

# Biophysics I

## 12. X-ray diagnostics

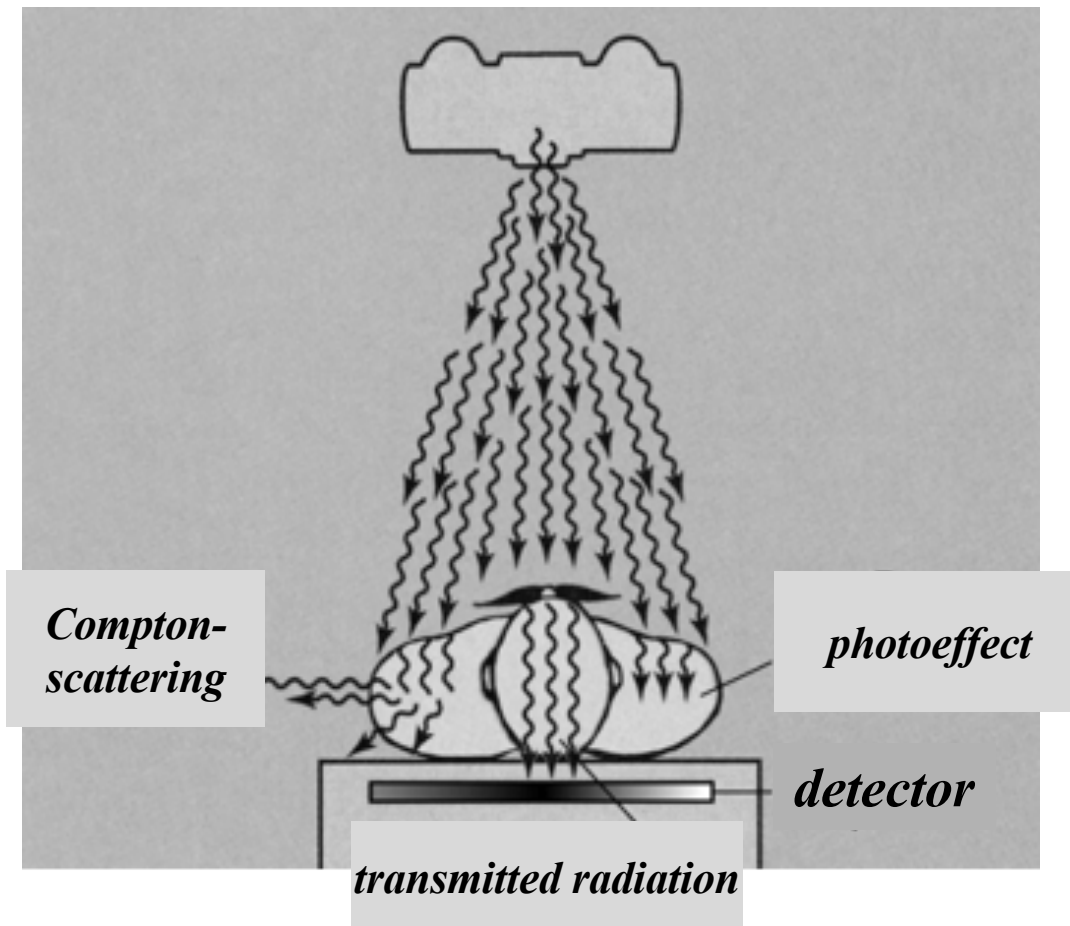
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24. 11. 2023.

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# The basis of X ray diagnostics: absorption



## *Interactions of photon:*

elastic scattering

photoeffect

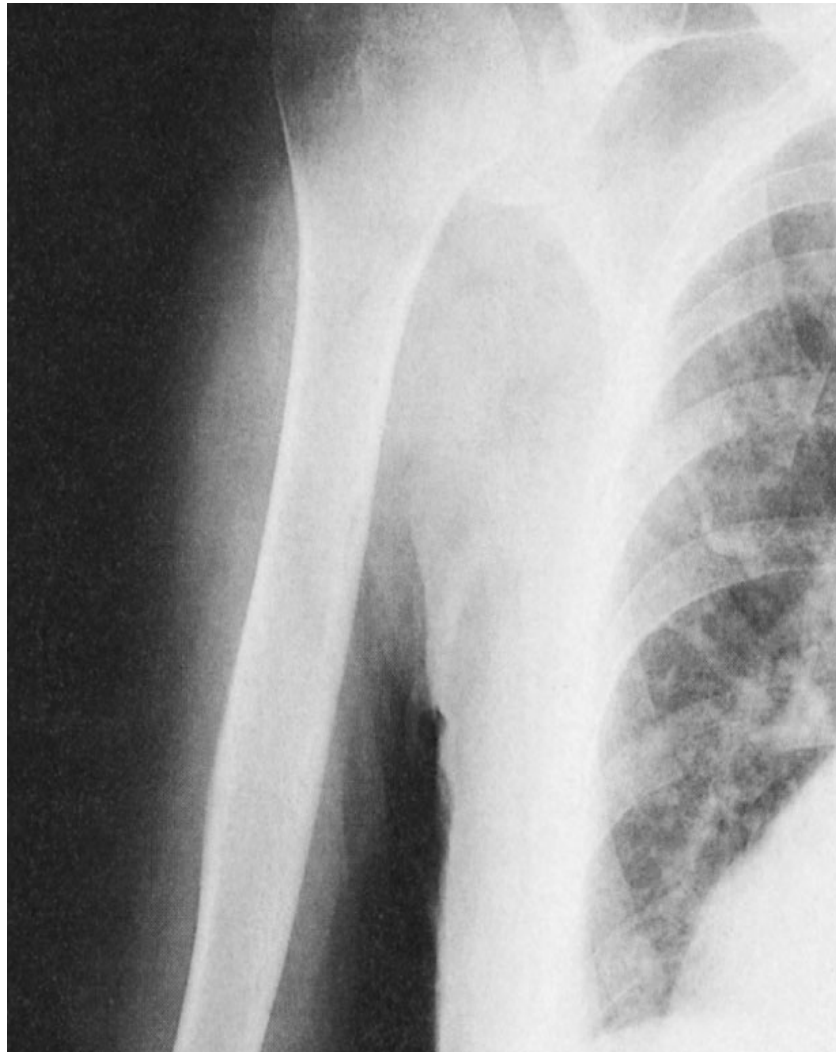
Compton scattering

pair production

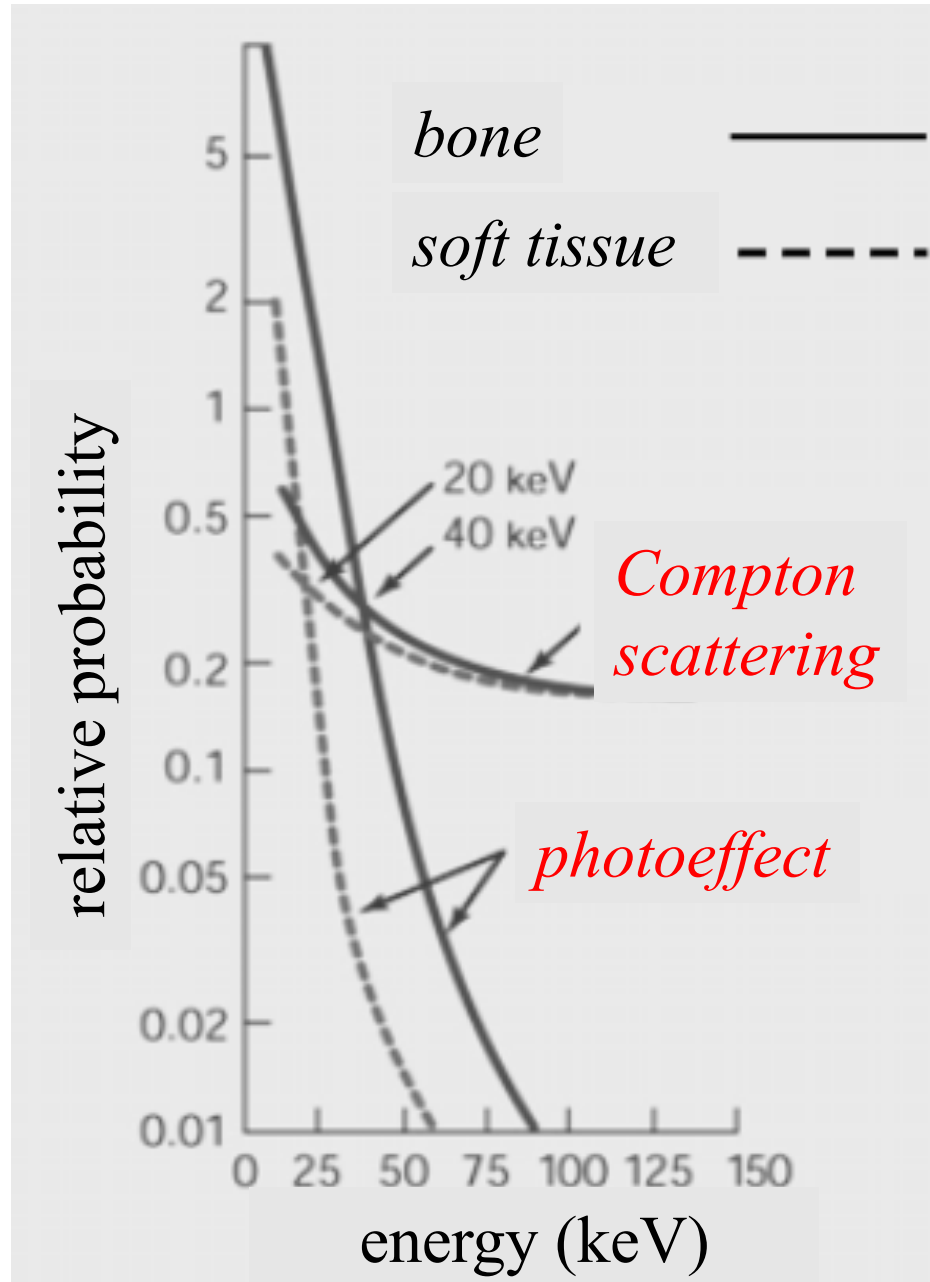
(no interaction)

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

	Dependence on E	Dependence on Z	Energy range in soft tissue
$\tau_m$	$\sim 1/E^3$	$\sim Z^3$	10 – 100 keV
$\sigma_m$	Slowly decreases with increasing E	$\sim Z/M$	0.5 – 5 MeV
$\kappa_m$	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.



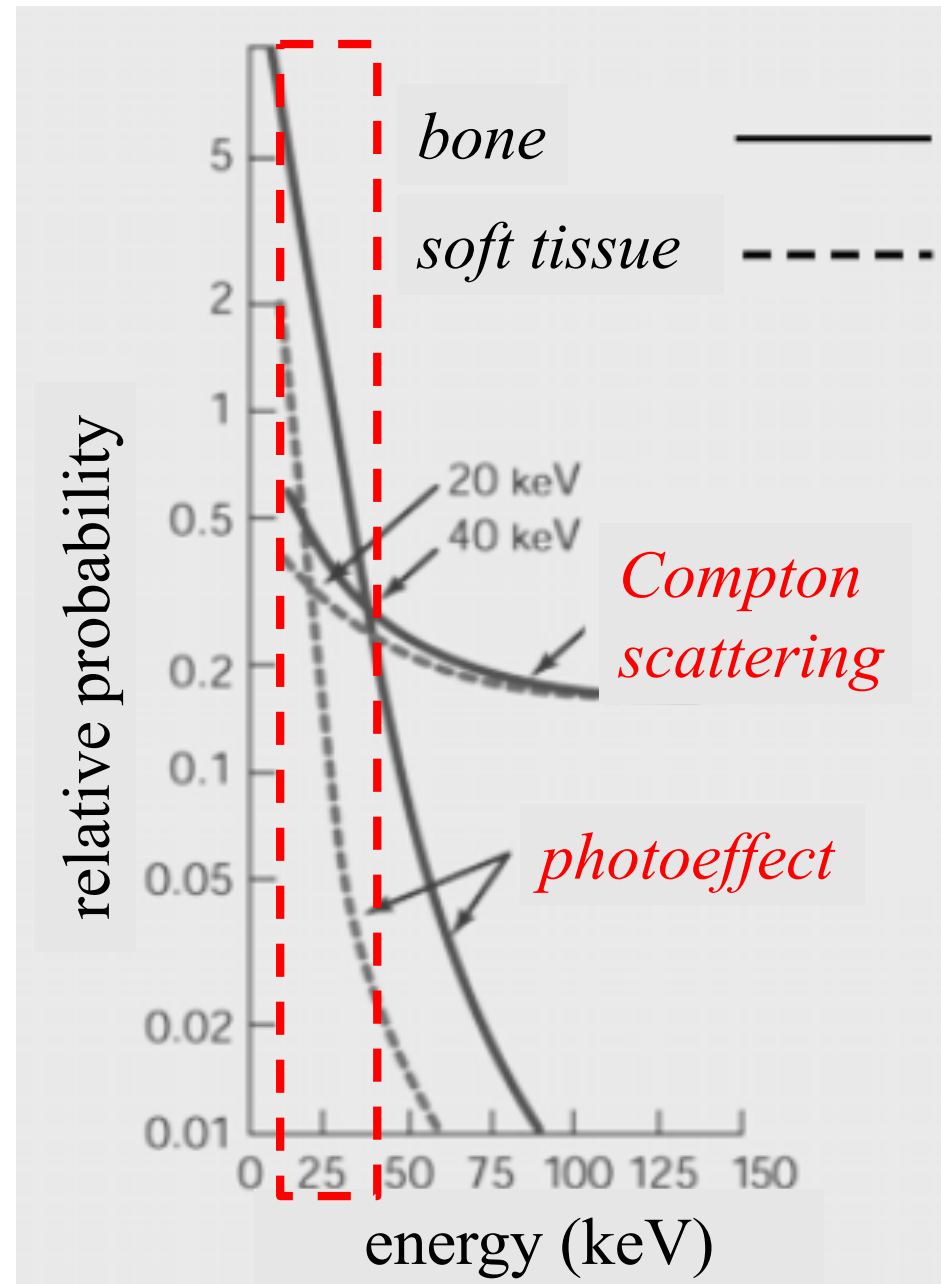


Increasing photon energy decreases attenuation by decreasing the photoeffect. In the low energy regime  $\tau_m$  is dominating the attenuation process.

$\tau_m$  depends strongly on the atomic number:

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

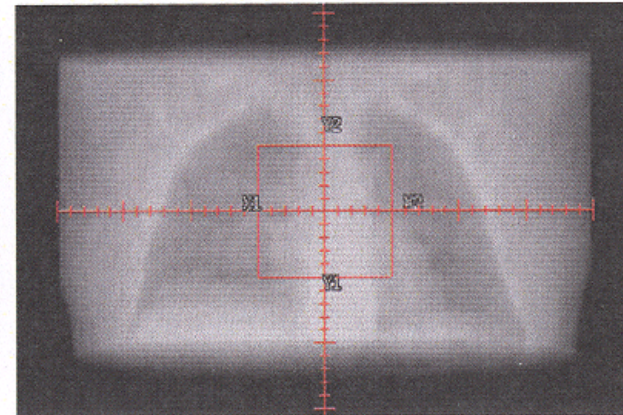
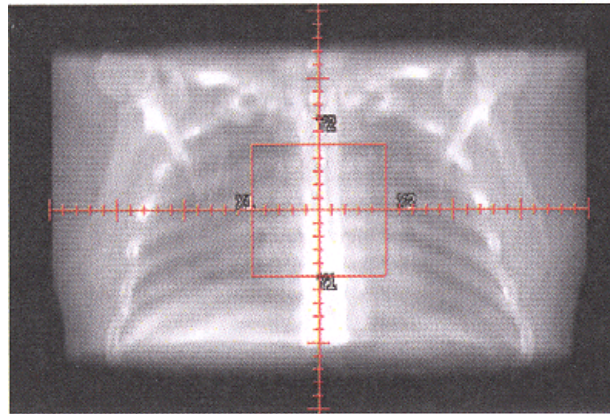
Change in photon energy can have a profound effect on the absorption process.



# Photonenergy - picture quality

$$U_1 < U_2$$

(30 keV) (2 MeV)



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

\*Mean values

# Photonenergy - picture quality

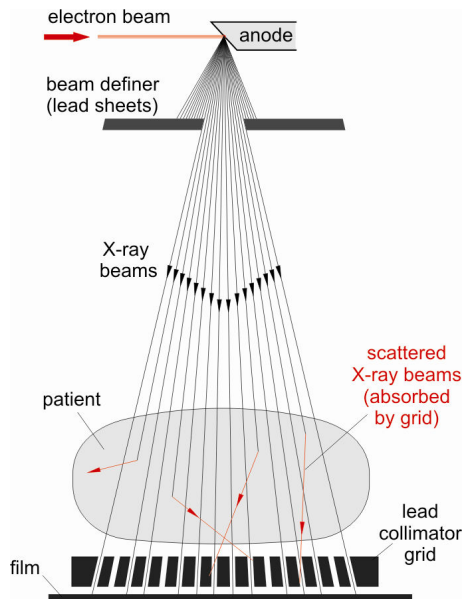


photonenergy: 60 keV  
contrast ratio: 200:1  
exposition: 141 mAs  
dose: 7,6 mGy

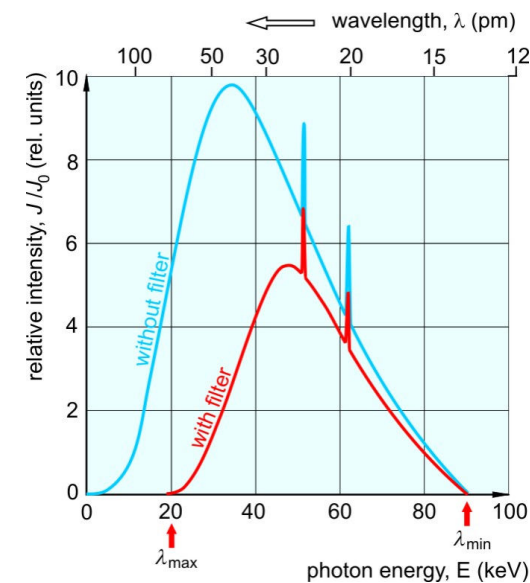


120 keV  
60:1  
6 mAs  
1,4 mGy

# Improving picture quality



with collimators

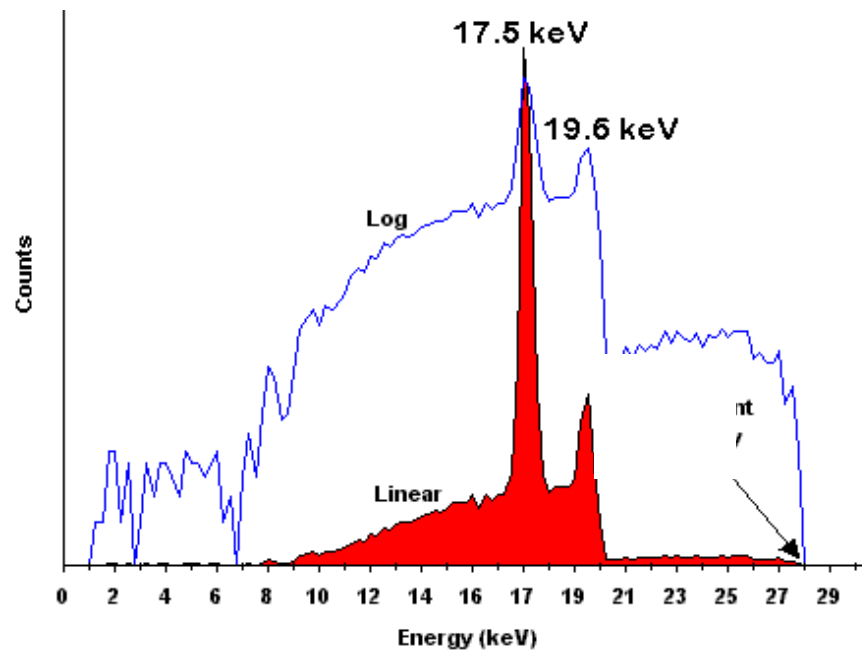


with filtering out soft X ray

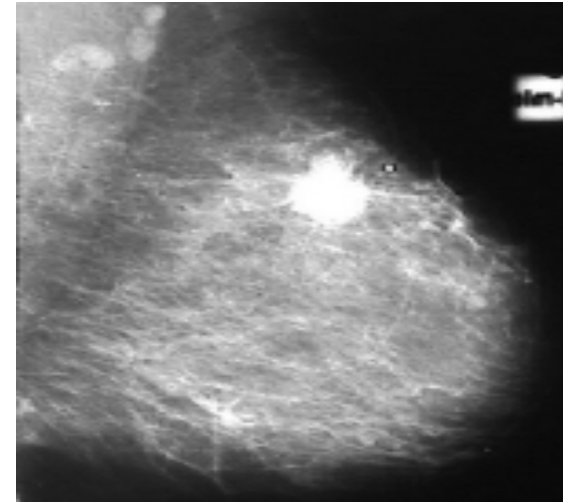
to reduce scattered radiation

— short exposure time to reduce unsharpness due to patient move

# Spectrum of X ray used in mammography



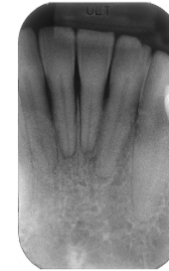
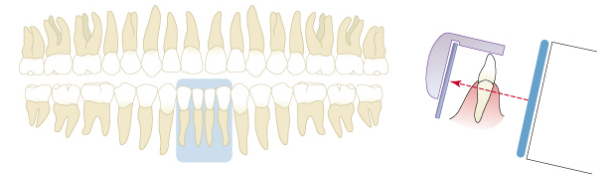
Characteristic lines of  
Molybdenum



*Mammogram showing  
malignant tissue*

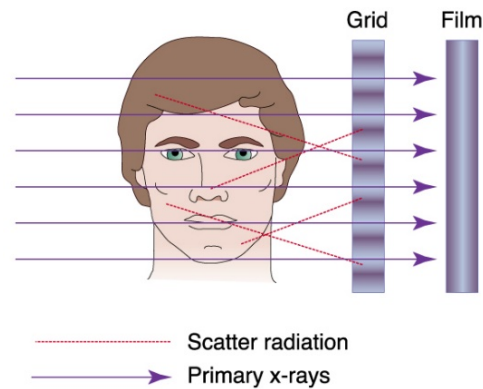


# Intraoral radiography

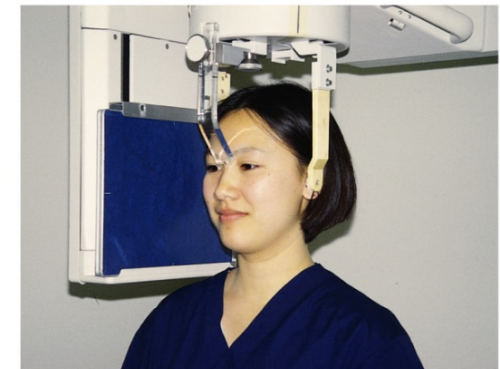


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# Extraoral radiography



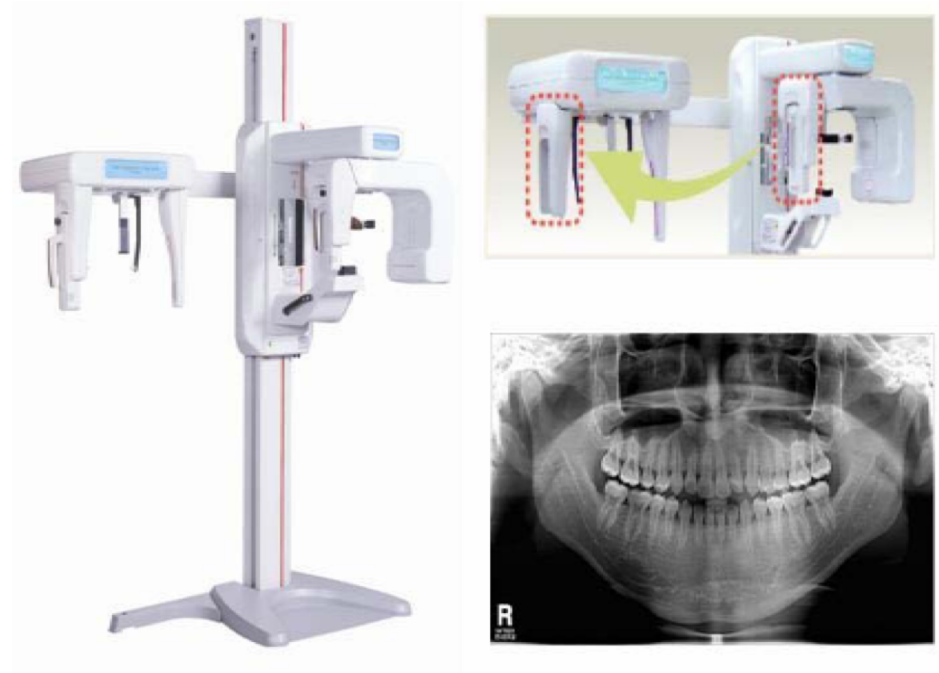
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# Panoramic dentistry imaging

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



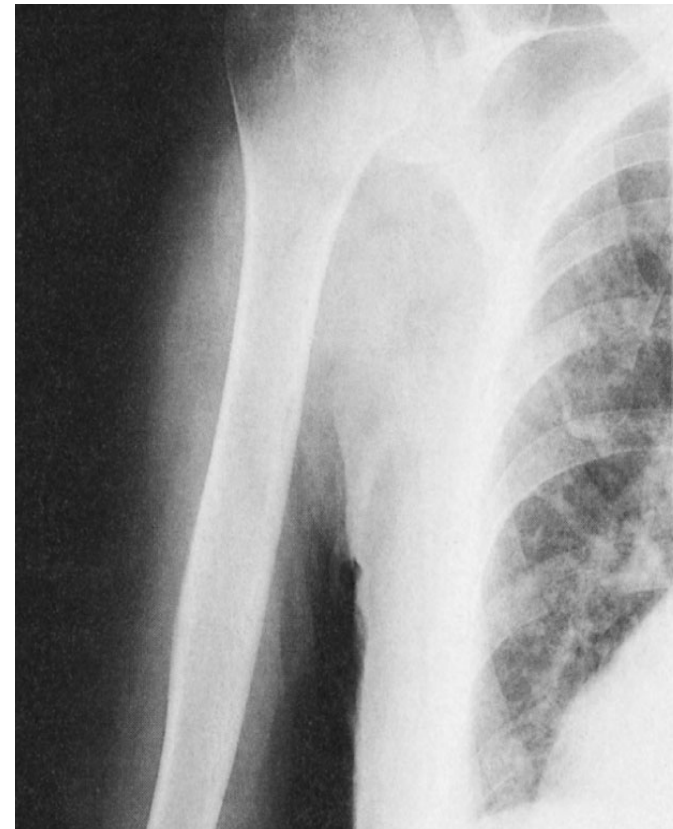


# Effective atomic number

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

material	$Z_{eff}$
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!

	$Z_{eff}$	$\rho \text{ (g/cm}^3\text{)}$
H <sub>2</sub> 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*

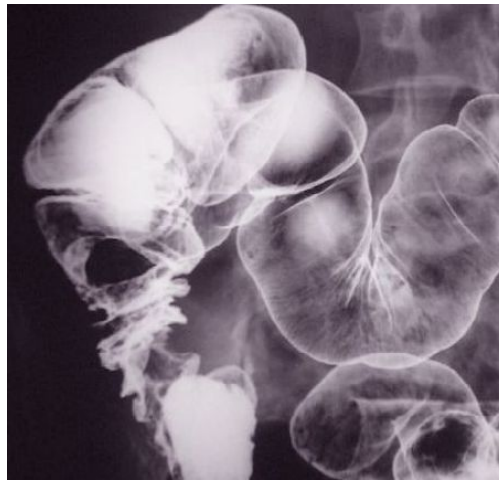
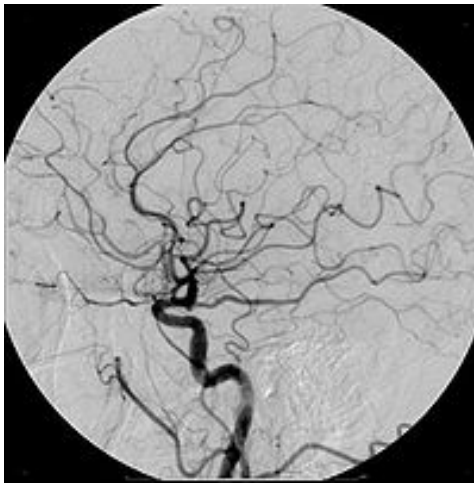
$$Z_{eff} > Z_{environment} \rightarrow \mu > \mu_{environment}$$

**Negative contrast**  $\rightarrow$  *lower attenuation to surroundings*

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

# Applying contrast materials

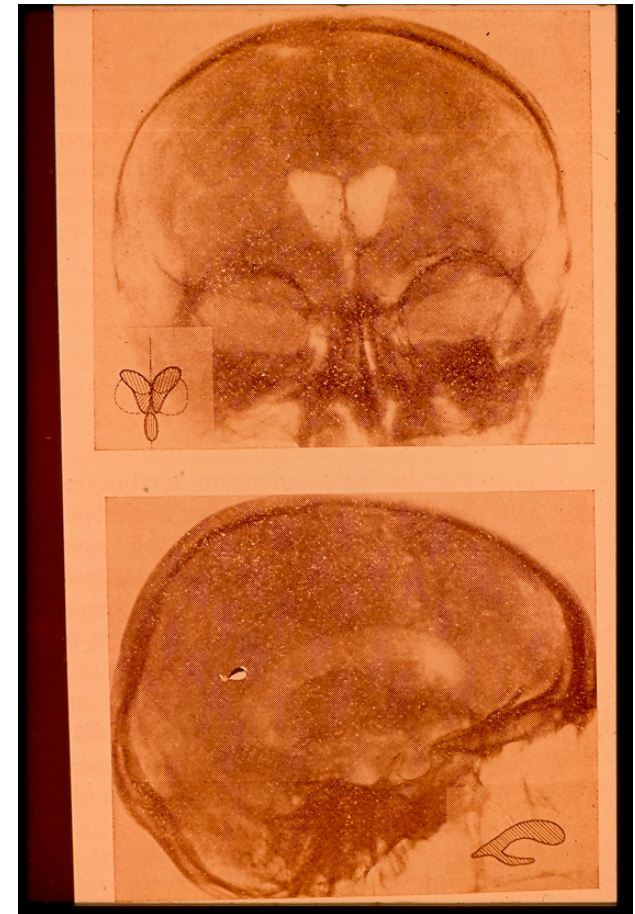
higher  $Z_{\text{eff}}$



Iodine or barium compounds

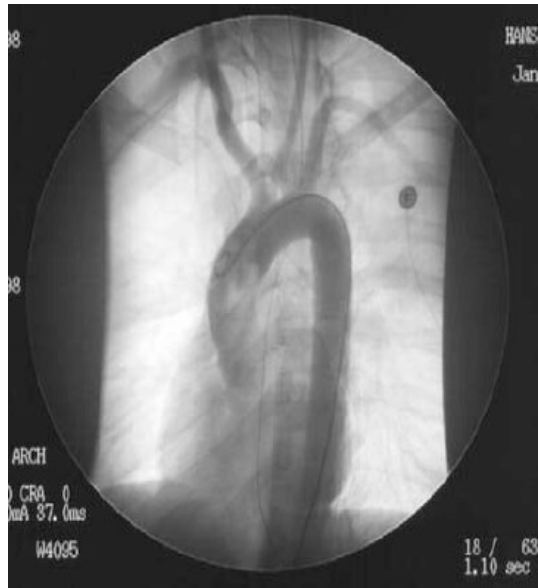


lower density

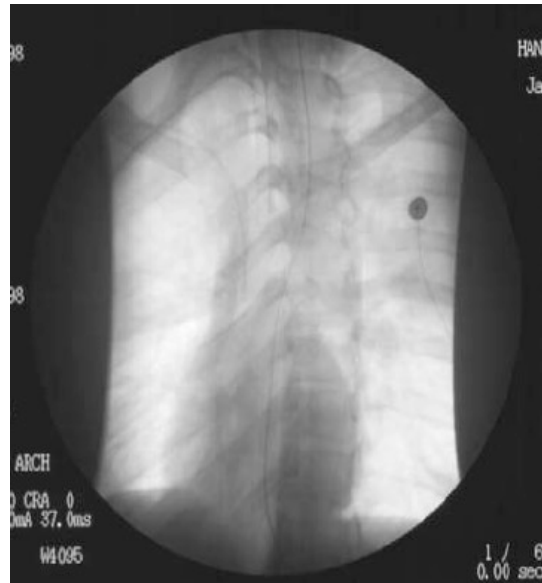


air,  $\text{CO}_2$

# Digital Subtraction Angiography (DSA)



*with contrast  
material*



*native*



*contrast - native*

# X ray image formation:

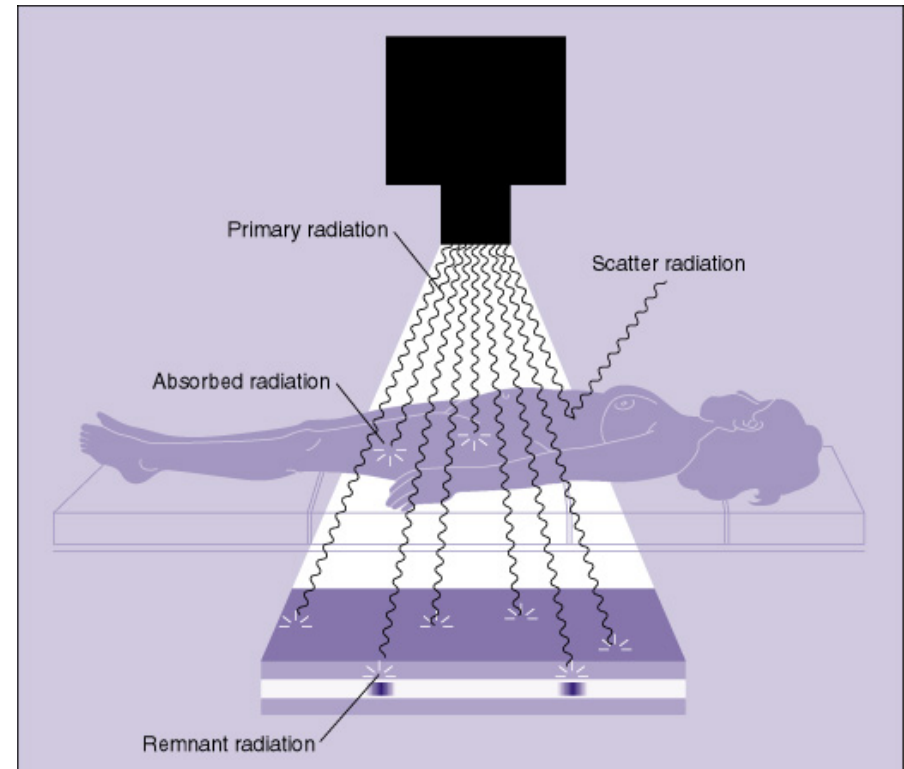
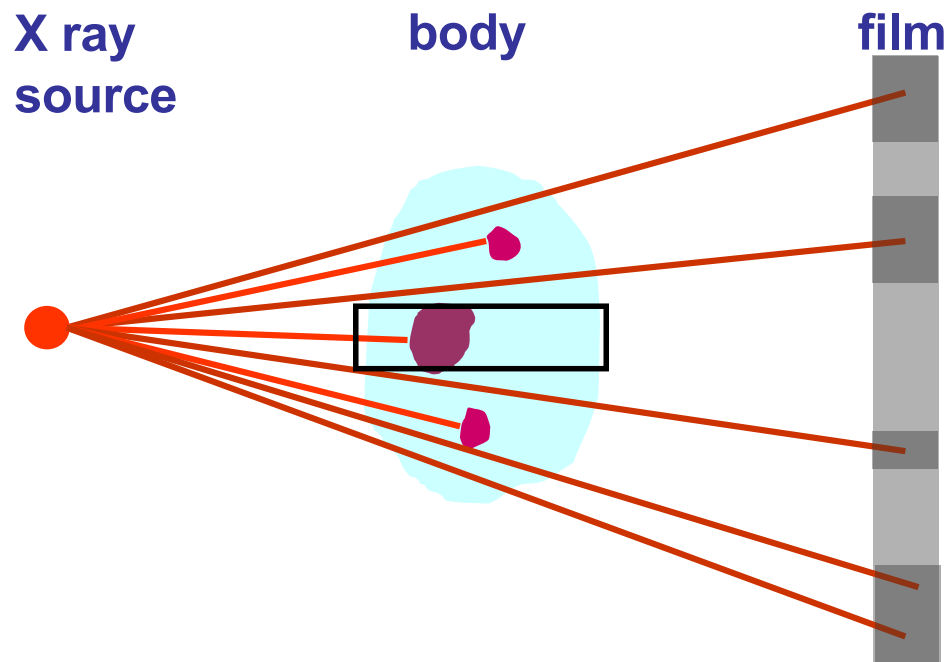
*Depicting intensity differences  
of radioation travelled through  
the specimen*

Visualize image with

- X ray film
- luminescence screen
- a digitized image

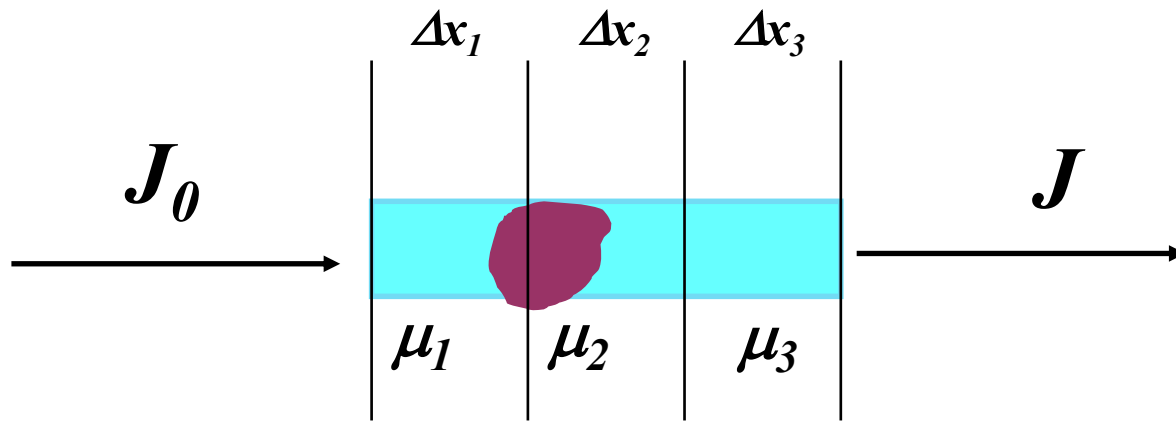


# Summation image

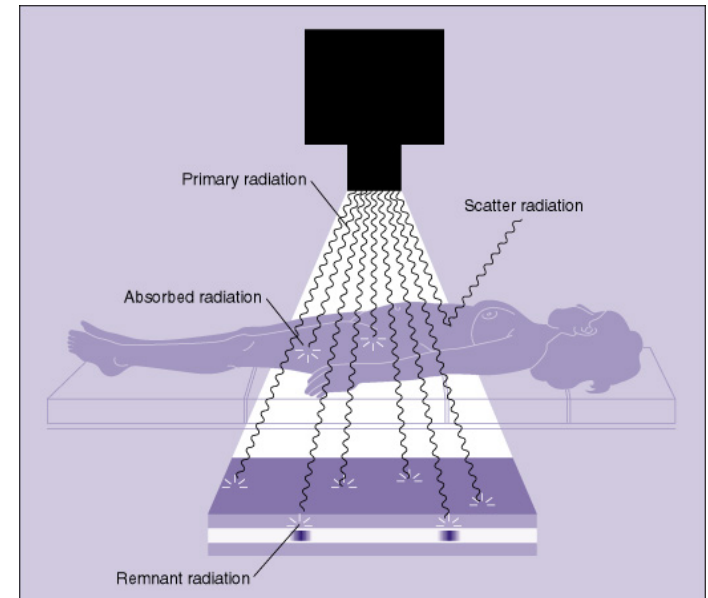


$$\begin{array}{c} \xrightarrow{J_0} \text{[Body]} \xrightarrow{J} \\ J = J_0 e^{-\mu x} \end{array}$$

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



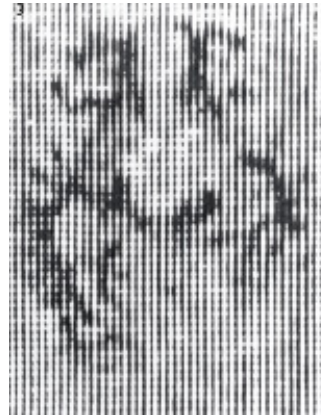
Allan Cormack

1979 – Nobel price in medicine

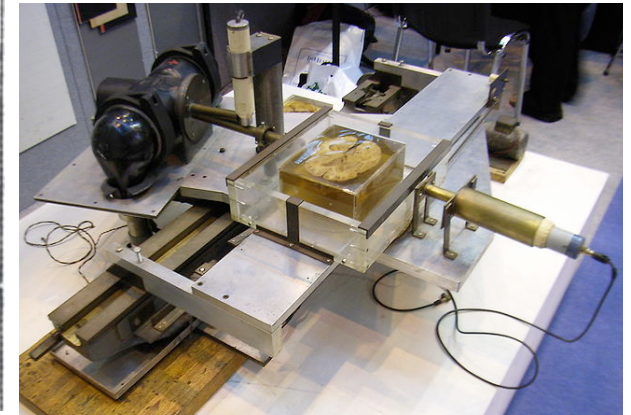


## Brief history:

- 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



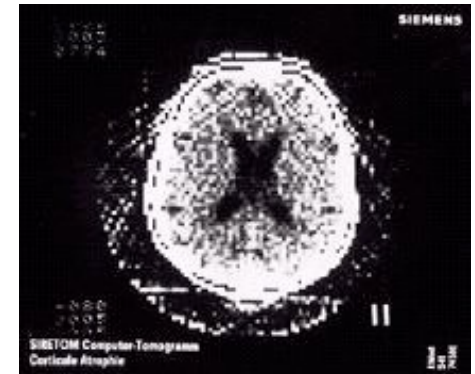
First lab CT of brain slice



Prototype CT (EMI)



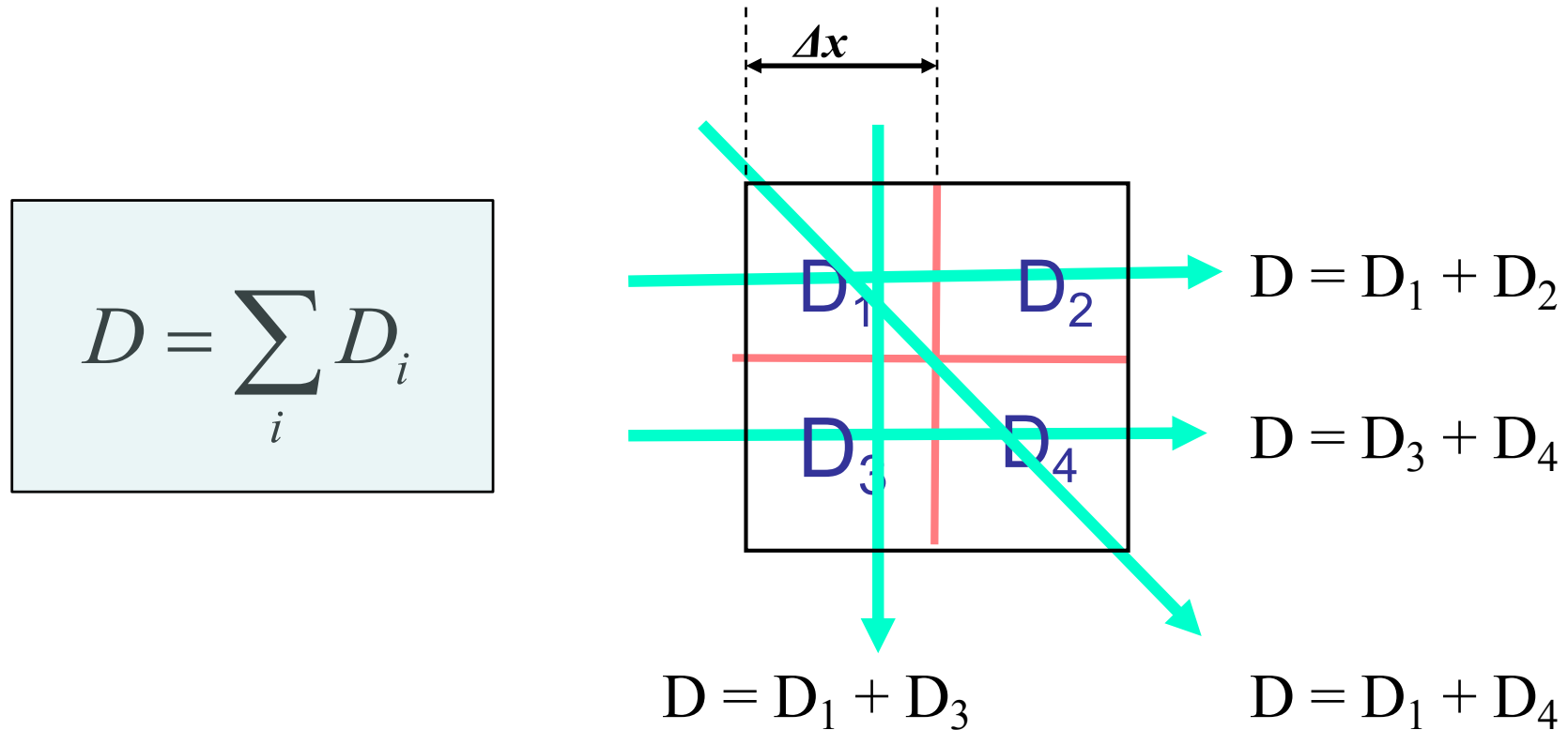
„Siretom” head scanner (1974)



128x128 pixel image (1975)



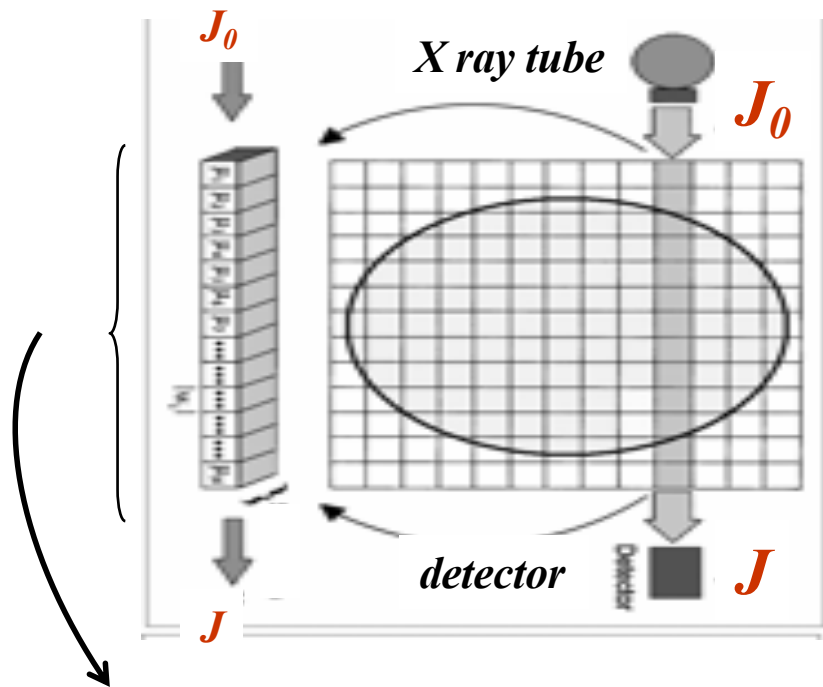
# Illustration of math principle:



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

*object*

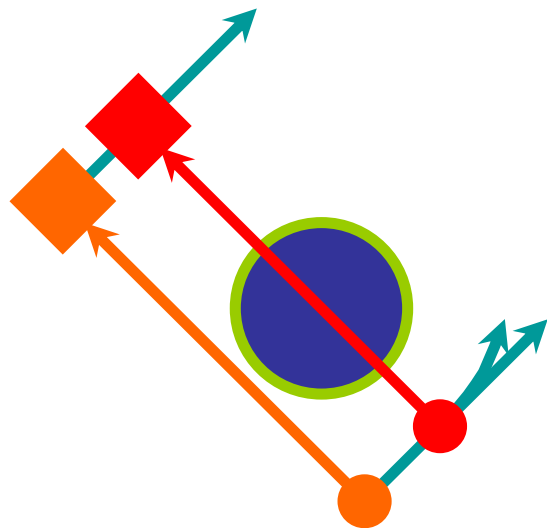
*digital image*



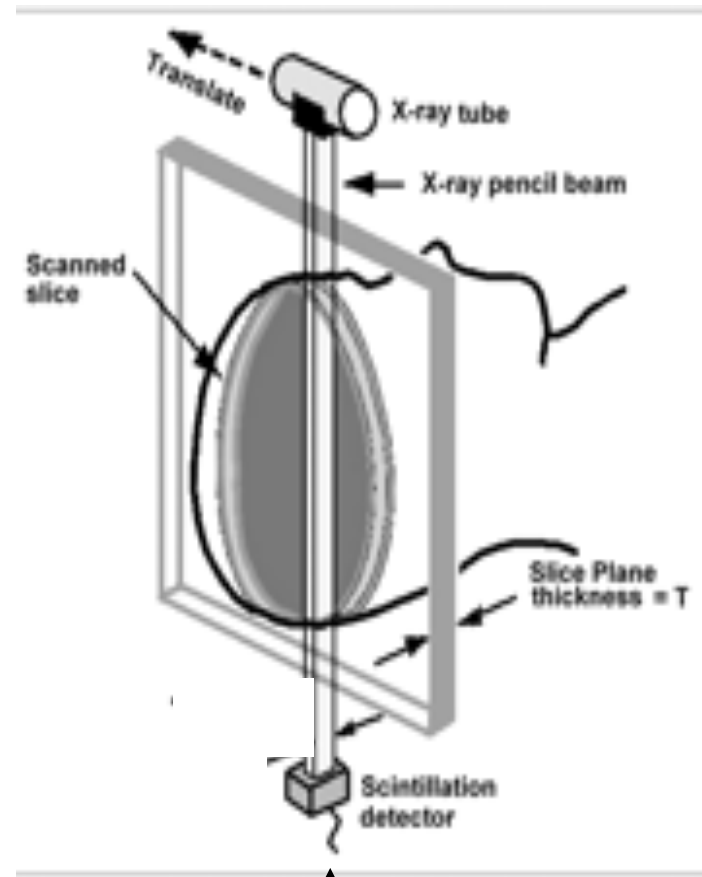
**Voxel :**  
volume element

**Pixel :**  
picture element

# First generation CT



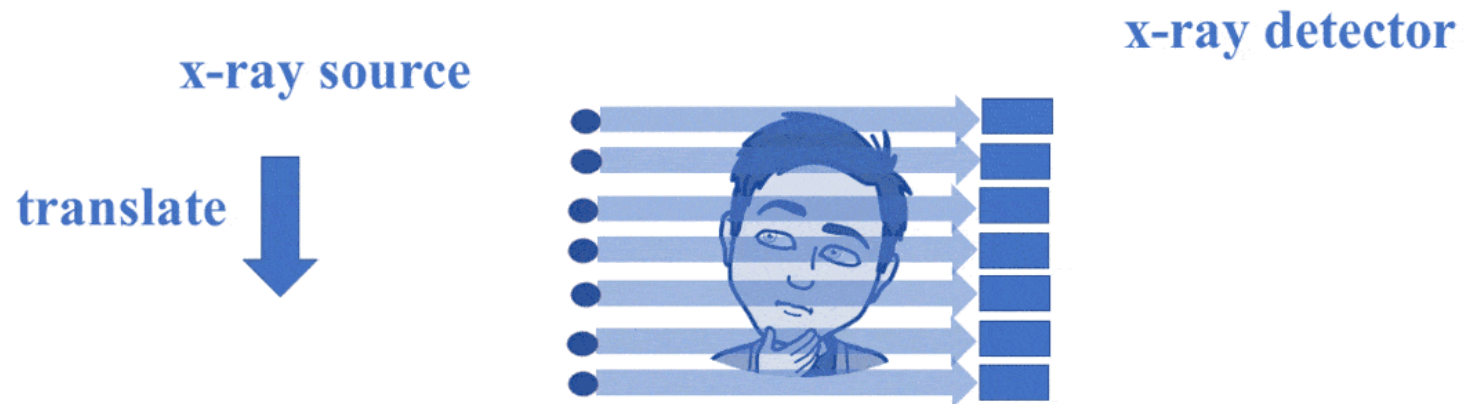
*Single detector*  
*Translation and rotation*  
*Parallel beams*



k-th position

# First generation CT

## 1<sup>st</sup> Gen Rotating CT



*Single detector*  
*Translation and rotation*  
*Parallel beams*

# Second generation CT

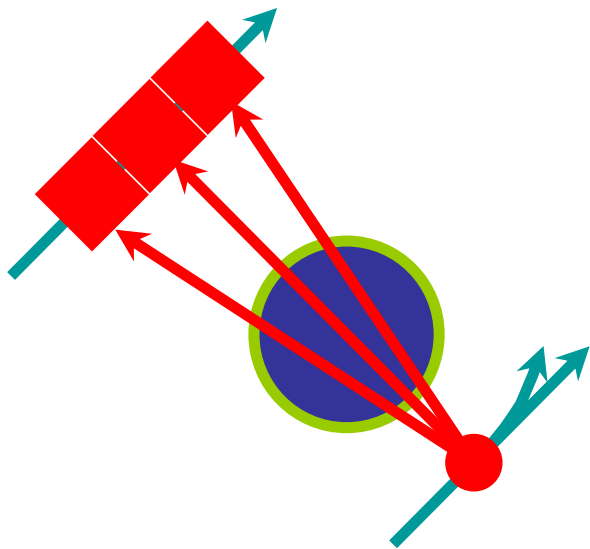
2<sup>nd</sup> Gen CT

x-ray source

translate



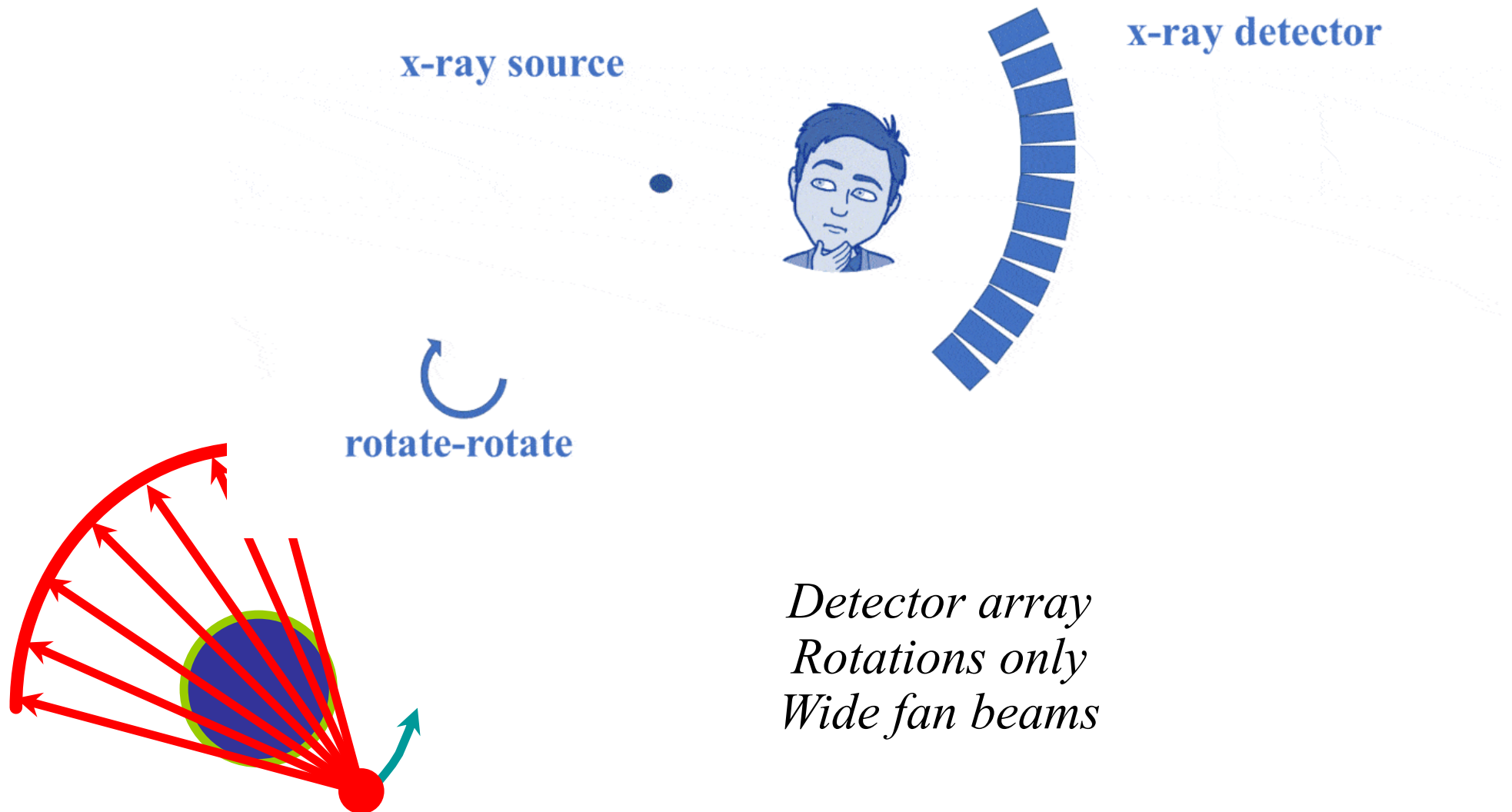
x-ray detector



*Multiple detectors  
Translation and rotation  
narrow fan beams*

# Third generation CT

3<sup>rd</sup> Gen CT

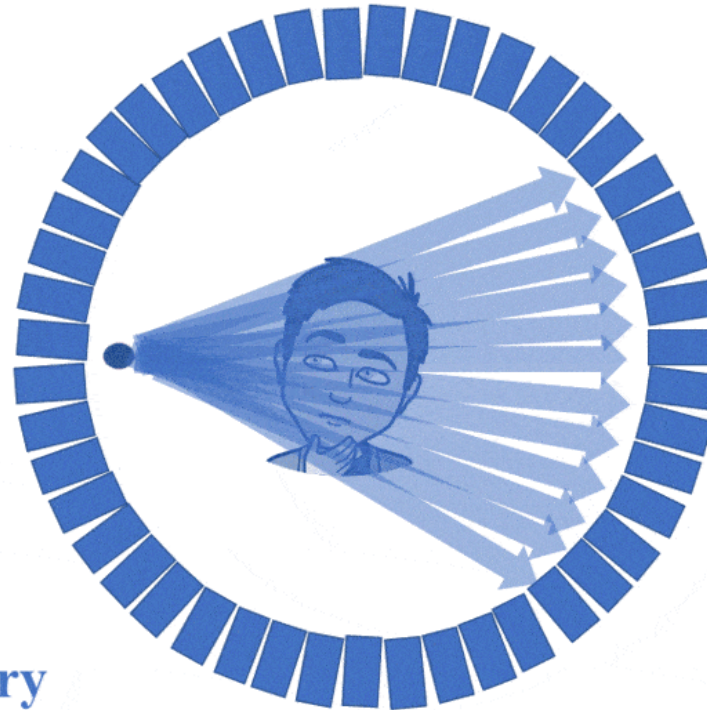


# Fourth generation CT

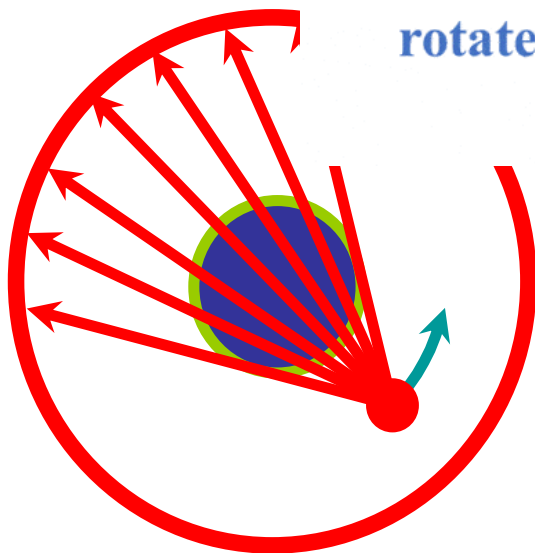
4<sup>th</sup> Gen CT

x-ray source

x-ray detector



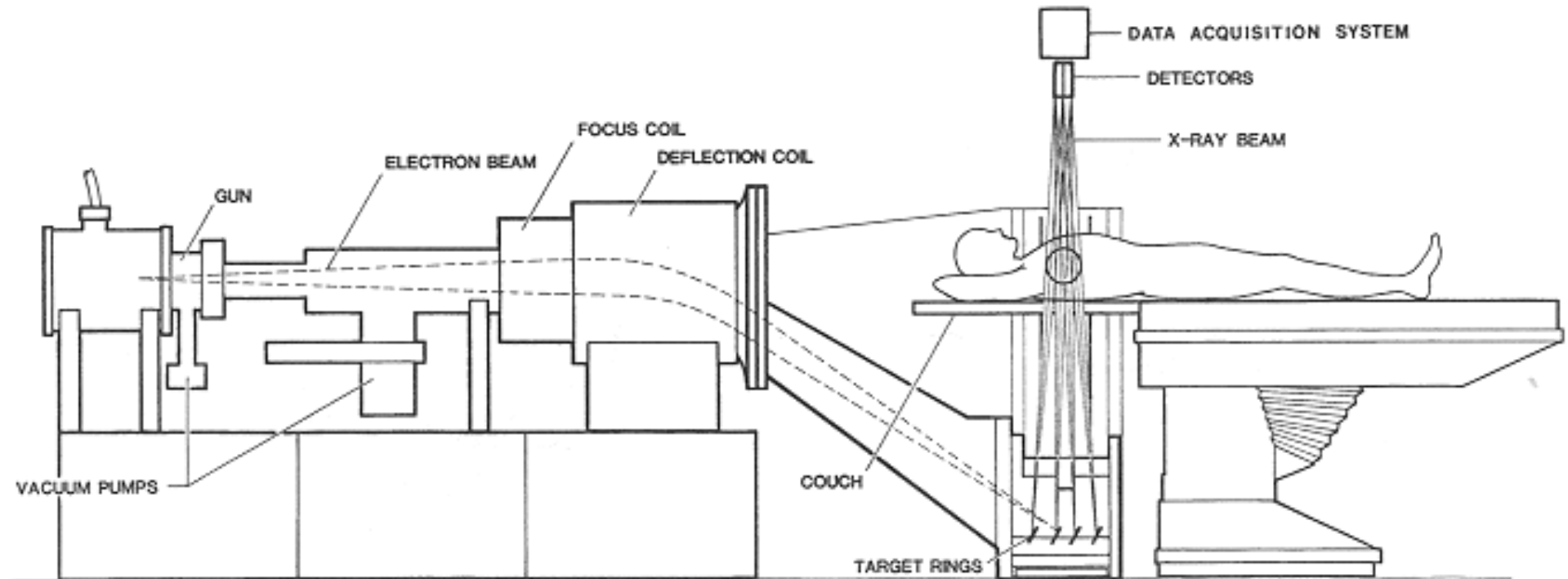
rotate-stationary



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

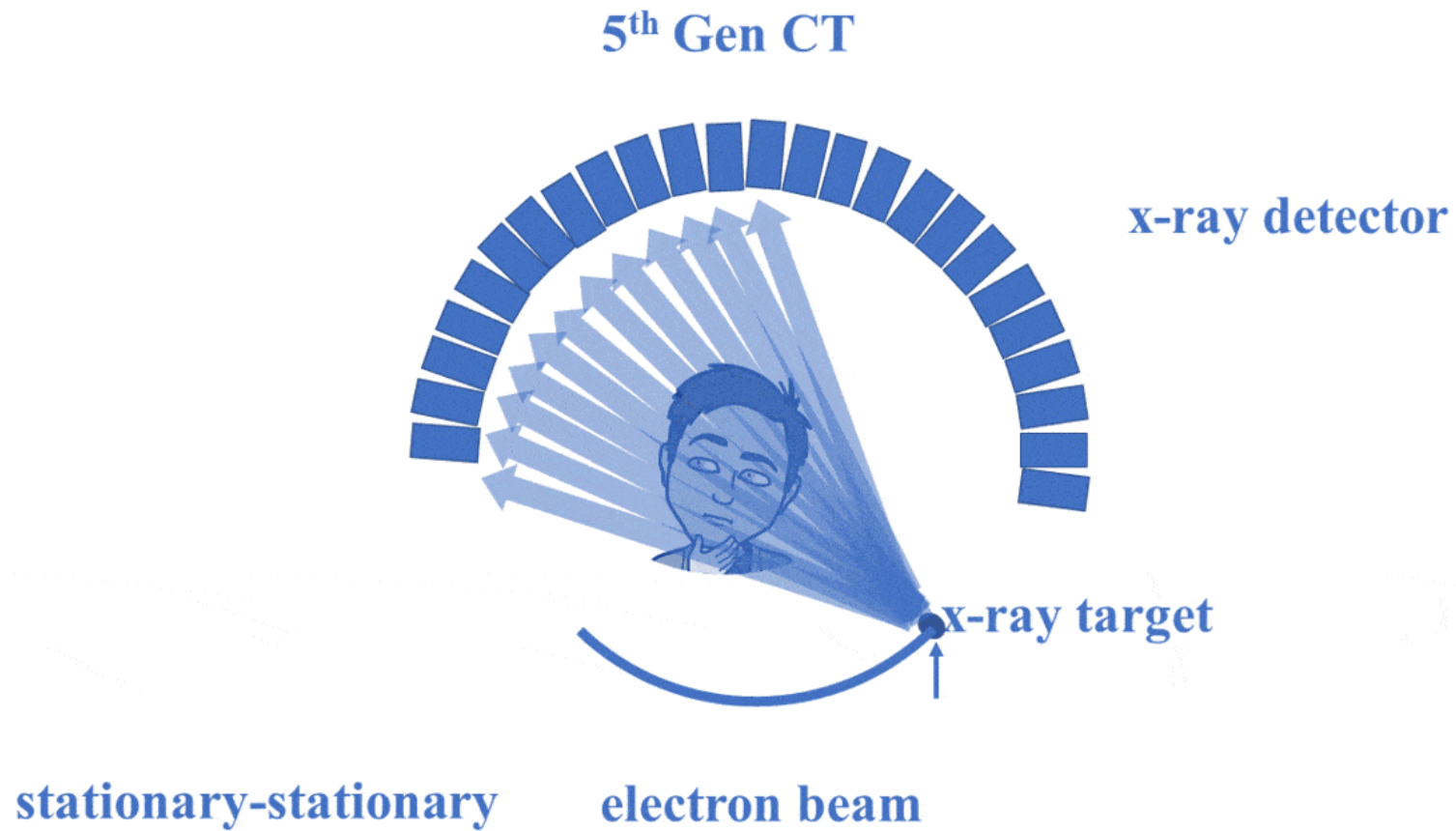


# Fifth generation CT



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

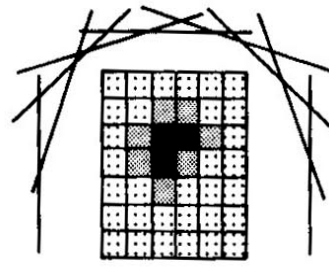
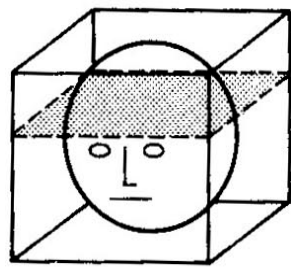
# Fifth generation CT



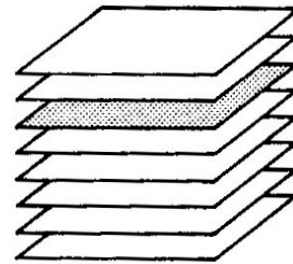
# Comparison of CT generations

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.

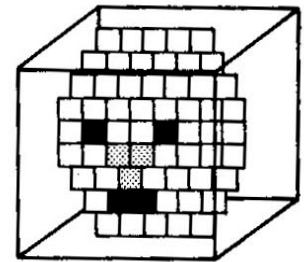
# 3D reconstructions



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

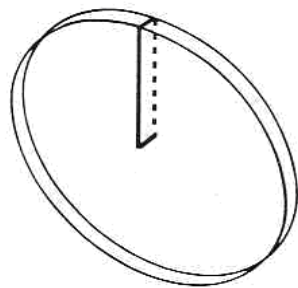


Many 2D slices

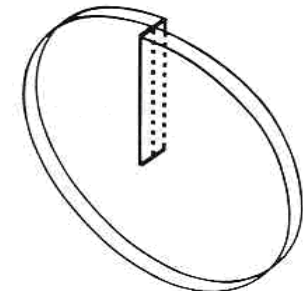
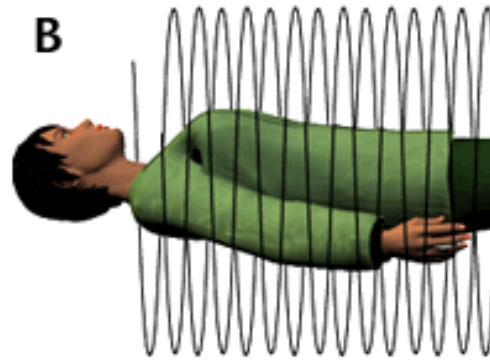
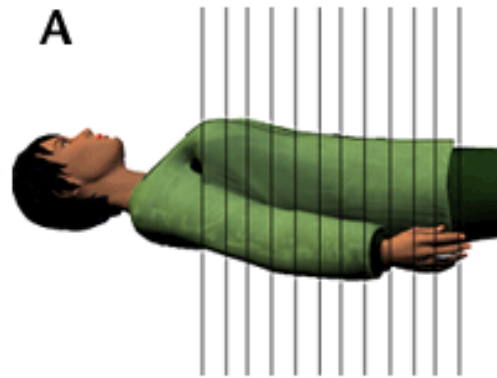


One 3D voxel model

# Spiral CT

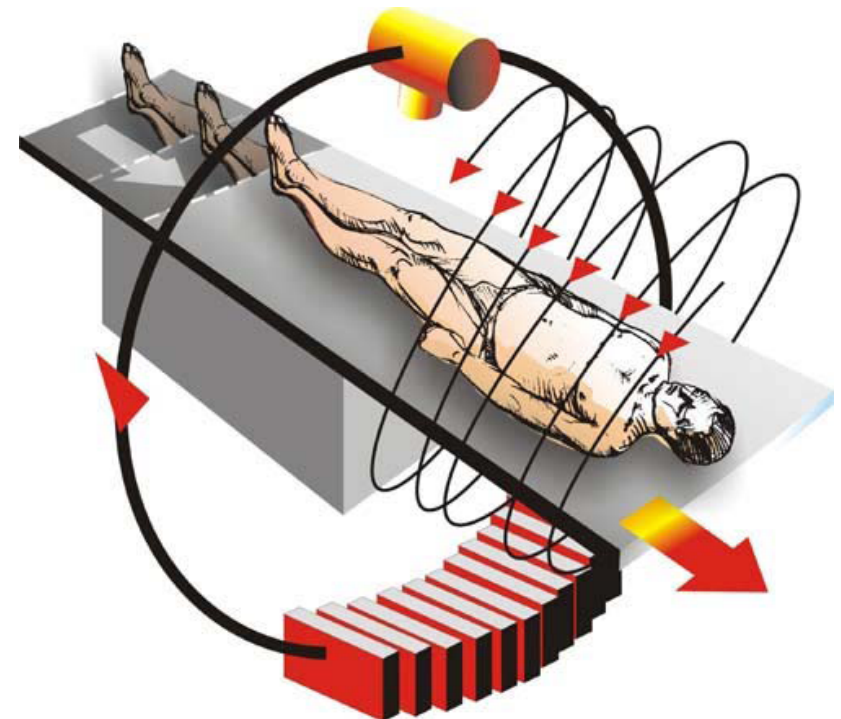
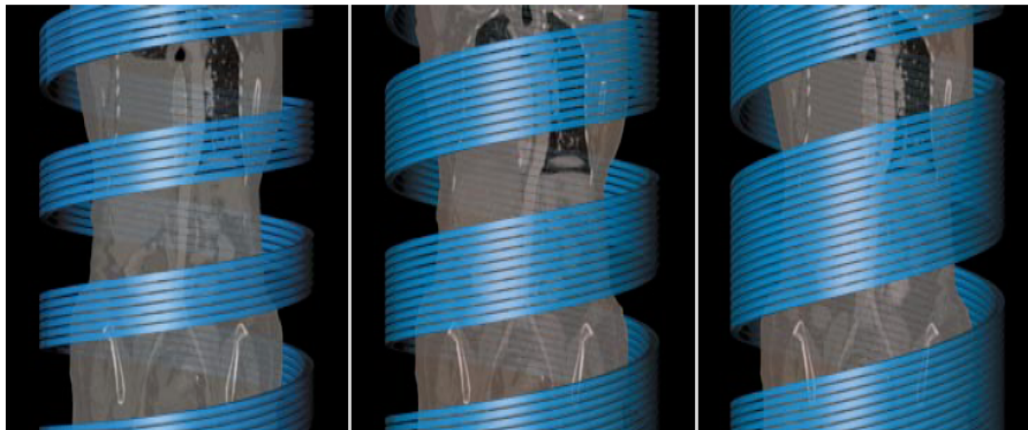


Conventional  
CT slice



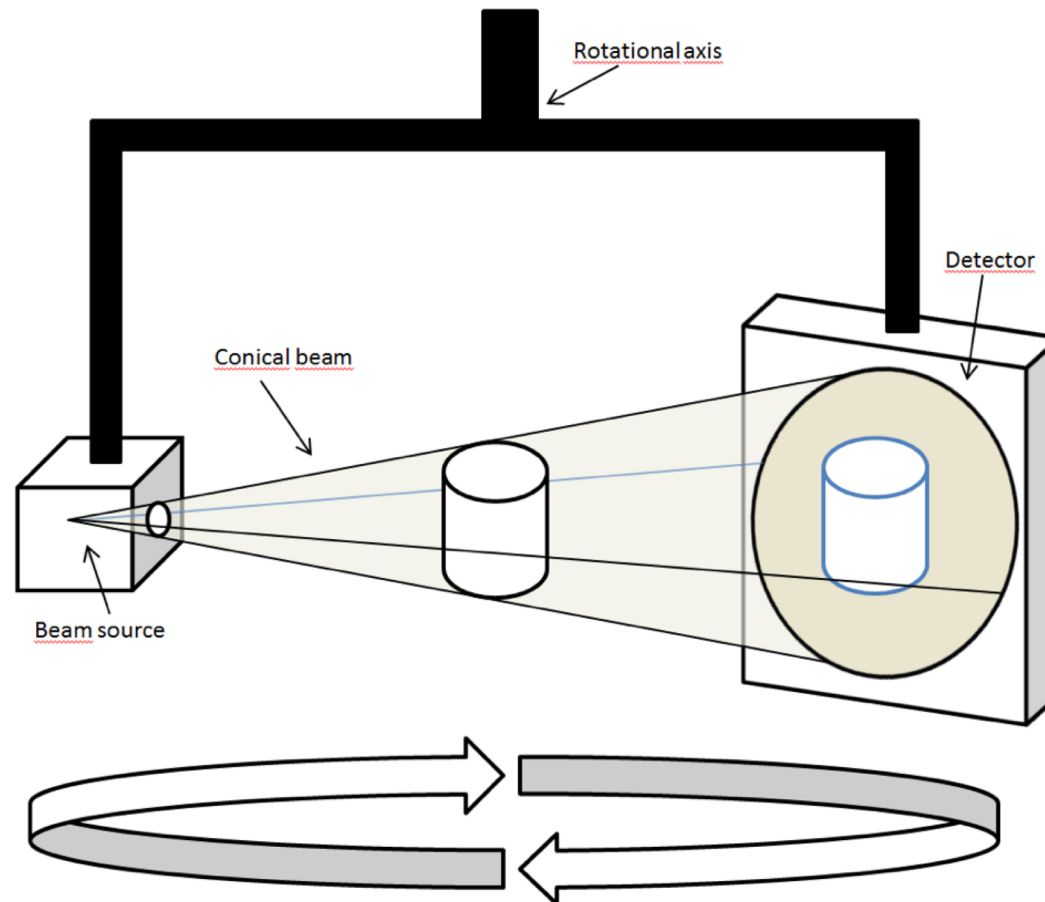
Spiral CT  
slice

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

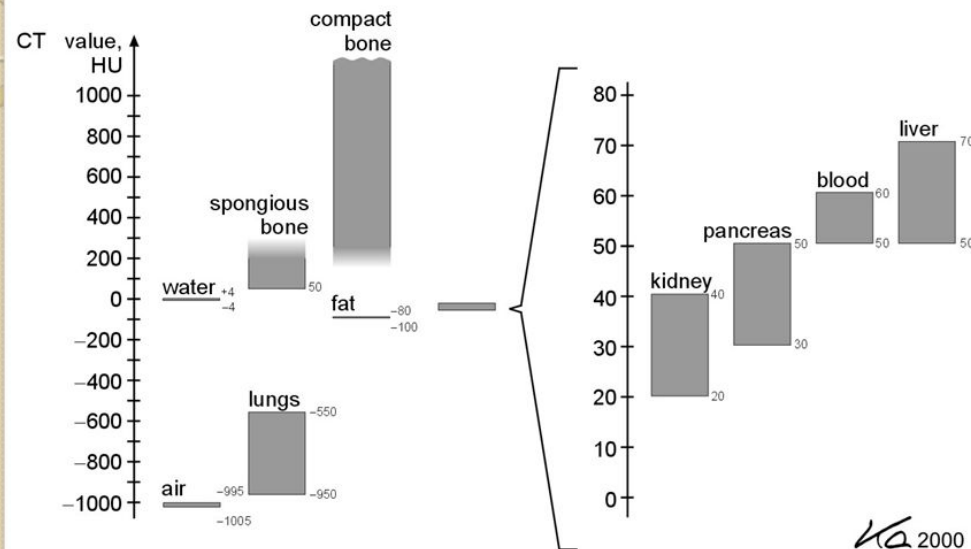
– density matrices ( $D_i$ )  $\rightarrow$  attenuation coefficients ( $\mu_i$ )

– *Hounsfield units*

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

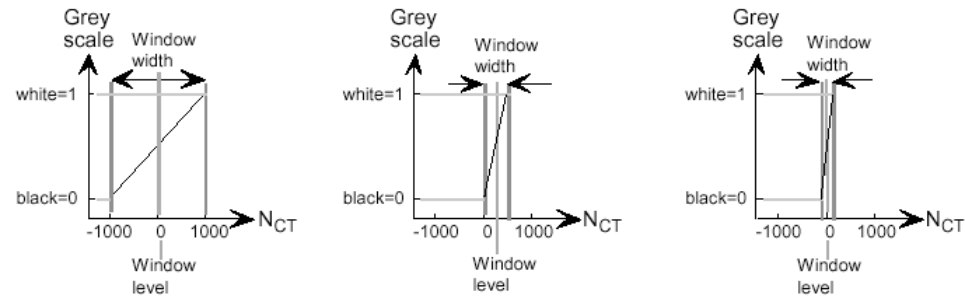
Hounsfield scale

## Hounsfield units of tissues

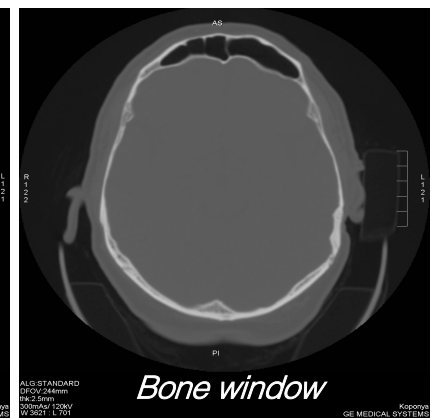
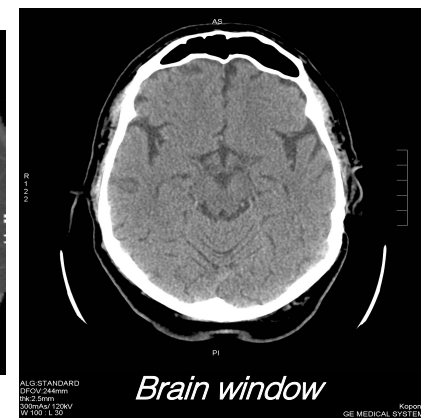
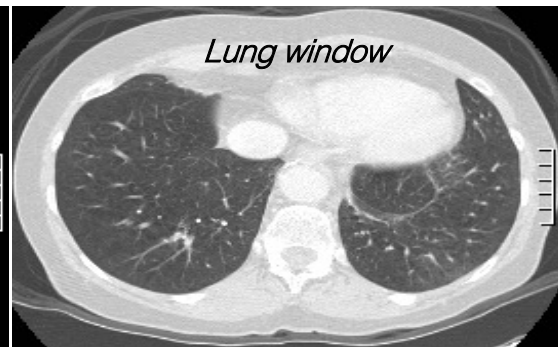
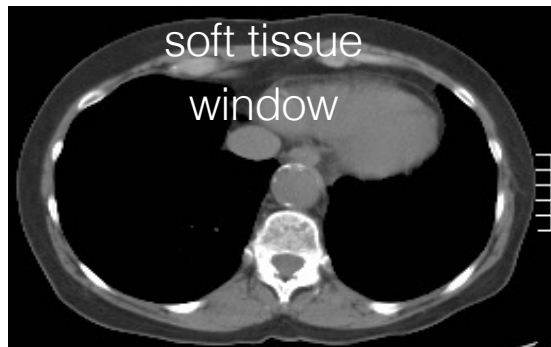
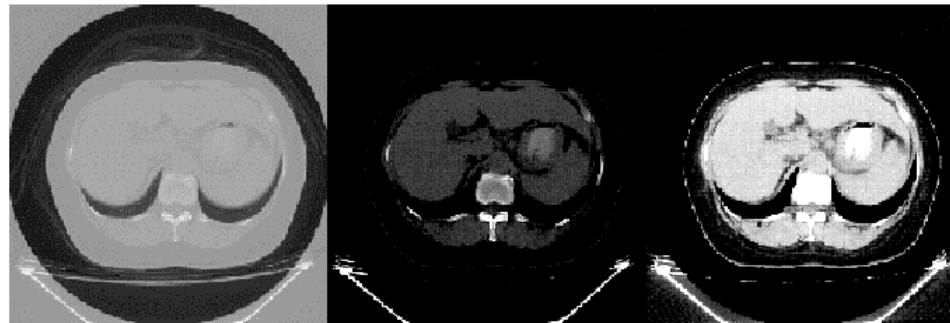


Taken from [1]

# CT contrast enhancement „windowing”

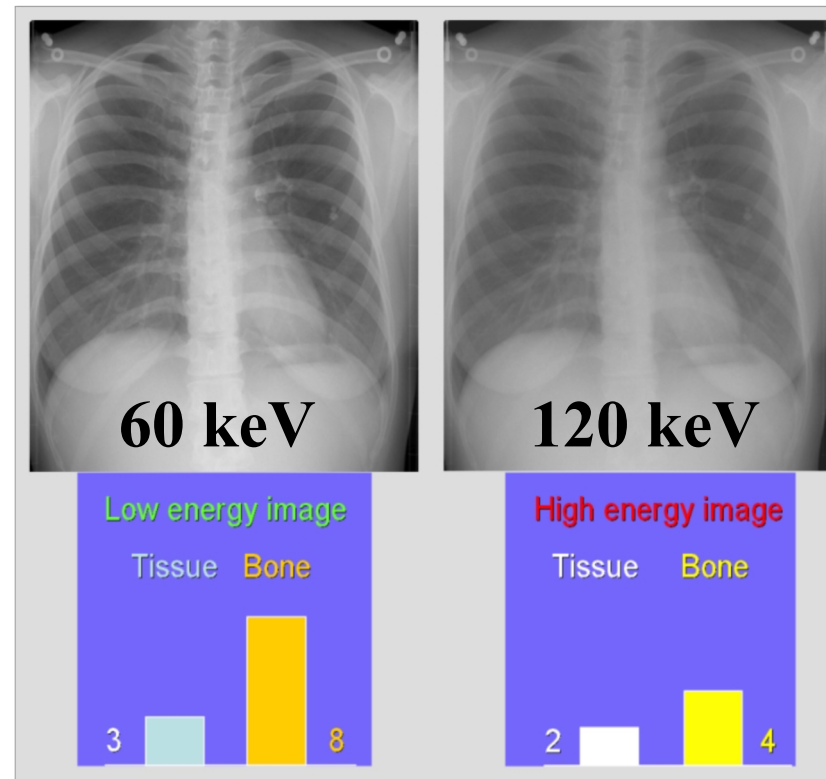


Same thoracic image  
with different windowing





# Contrast enhancement with dual source CT



## Weighted subtraction and scaling

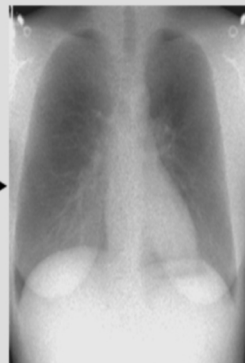
Tissue only: remove bone signal

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:

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

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

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



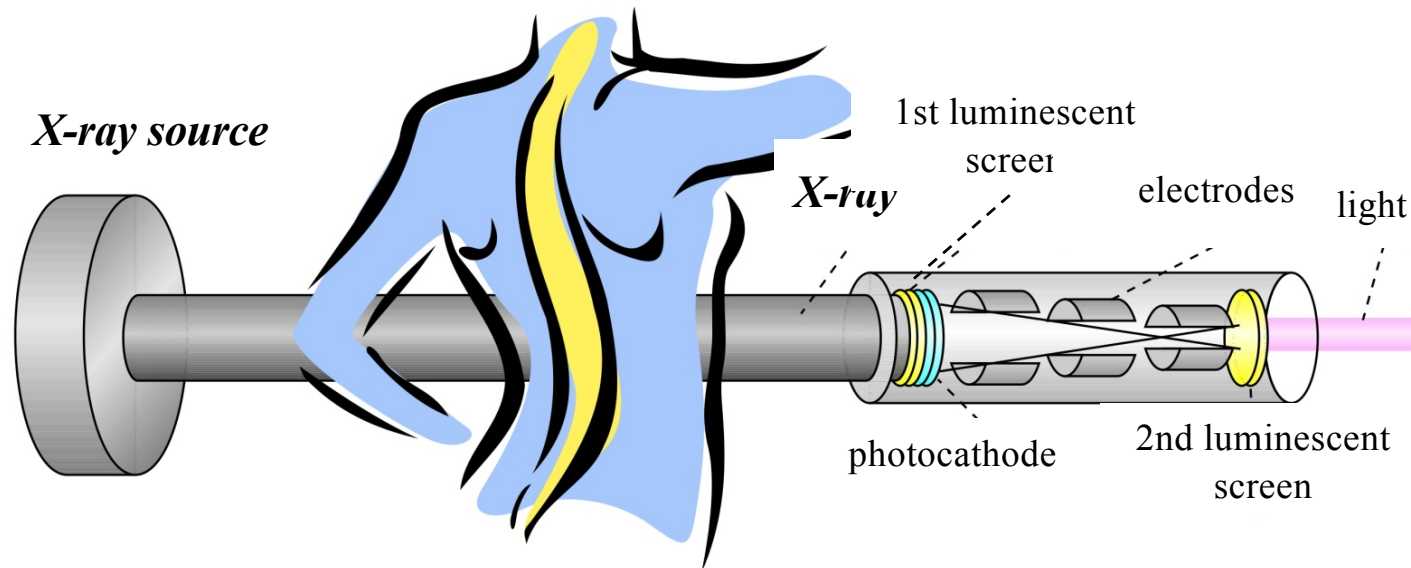
## Brief summary of *CT*

- Imaging is based on the differences in X ray absorption / attenuation
- 3D image that can be 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 exposure 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