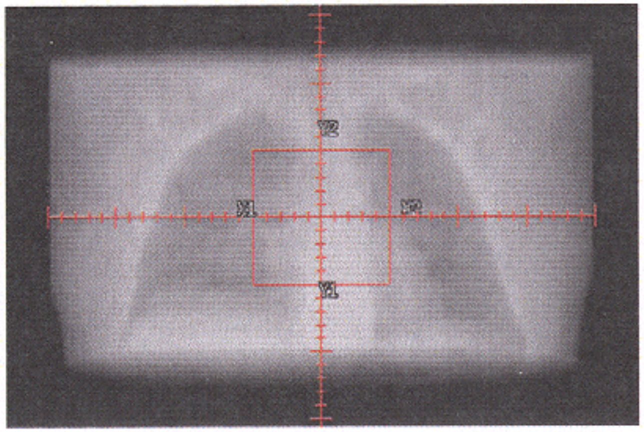
Change in photon energy can have a profound effect on the absorption process.



Photonenergy - picture quality

U_1	<	U_2
(30 keV)		(2 MeV)





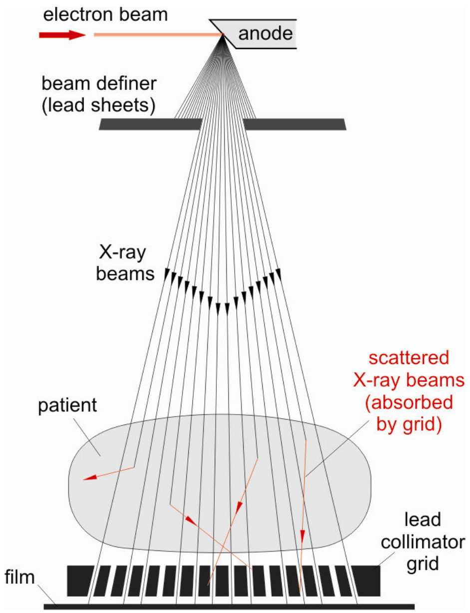
*Photoeffect**	*36%*	*0%*
*Compton scattering**	*51%*	*99%*
*Pair production**	*0%*	*1%*

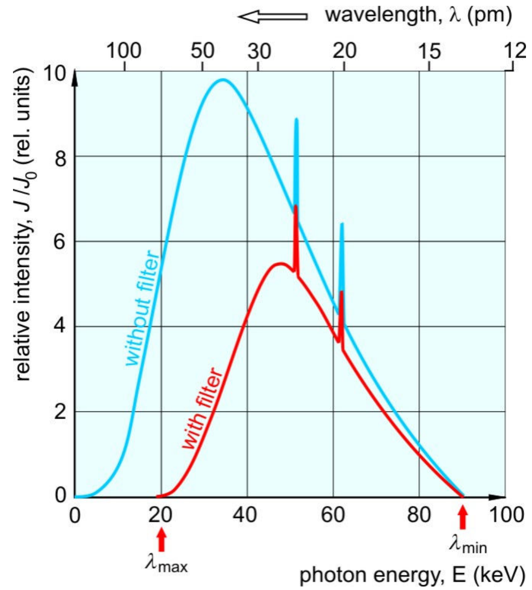
*Mean values

Photonenergy – picture quality

photonenergy:	60 keV	120 keV
contrast ratio:	200:1	60:1
exposition:	141 mAs	6 mAs
dose:	7,6 mGy	1,4 mGy

Improving picture quality



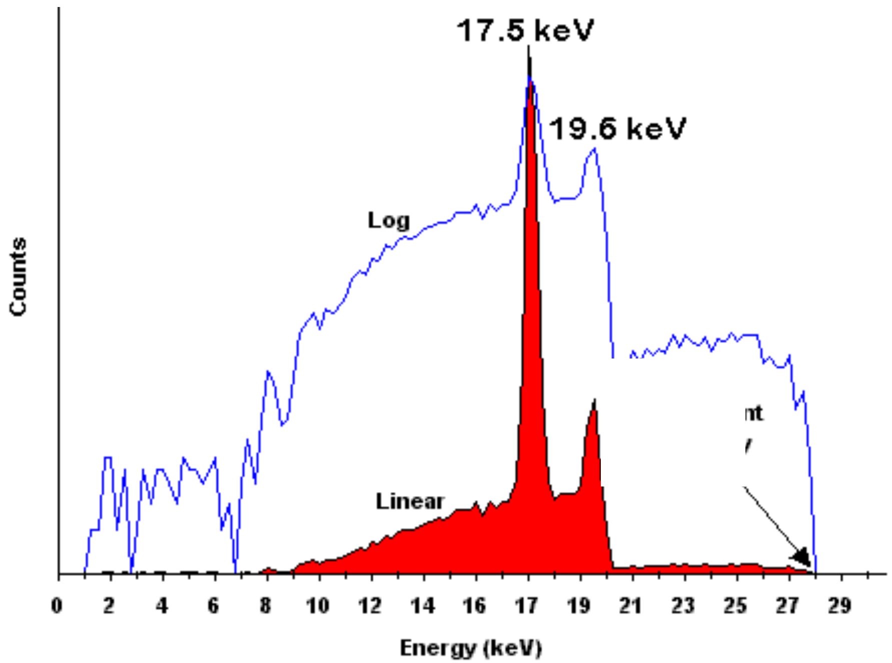


with collimators with filtering out soft X ray

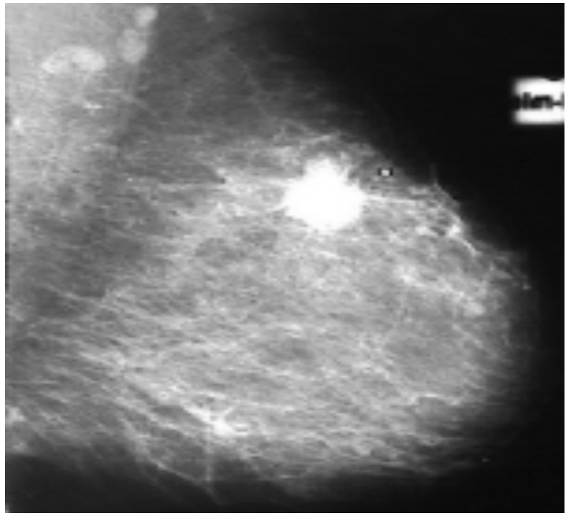
to reduce scattered radiation

– short exposure time to reduce unsharpness due to patient move

Spectrum of X ray used in mammography

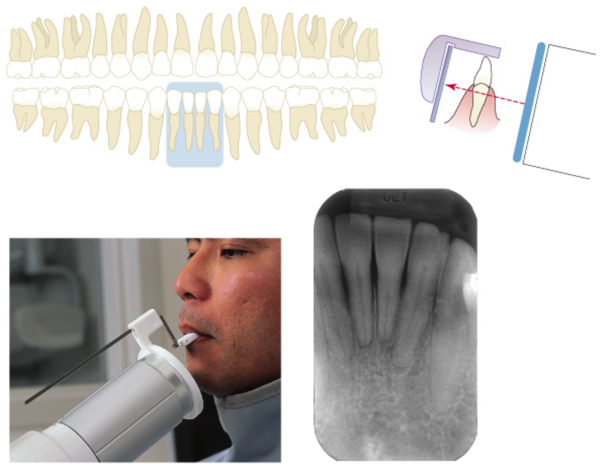


Characteristic lines of Molybdenum

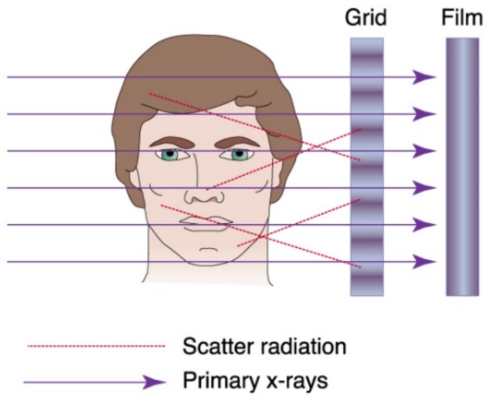


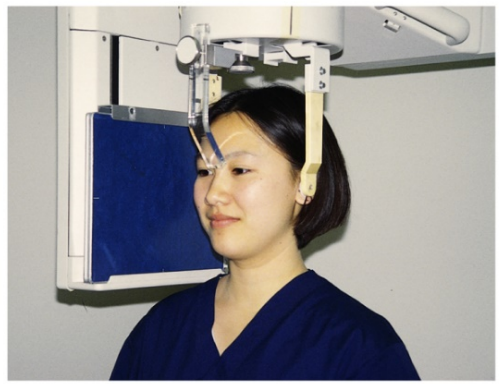
Mammogram showing malignant tissue

Intraoral radiography



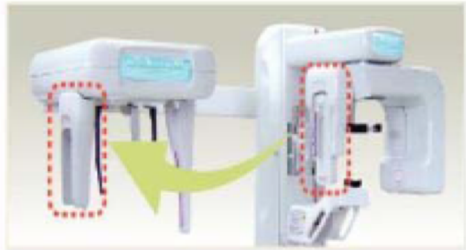
Extraoral radiography





Panoramic dentistry imaging

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

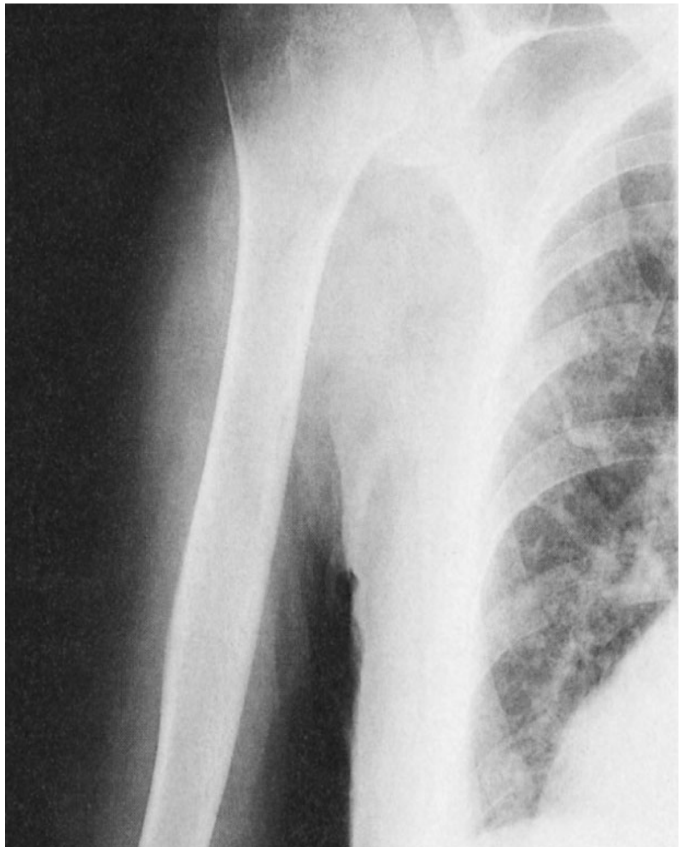


Effective atomic number

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

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

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



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}	ρ (g/cm^3)
H_2O	7.7	1
Soft tissue	7.4	1
Bone	13.8	1.7 - 2.0
Air	7.3	1.29 - 10^{-3}

Positive contrast → ***higher attenuation to surroundings***

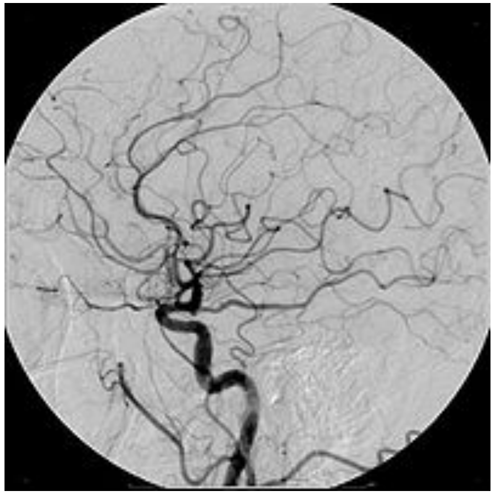
$$Z_{eff} > Z_{environment} \rightarrow \mu > \mu_{environment}$$

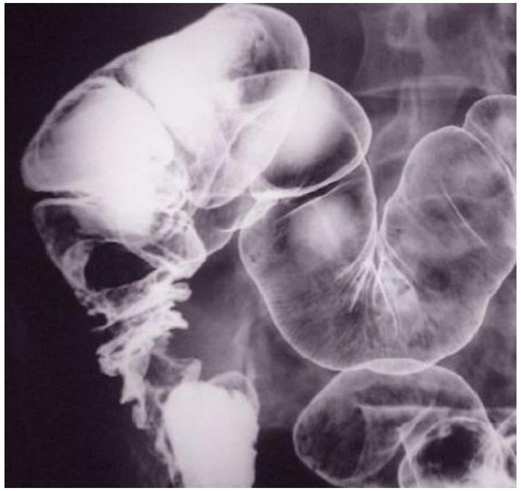
Negative contrast → ***lower attenuation to surroundings***

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

Applying contrast materials

higher Z_{eff}





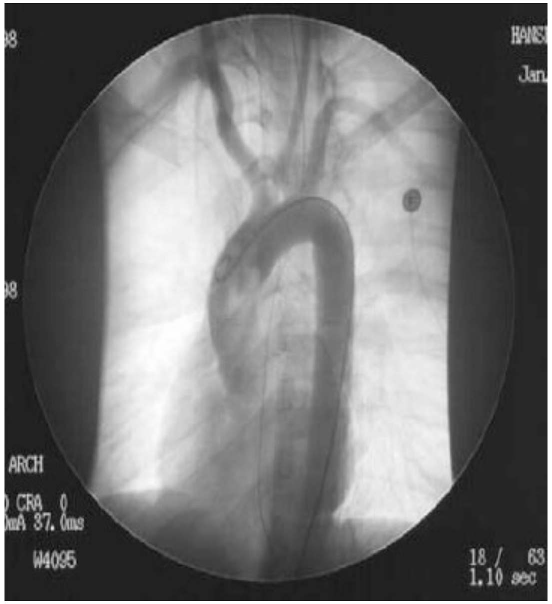
Iodine or barium compounds

$^{56}BaSO_4$, ^{53}J

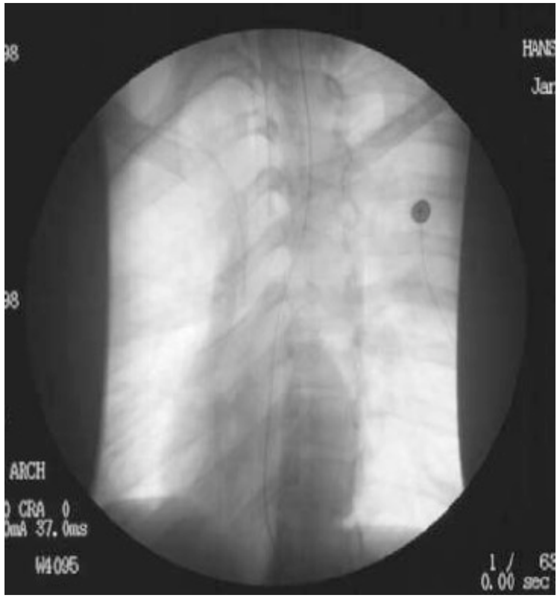
lower density

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

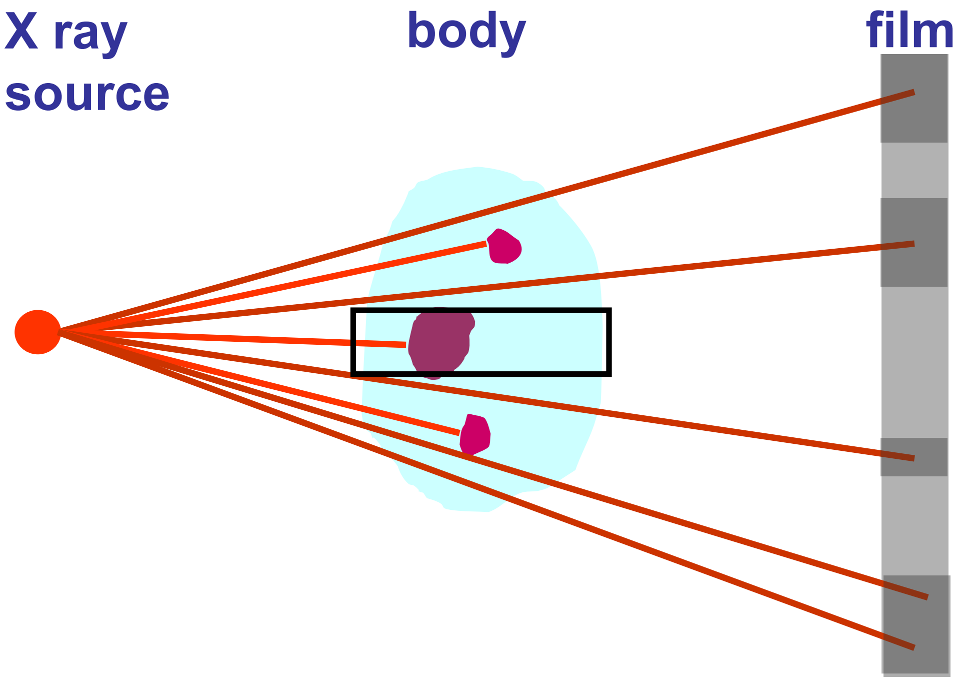
Visualize image with

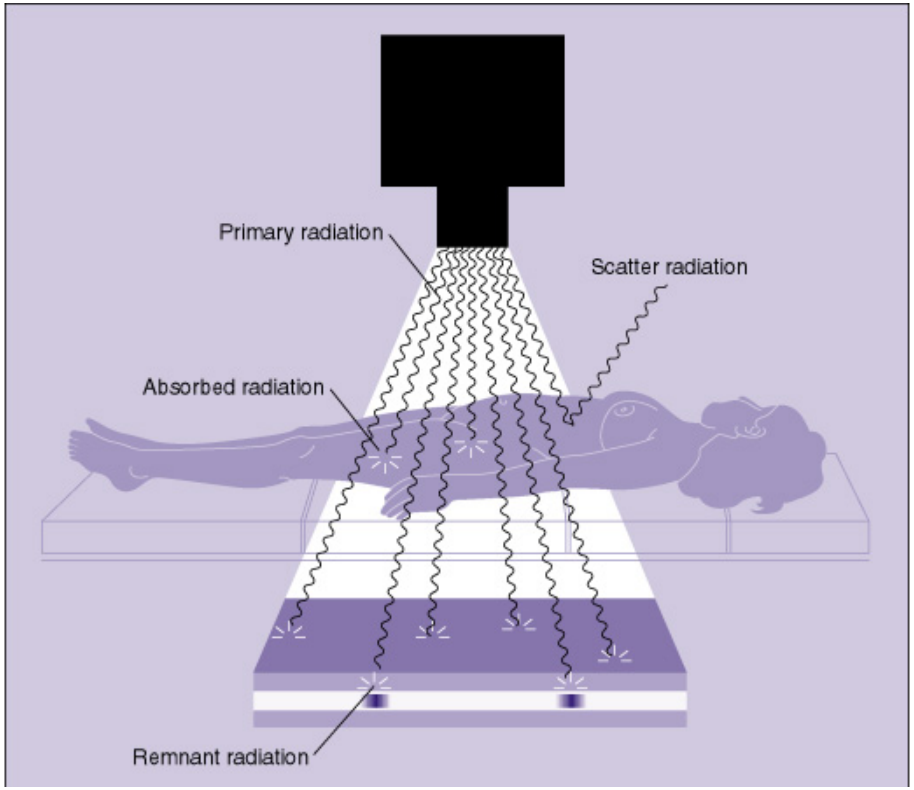
– X ray film

– luminescence screen

– a digitized image

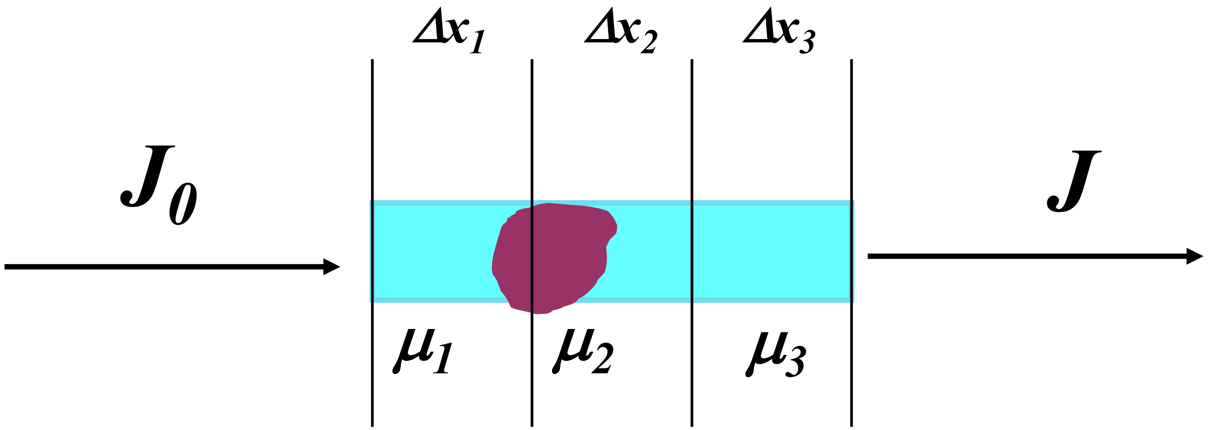
Summation image

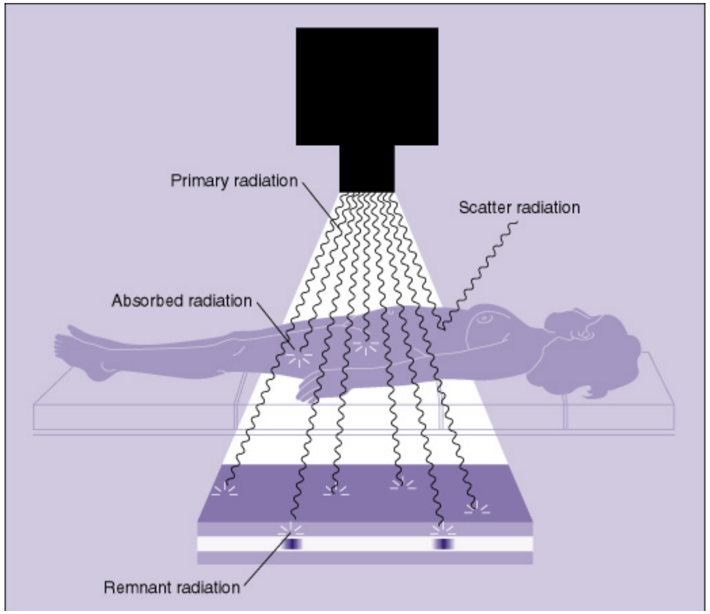




$$J = J_0 e^{-\mu x}$$

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





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

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

This information is missing!

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

$$D = \sum_i D_i$$

Solution:
CT - computed tomography

Godfrey Hounsfield

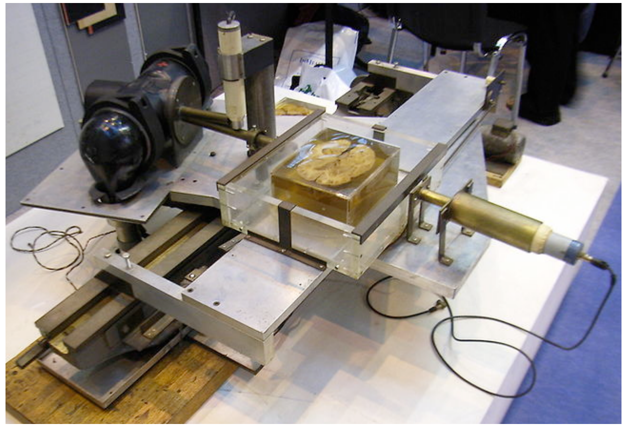
Allan Cormack

1979 – Nobel price in medicine

Brief history:

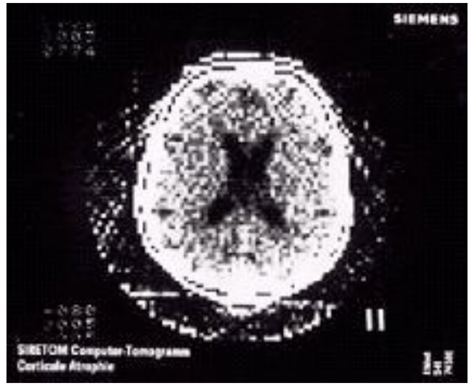
- 1967: first CT image
- 1972: prototype of CT
- 1974: first clinical CT image
- 1976: whole body CT
- 1979: Nobel price
- 1990: spiral CT
- 1992: multislice CT
- 2006: 64 slices
- multiplex and hybrid CT:
  SPECT-CT, PET-CT,
  “Dual-source” CT

First lab CT of brain slice



Prototype CT (EMI)

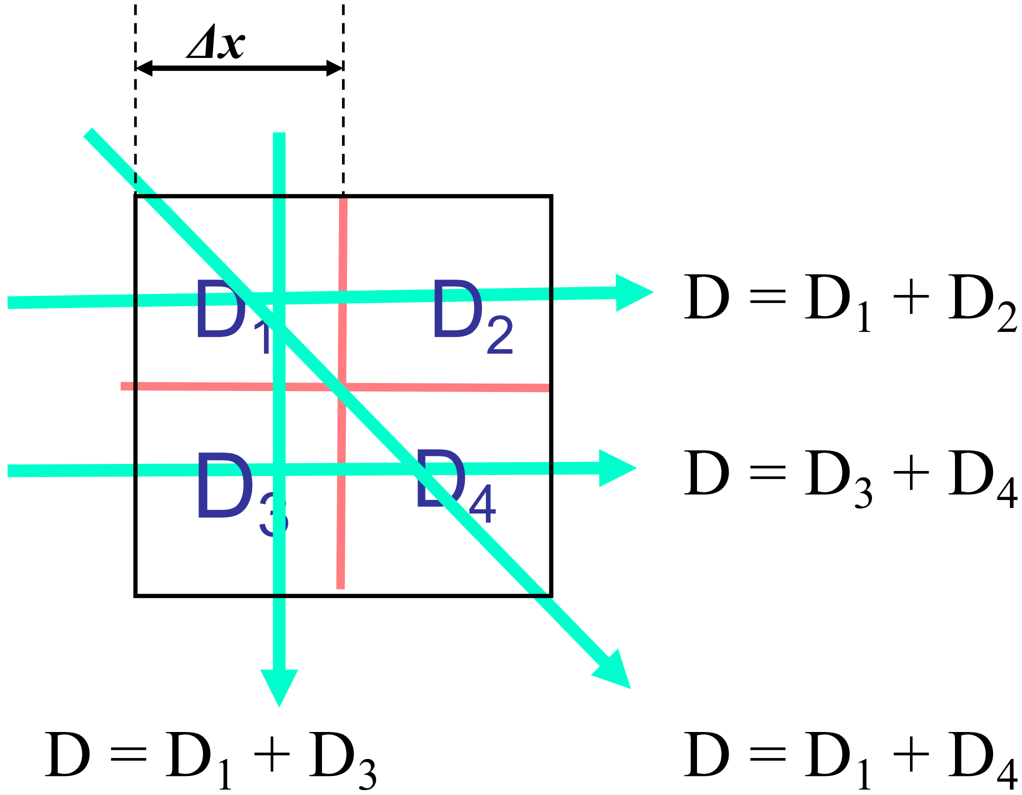
„Siretom” head scanner (1974)



128x128 pixel image (1975)

Illustration of math priciple:

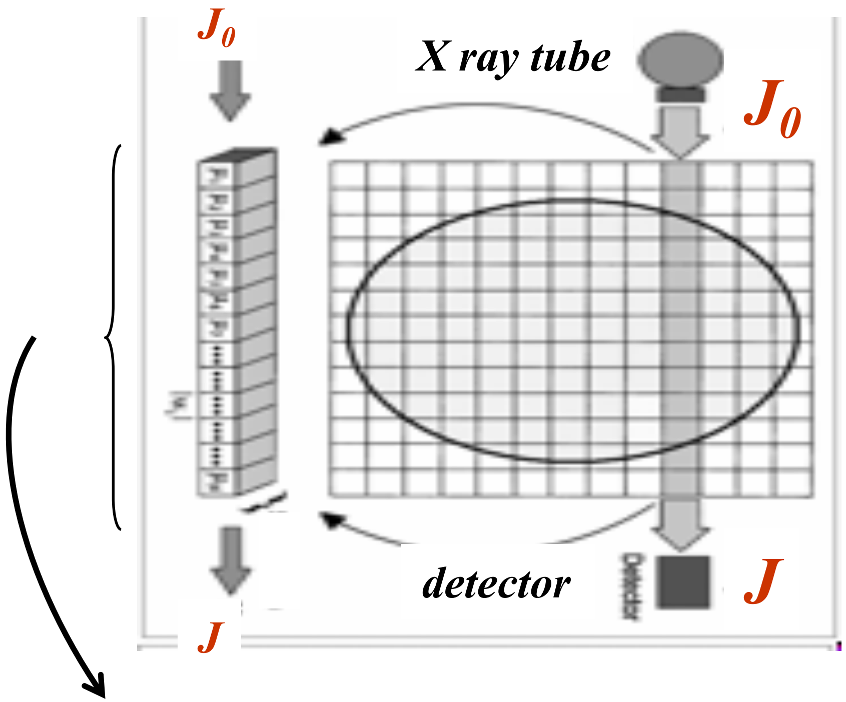
$$D = \sum_i D_i$$



“n” independent equation for „n” unknowns

➔ unambigous solution exists!

object



Voxel :

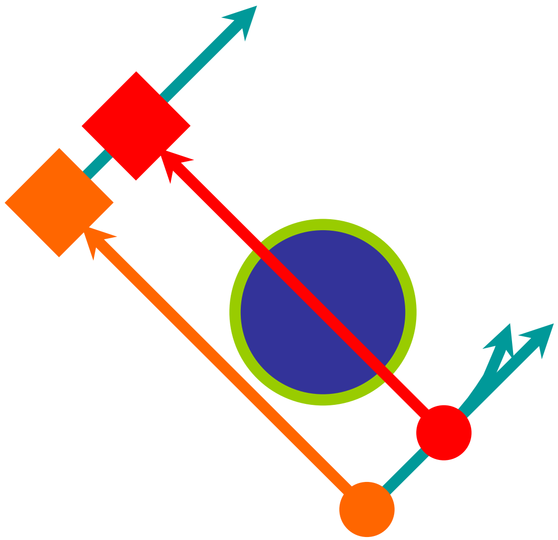
volume element

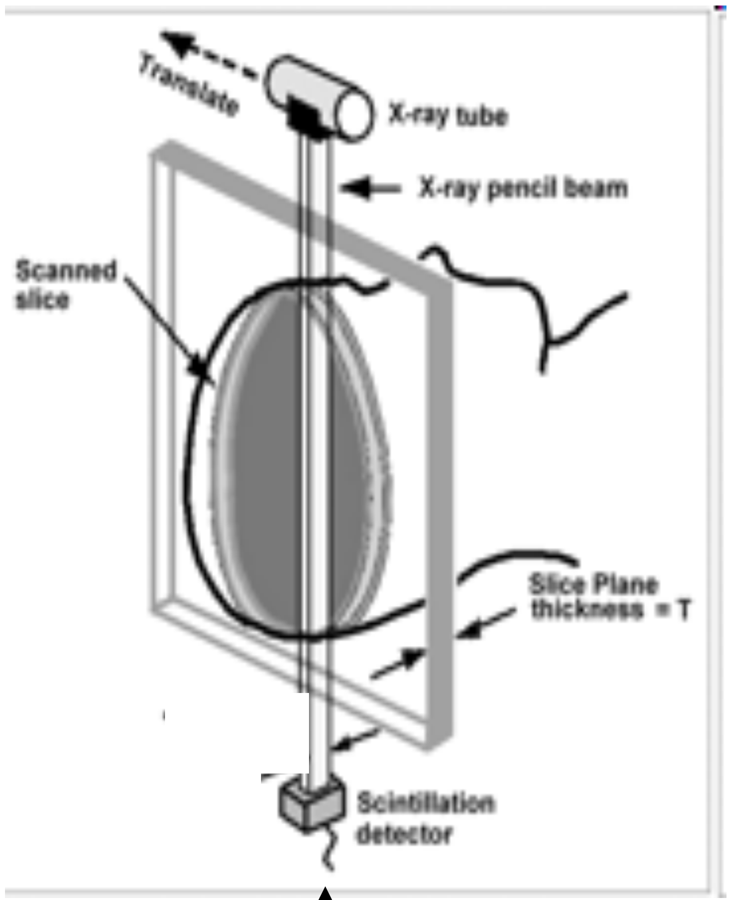
digital image

Pixel :

picture element

First generation CT

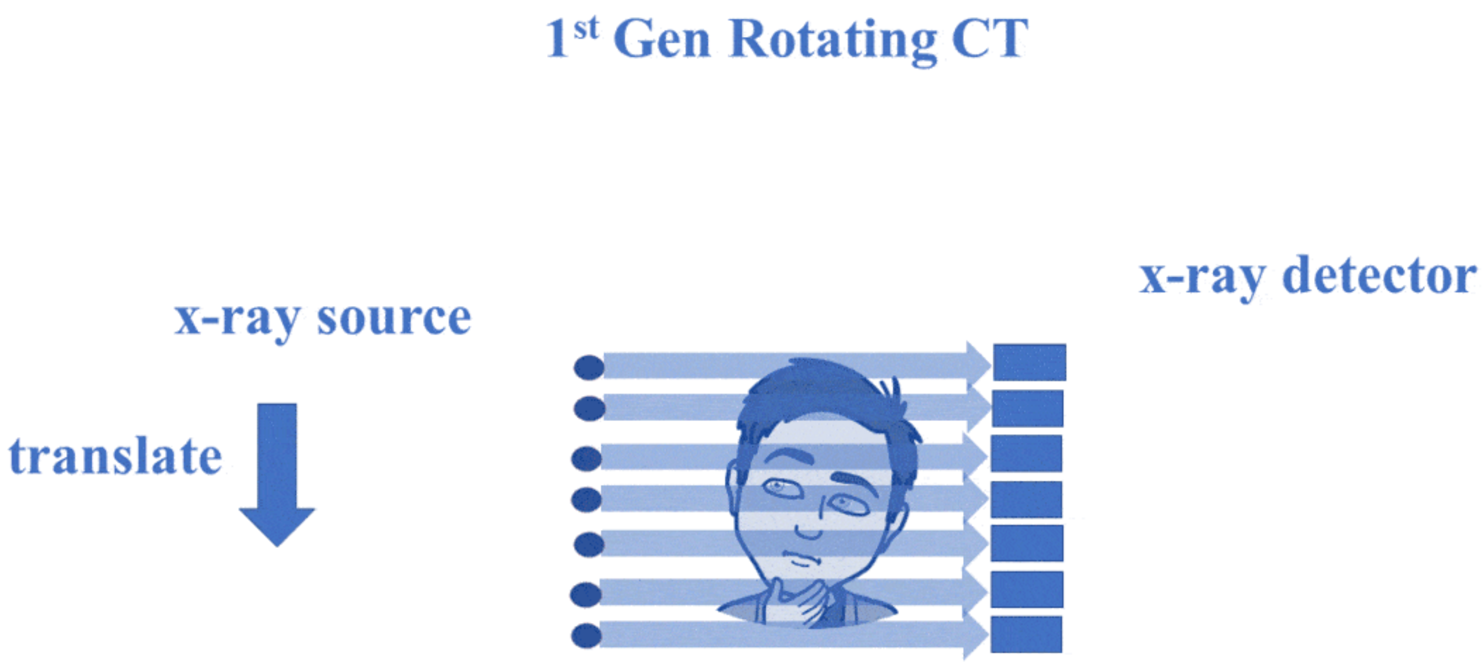




k-th pozition

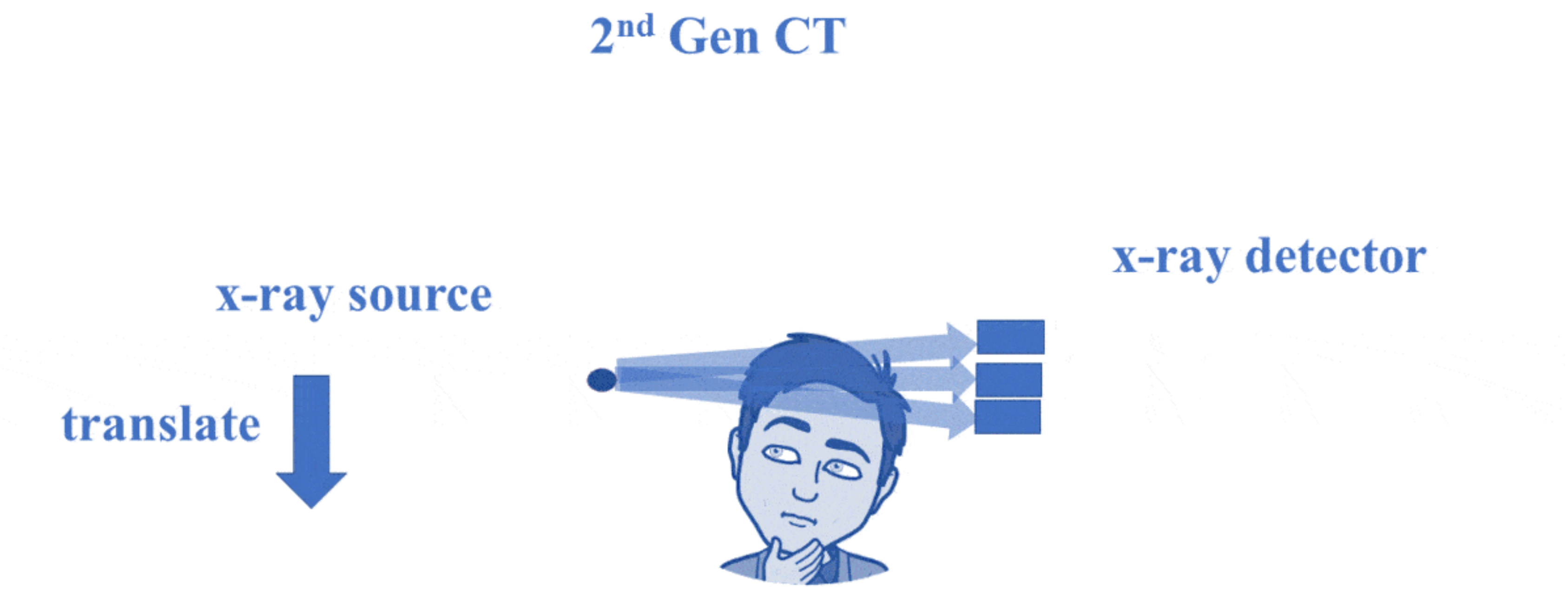
Single detector
Translation and rotation
Parallel beams

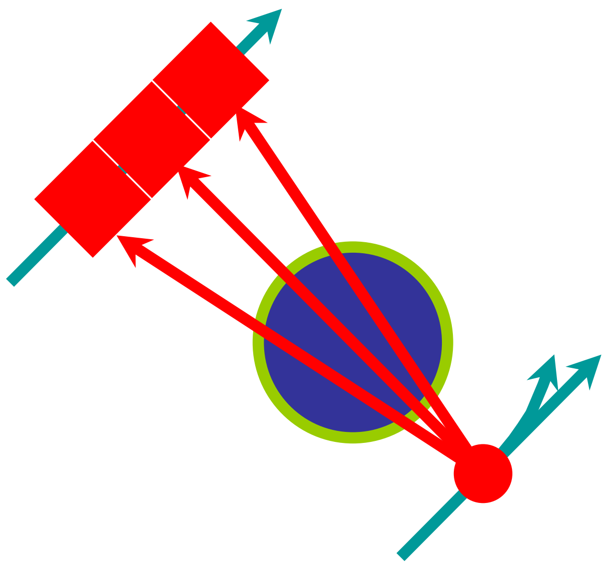
First generation CT



Single detector
Translation and rotation
Parallel beams

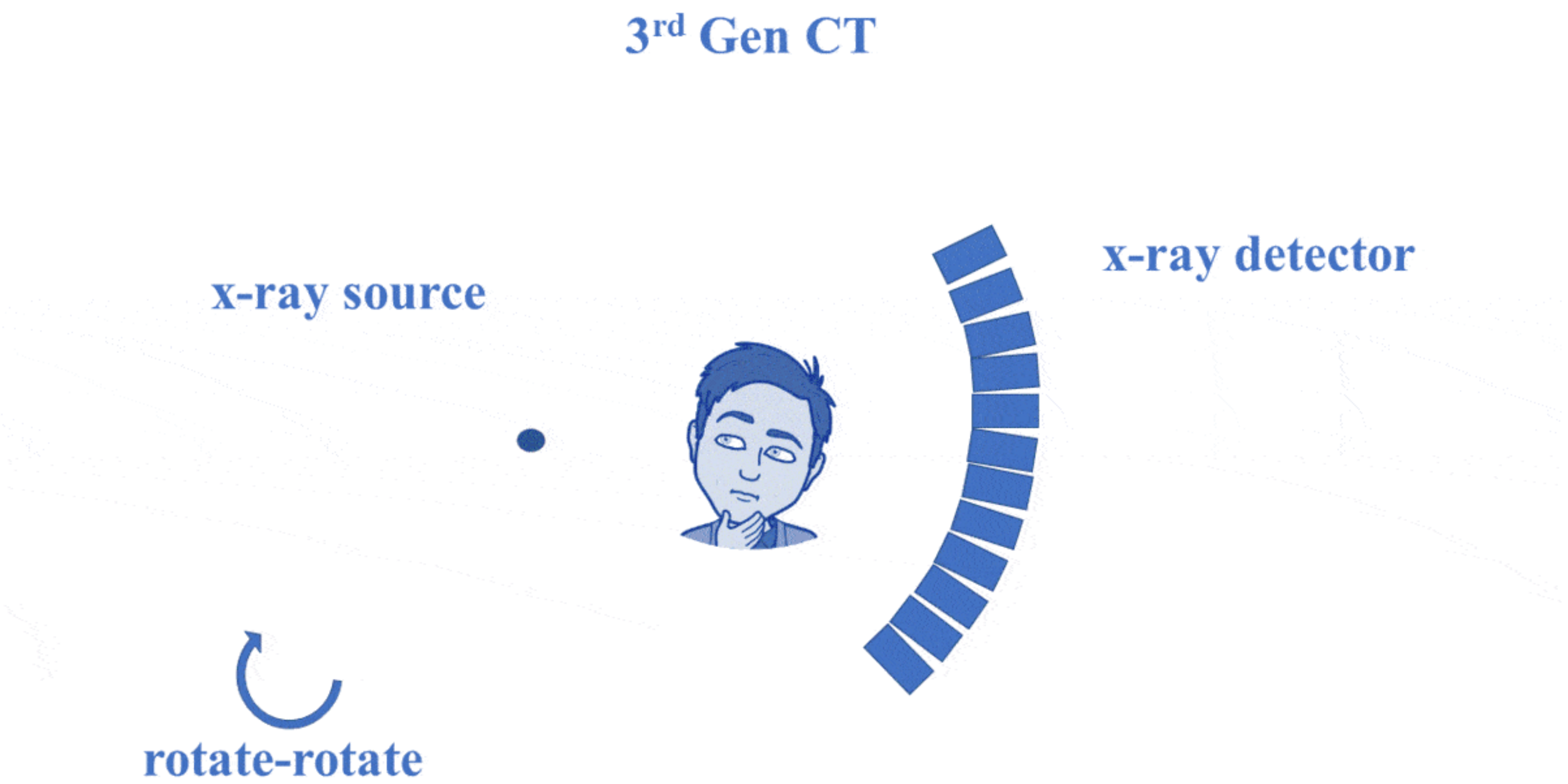
Second generation CT

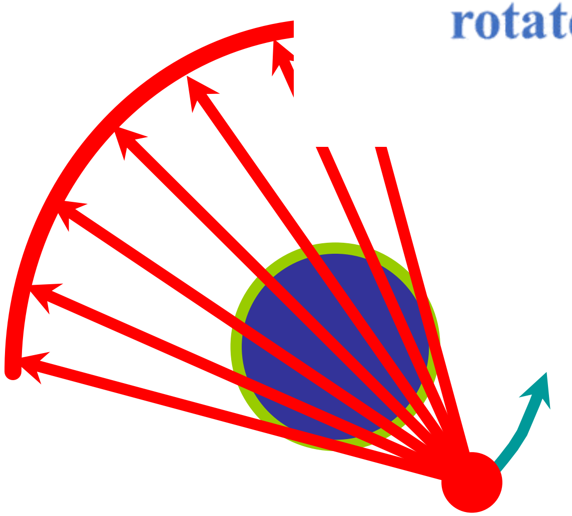




Multiple detectors
Translation and rotation
narrow fan beams

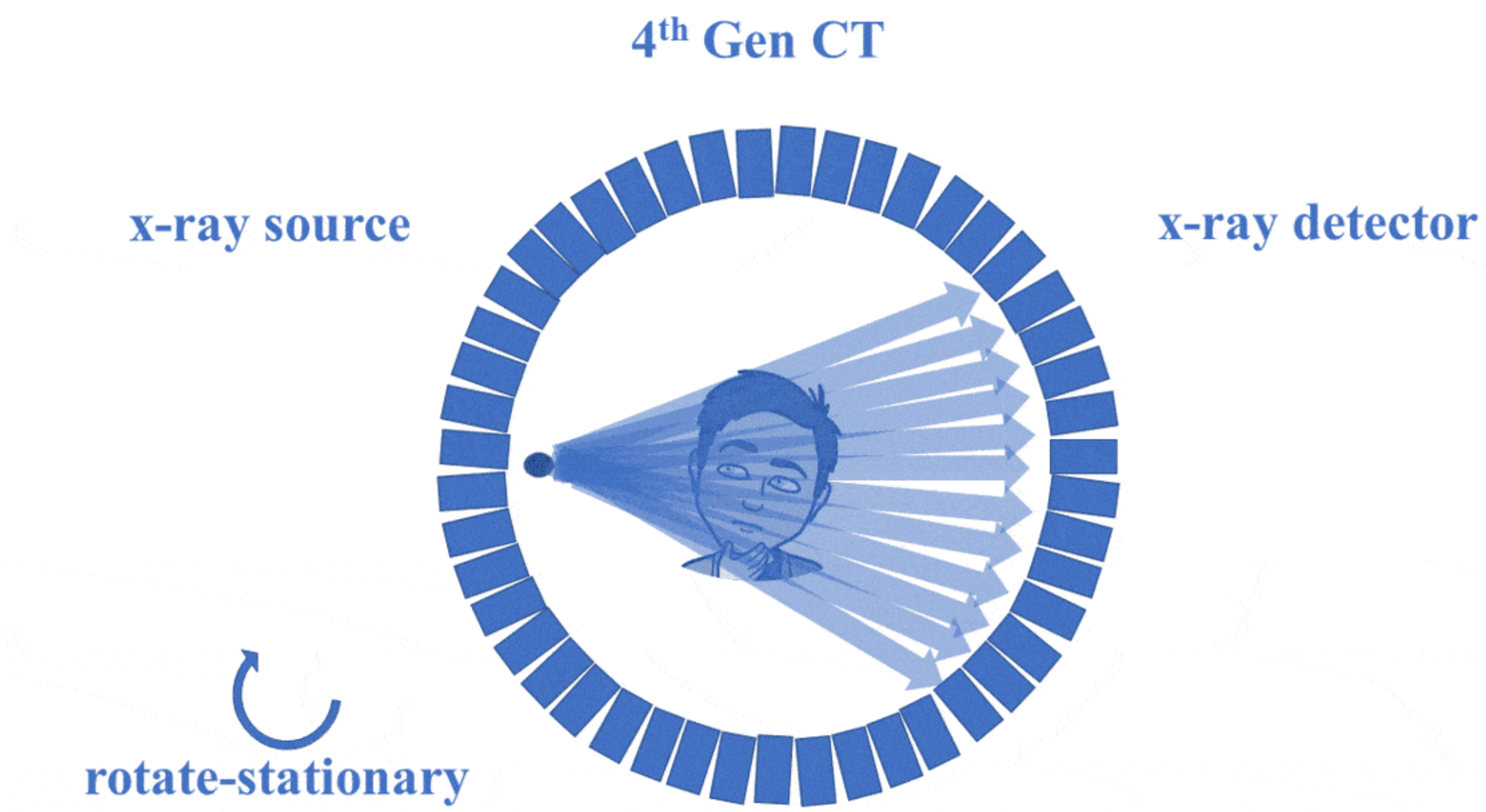
Third generation CT

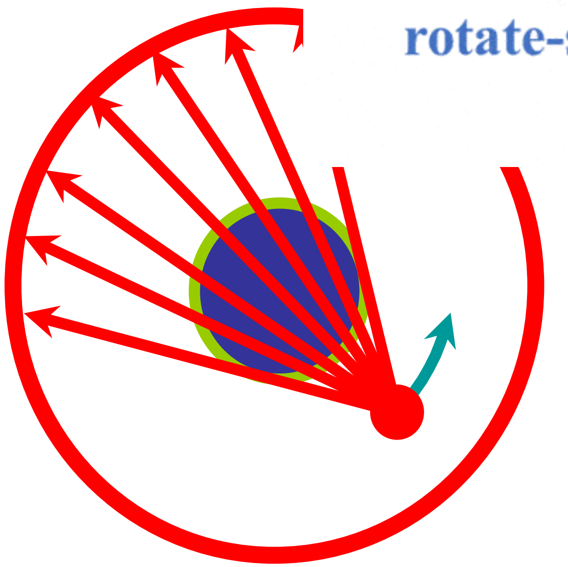




Detector array
Rotations only
Wide fan beams

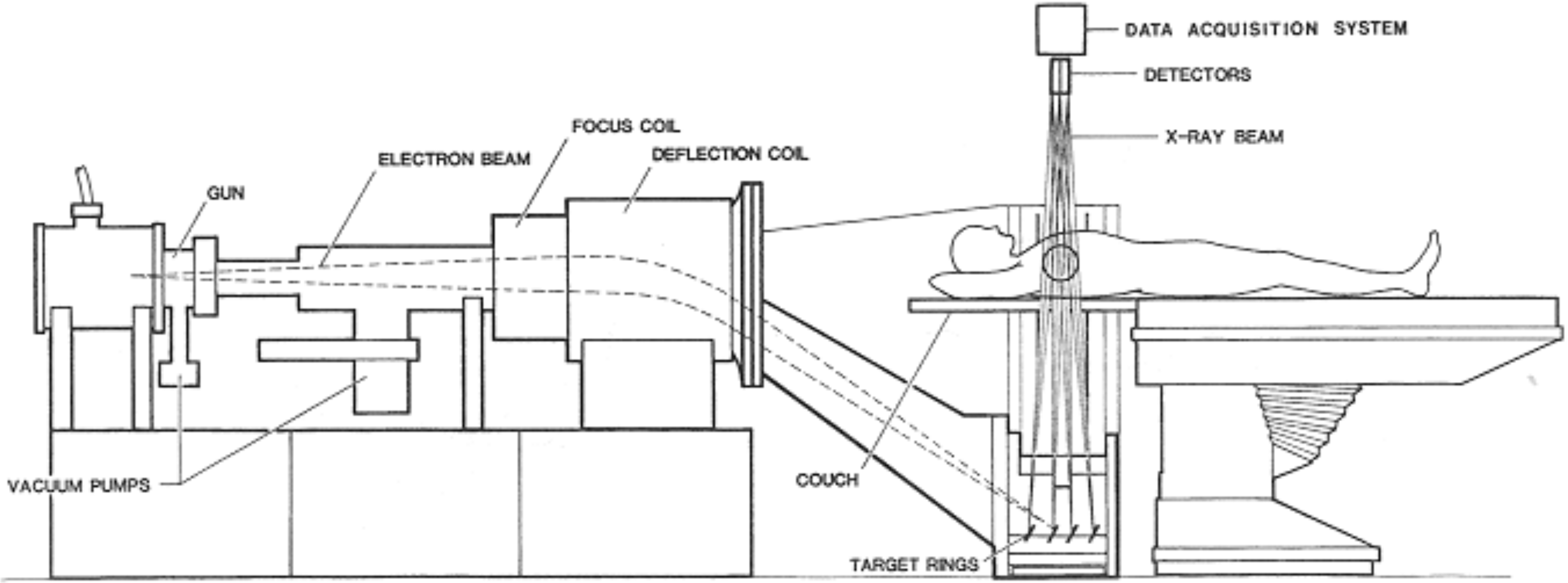
Fourth generation CT





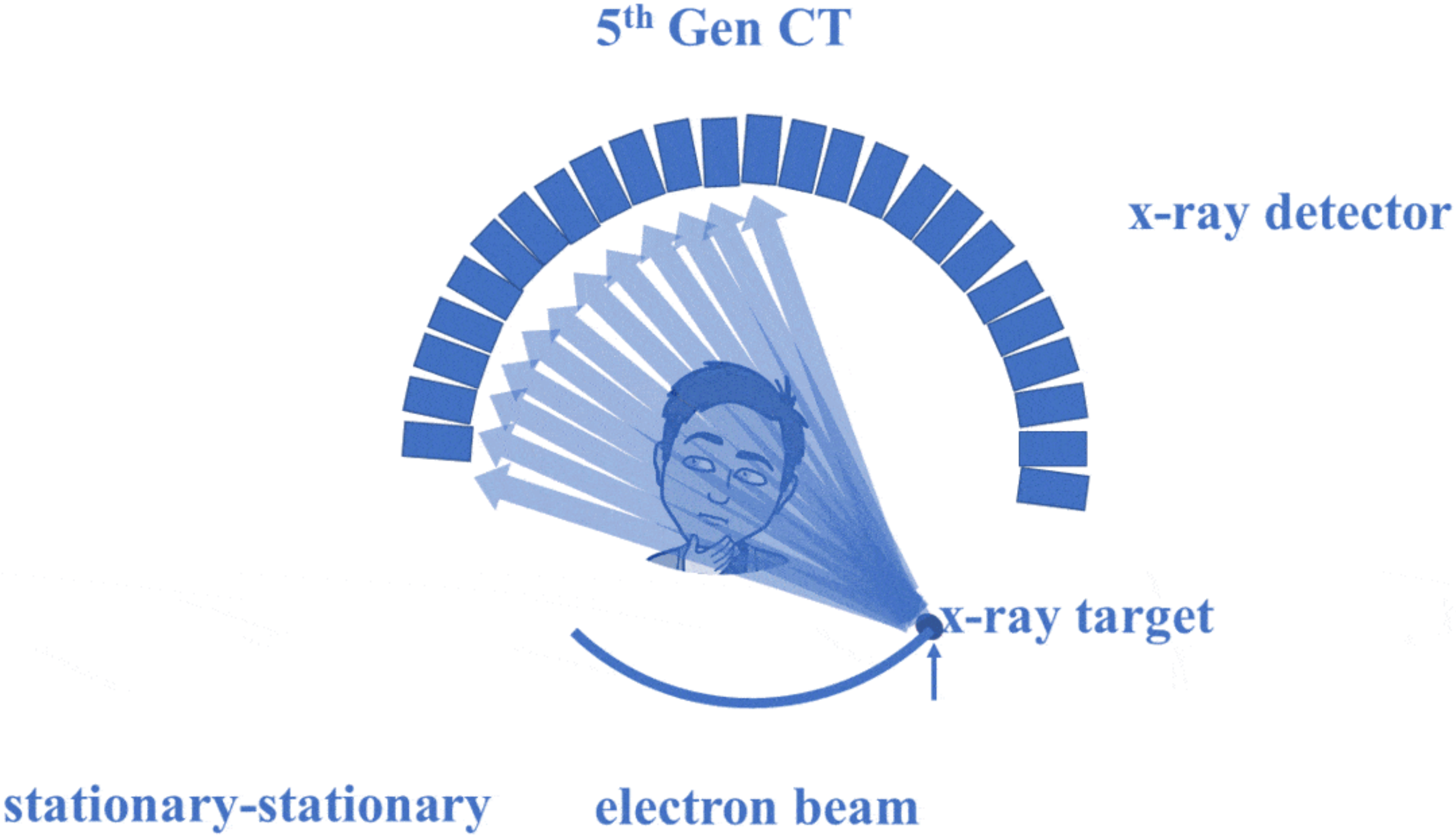
Detector ring fixed
Rotation of X ray source only
Wide fan beams

Fifth generation CT



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

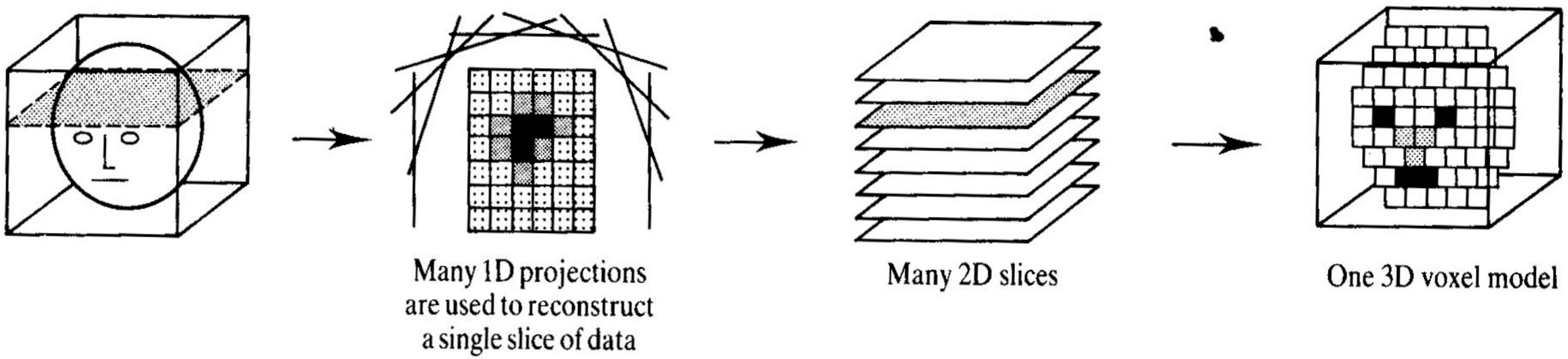
Fifth generation CT



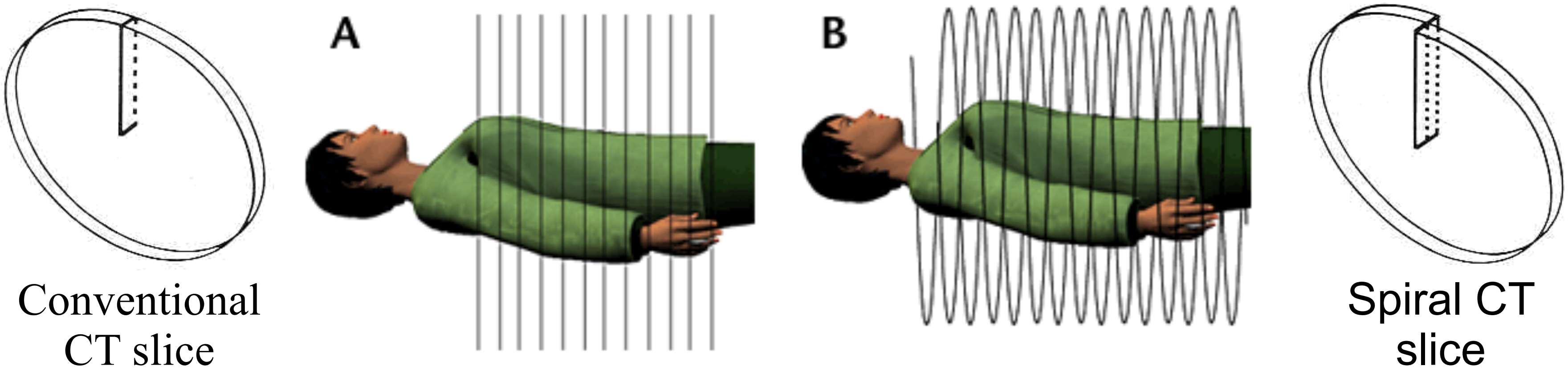
Comparison of CT generations

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.

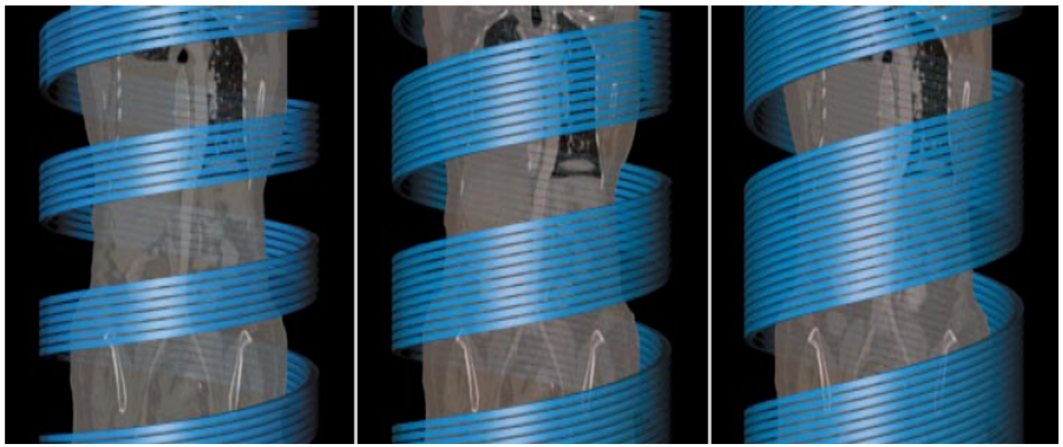
3D reconstructions

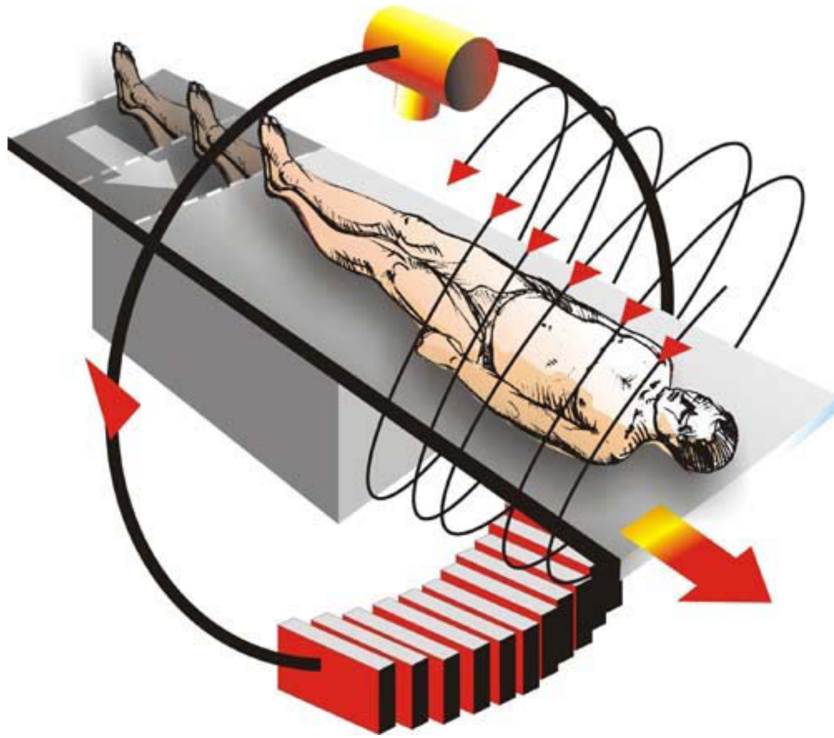


Spiral CT



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*

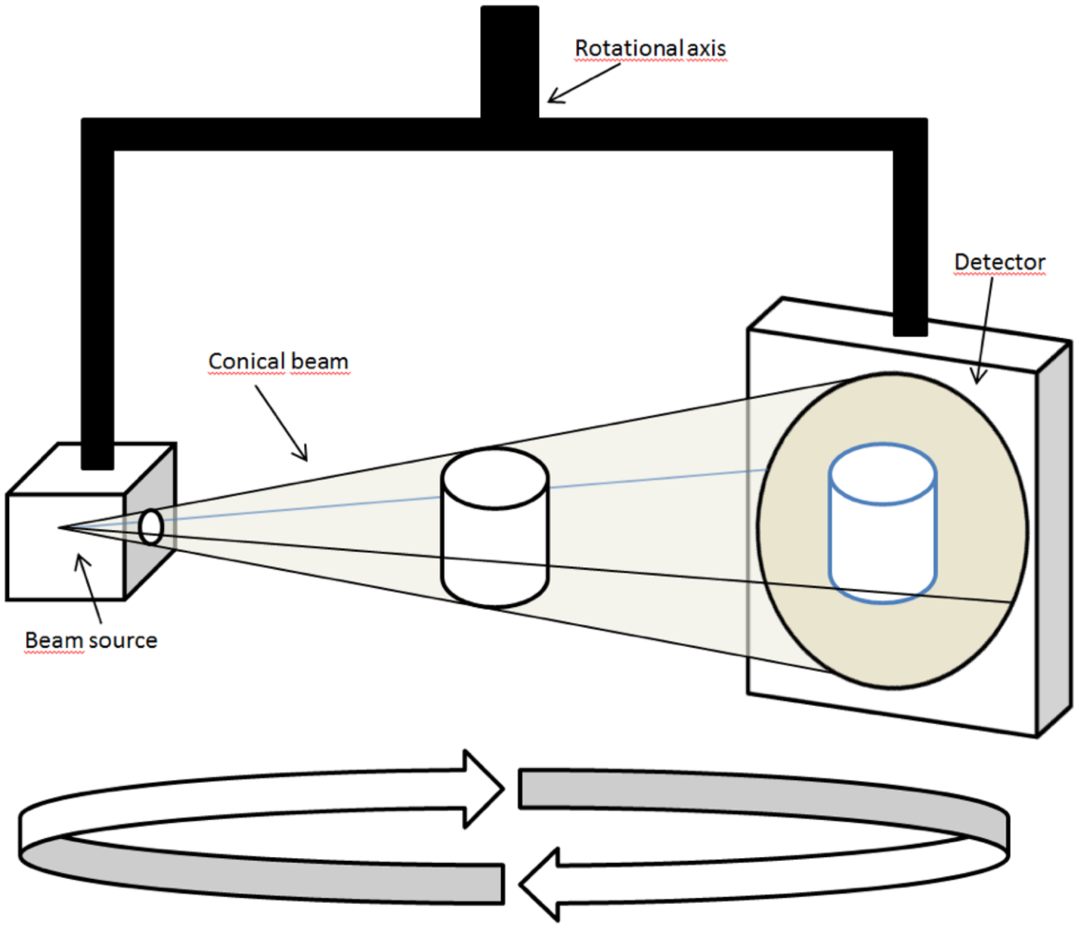
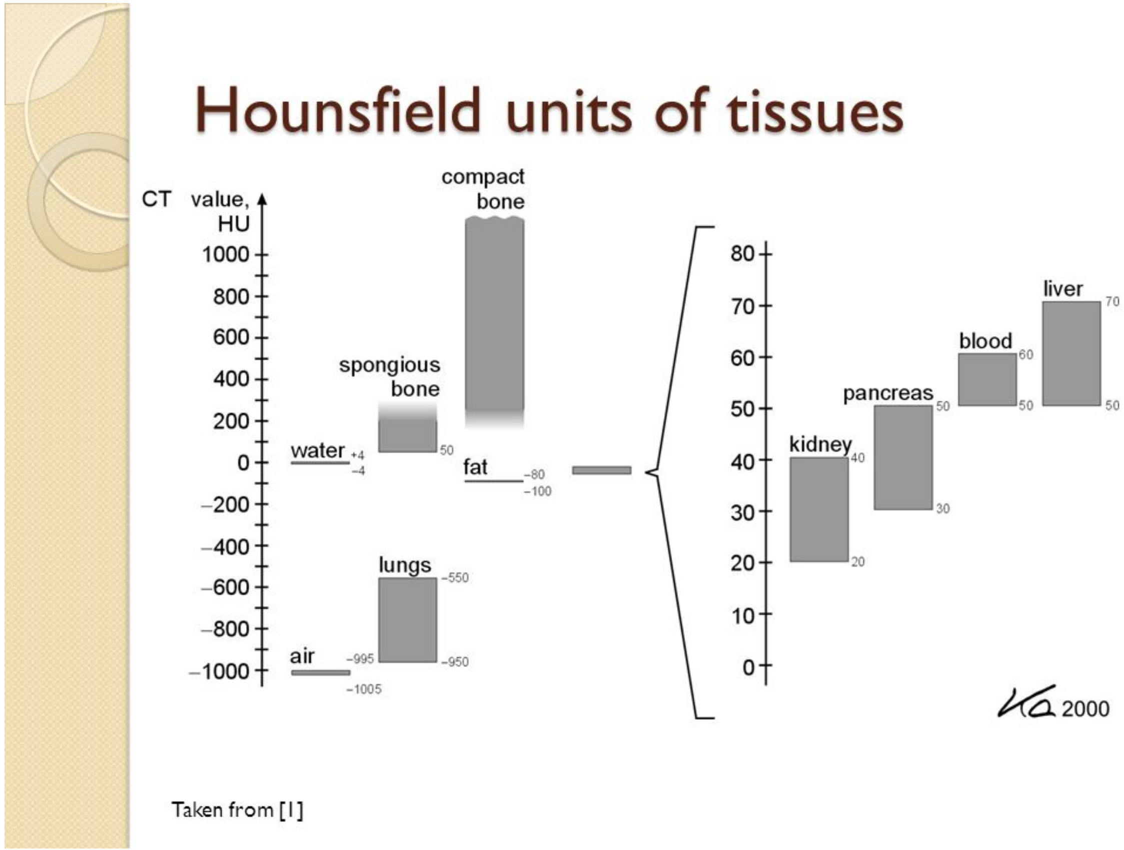


Image reconstruction

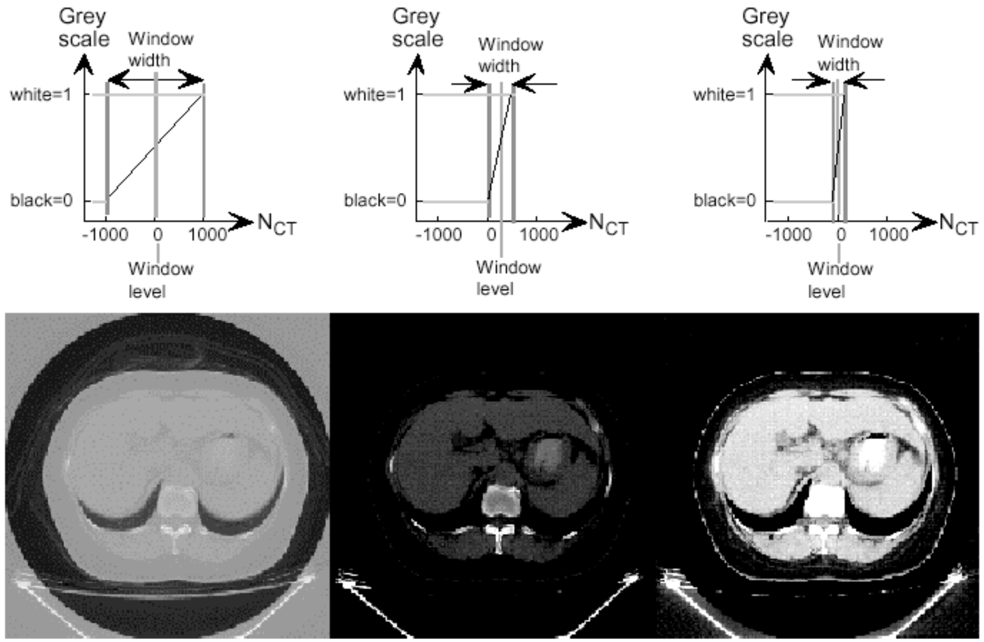
– density matrices (D_i) ➜ attenuation coefficients (μ_i)

– *Hounsfield units* $$H_{CT} = 1000 \frac{\mu - \mu_{water}}{\mu_{water}}$$

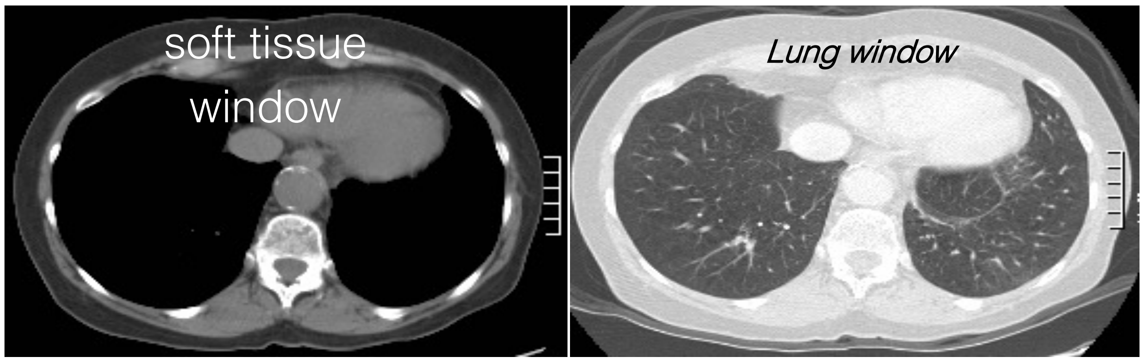
Hounsfield scale

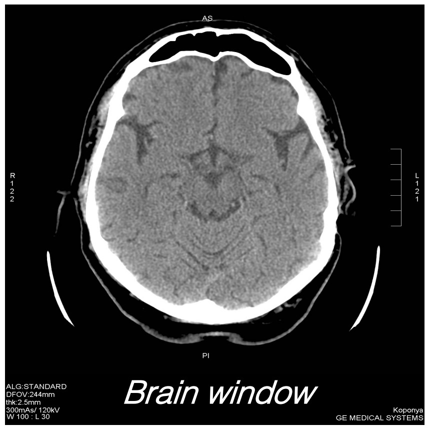


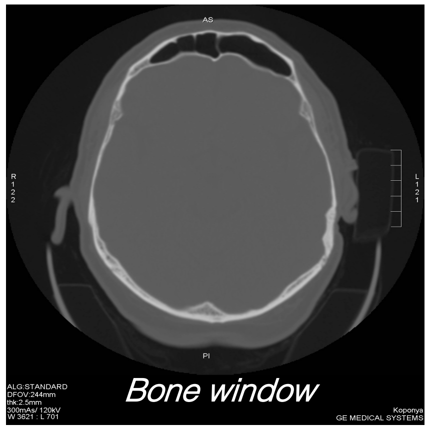
CT contrast enhancement
„windowing”



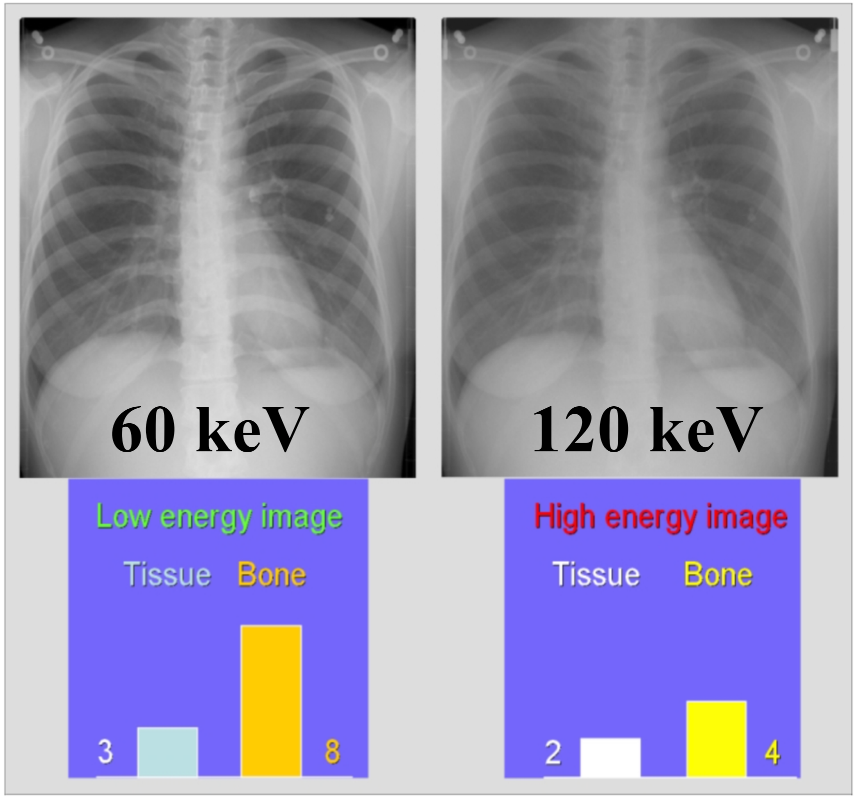
Same thoracic image with different windowing







Contrast enhancement with dual source CT



Weighted subtraction and scaling

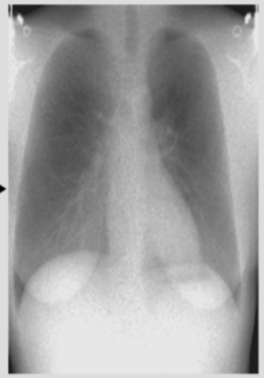
Tissue only: remove bone signal

Choose constants to remove bone:

(high * 2 - low * 1) * k_t → Tissue signal scaling factor, k_t

(4 * 2 – 8 * 1) = 0 (bone residual)

(2 * 2 – 3 * 1) = 1 (soft tissue residual)



Bone only: remove tissue signal

Choose constants to remove tissue:

(low * 2 - high * 3) * k_b → Bone signal scaling factor, k_b

(8 * 2 – 4 * 3) = 4 (bone residual)

(3 * 2 – 2 * 3) = 0 (soft tissue residual)

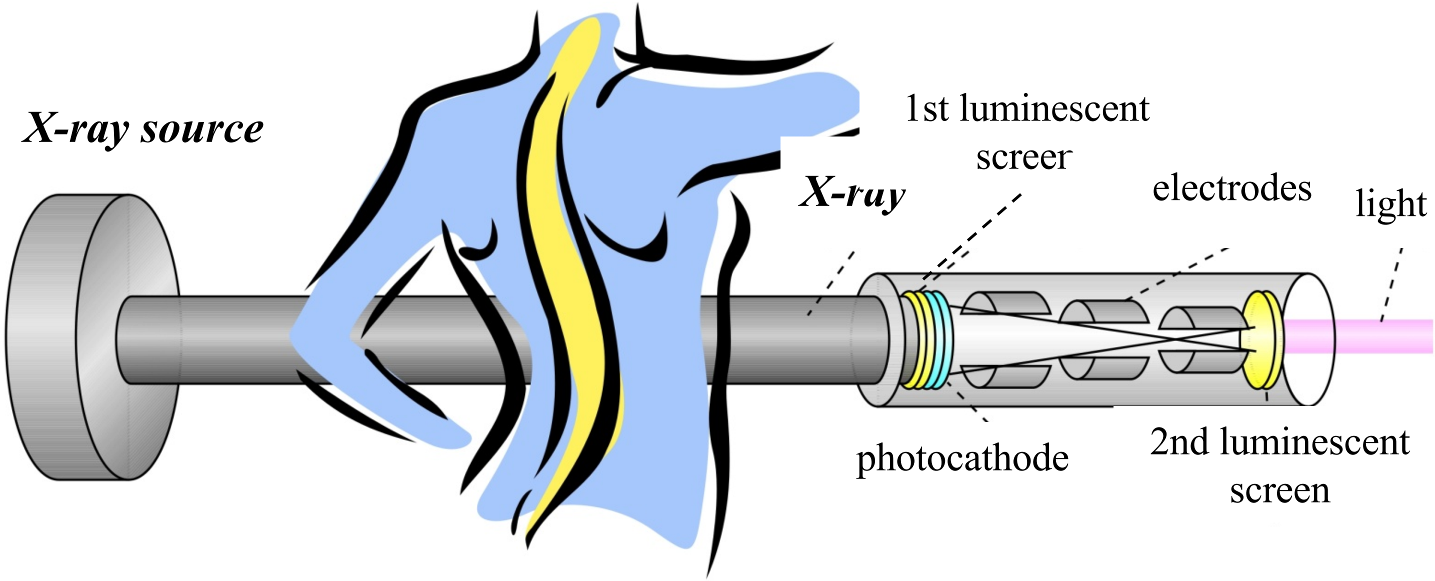
Brief summary of *CT*

- 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 detektorsor): 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 radioation

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