X-ray

Applications

Medical Biophysics II.

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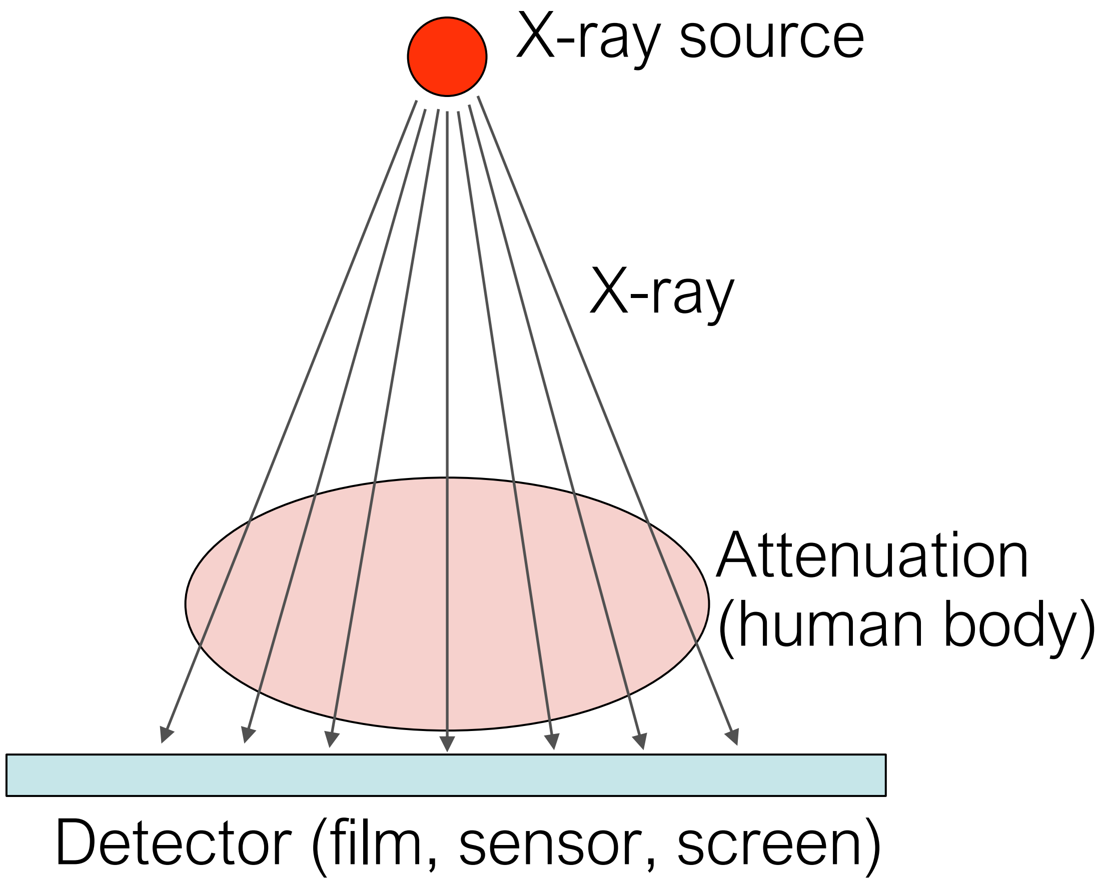
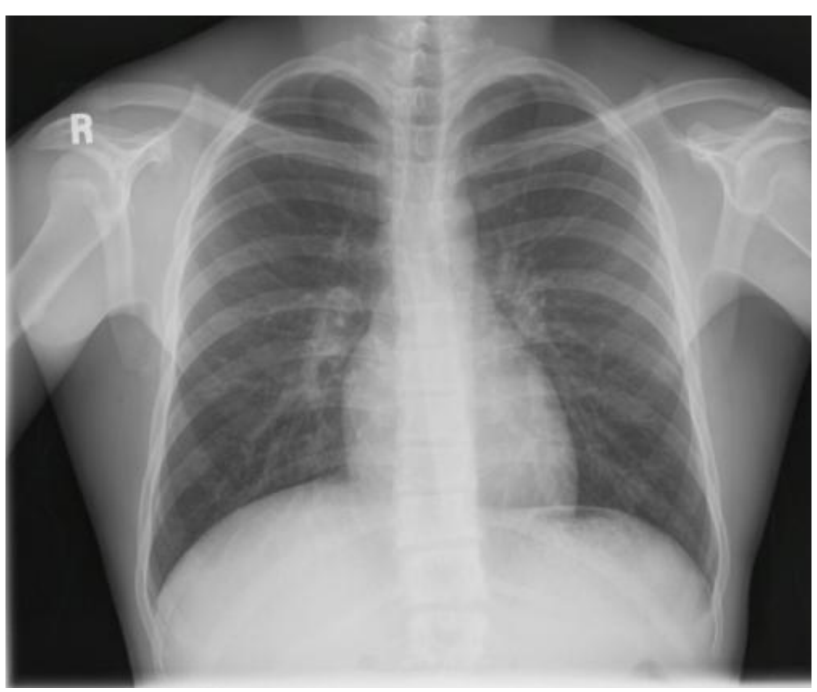
SEMMELWEIS EGYETEM 1769

Application I. X-ray imaging





The X-ray image

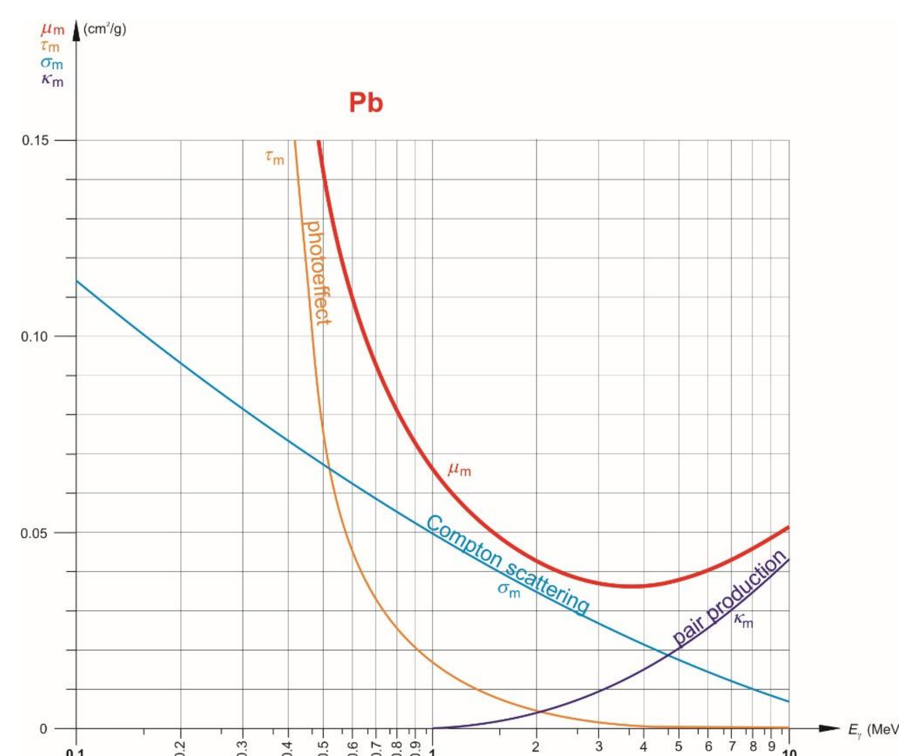
$$J = J_0 e^{-\mu x}$$

$$\mu = \mu_m \rho$$

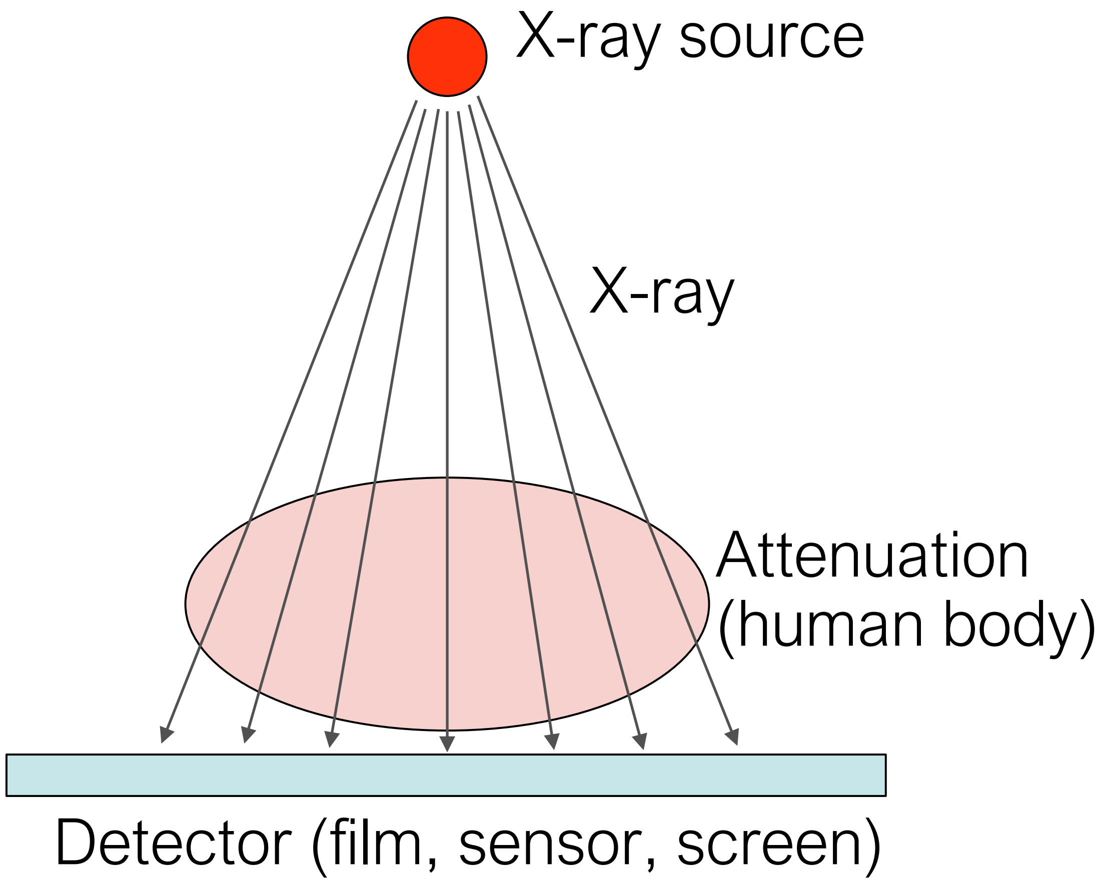
$$J = J_0 e^{-\mu_m \rho x}$$

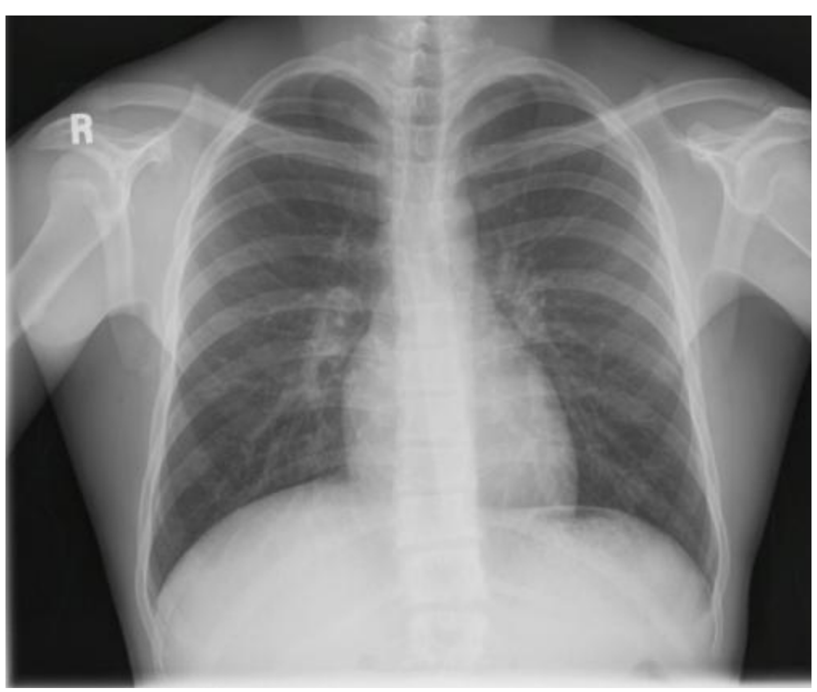
$$\mu_m = \tau_m + \sigma_m + \kappa_m$$

$$\tau_m \sim Z^3$$

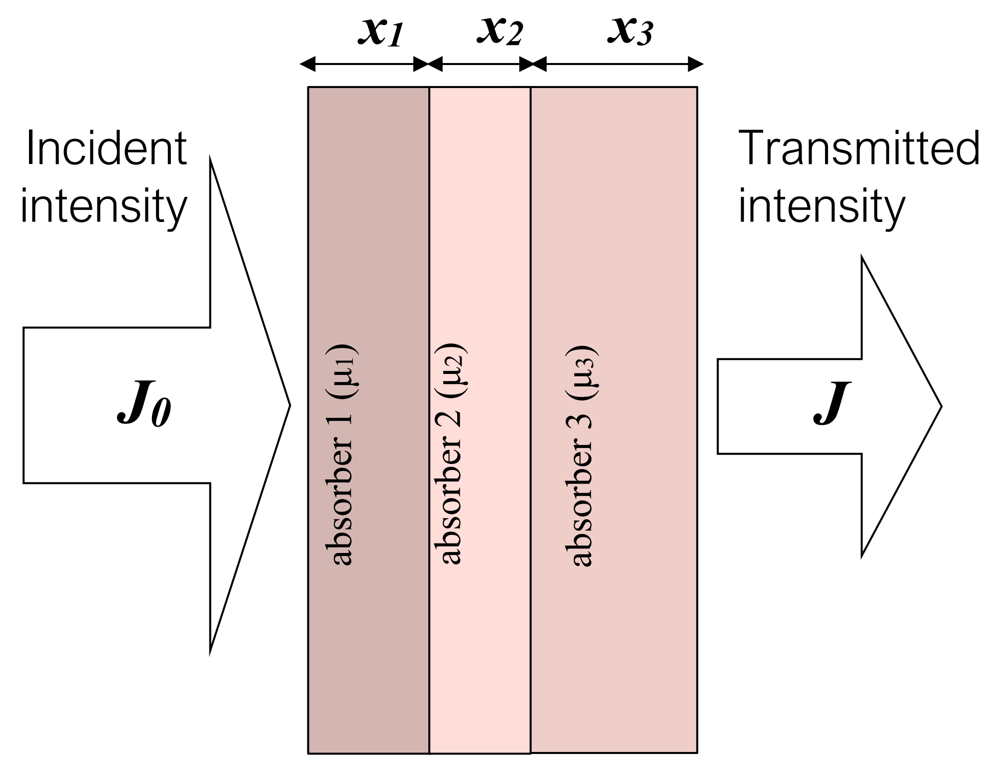


Application I. X-ray imaging





The X-ray image is a **summation image**
Contrast arises due to spatially varying attenuation.



μ_n : n^{th} absorber's attenuation coefficient
x_n : n^{th} absorber's thickness

$$J_1 = J_0 e^{-\mu_1 x_1}$$

$$J_2 = J_1 e^{-\mu_2 x_2} = J_0 e^{-\mu_1 x_1} e^{-\mu_2 x_2} = J_0 e^{-(\mu_1 x_1 + \mu_2 x_2)}$$

$$J = J_0 e^{-(\mu_1 x_1 + \cdots + \mu_n x_n)}$$

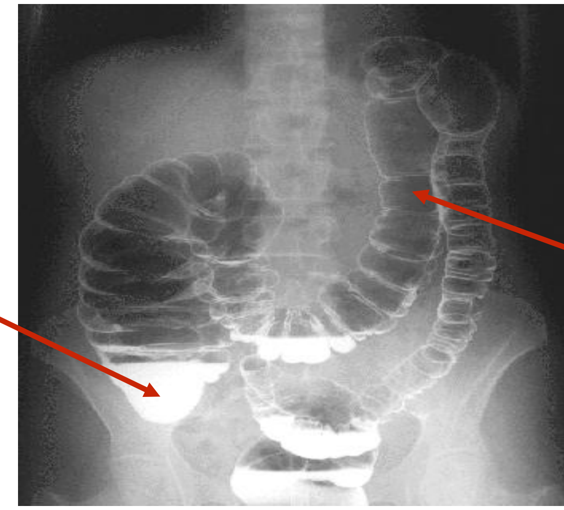
$$\frac{J_0}{J} = e^{(\mu_1 x_1 + \cdots + \mu_n x_n)}$$

$$D = lg \frac{J_0}{J} = (\mu_1 x_1 + \cdots + \mu_n x_n) \cdot lge$$

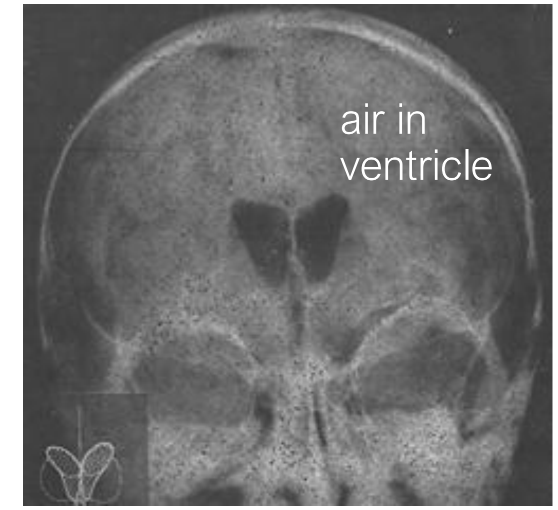
Improving X-ray imaging I.

Increasing contrast:
contrast agents

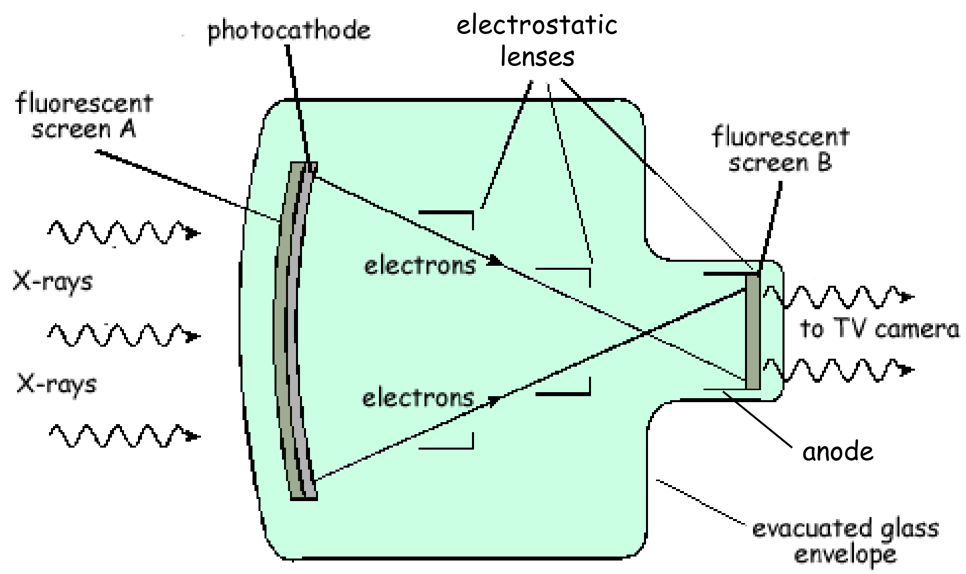
Positive contrast (large Z, e.g., Ba)



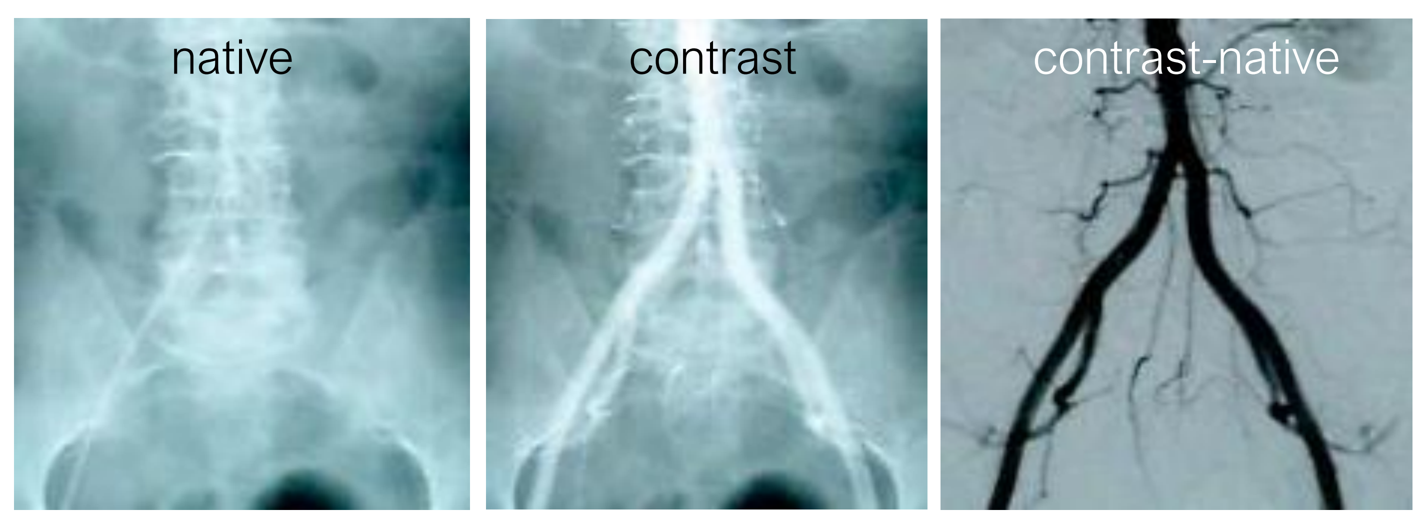
Negative contrast (small density, e.g., air)



Enhancing sensitivity:
intensifier

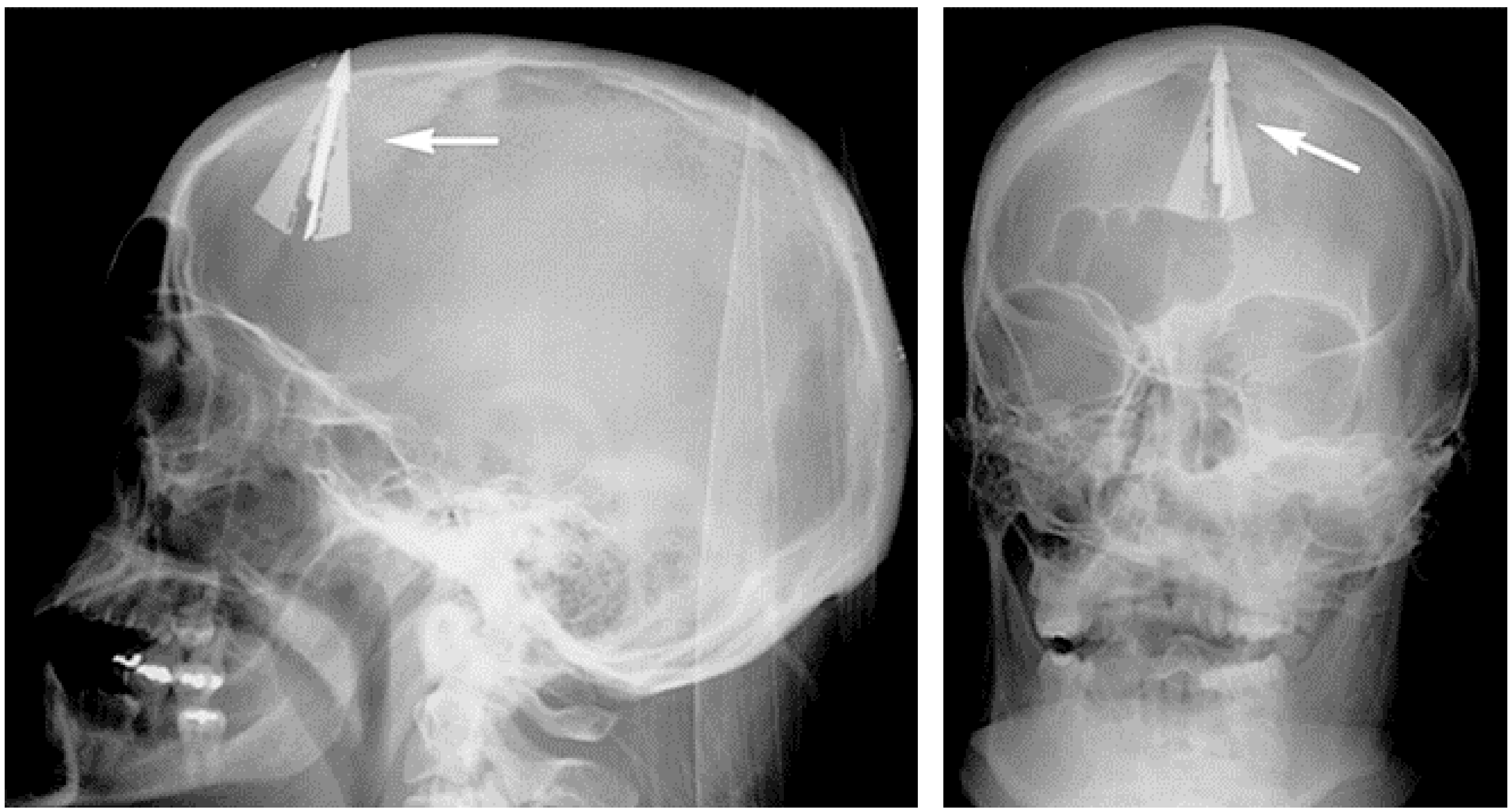


Background subtraction:
"Digital Subtraction Angiography" (DSA)



Improving X-ray imaging II. Spatial resolution

Bi-directional X-ray imaging

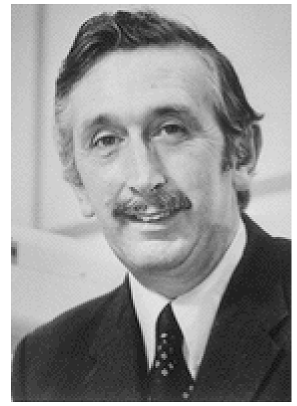


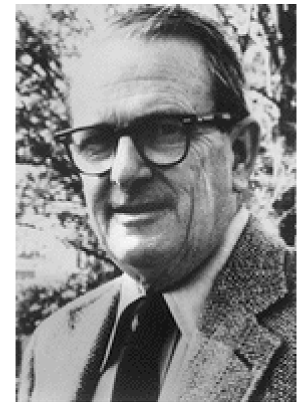
Bi-directional cranial X-ray of an individual who tried to commit suicide with a crossbow.

Improving X-ray imaging: the CAT scanner

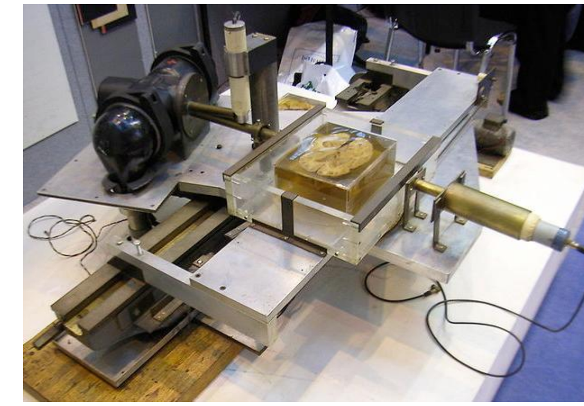
History

- Röntgen, Hounsfield and Cormack
- 1967: first CAT scan
- 1972: prototype
- 1974: first clinical CAT image (head)
- 1976: whole body CAT scan
- 1979: Nobel-prize
- 1990: spiral CAT scanner
- 1992: multislice CAT scanner
- 2006: 64 slice (and more…)
- multiple and hybrid modes: SPECT-CT, PET-CT, Dual-source CT


Godfrey Hounsfield

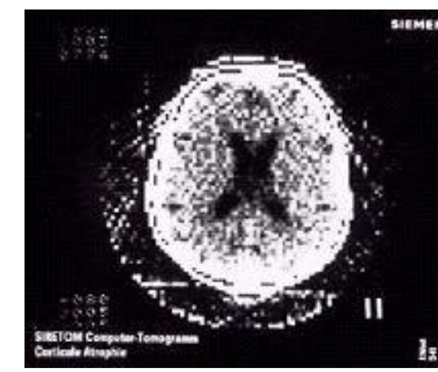

Allan Cormack


First, lab CT of a brain slice

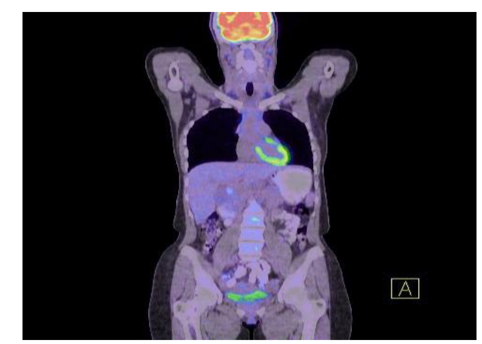

Prototype CAT scanner (EMI)

„Siretom" head scanner (1974)

128x128 pixel image (1975)



Multi-modal (combined) images



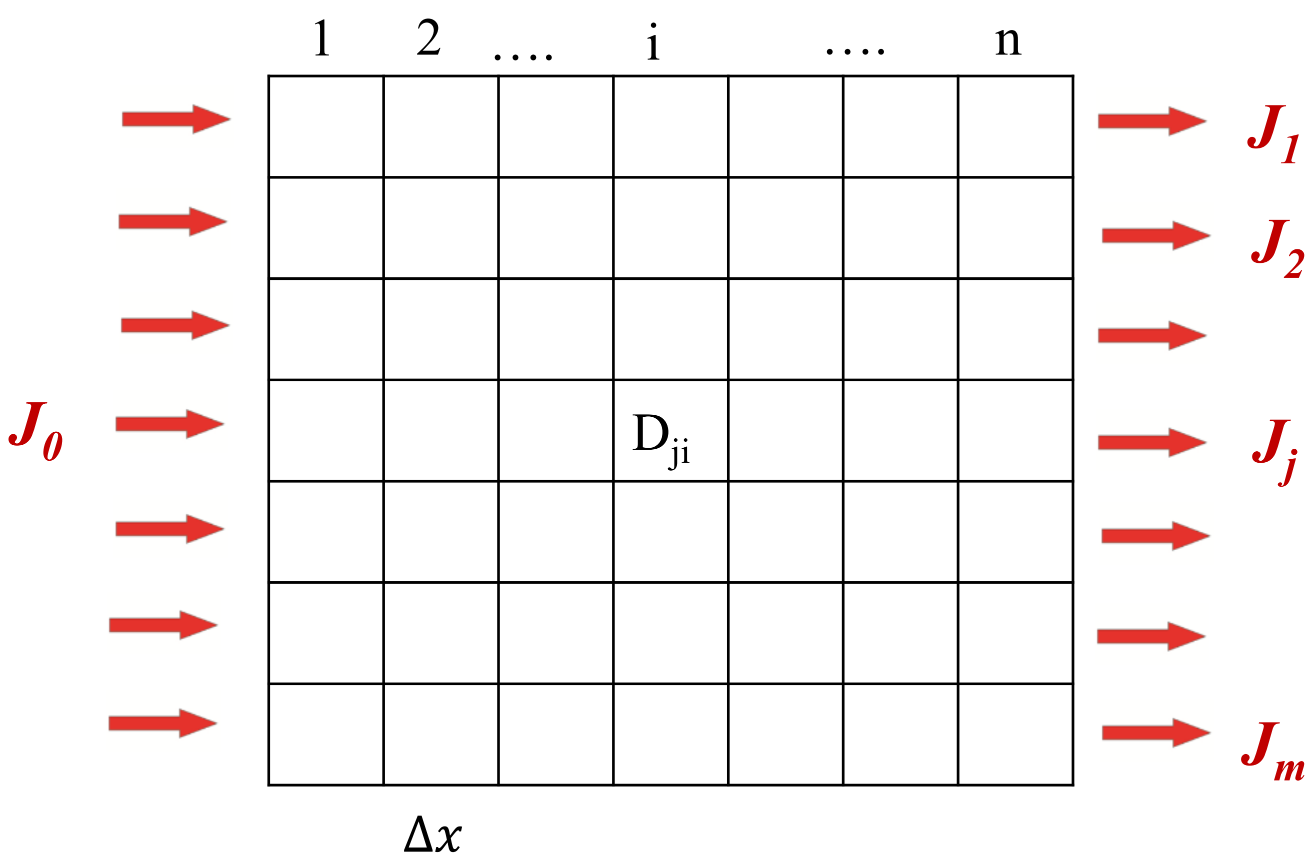
Summary

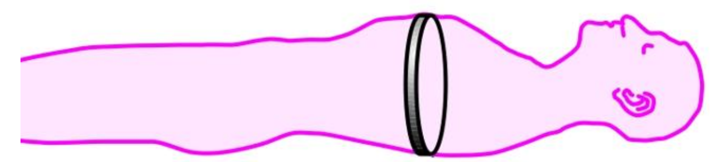
- **Tomographic** digital imaging method that uses **x-rays:** displays x-ray **absorbance** by the different points of the tomographic slice.
- **Multidetector** spiral CT (4-64 detector array): one slice 0.4-1 s; entire examination 5-15 s.
- **Ionizing** radiation. Absorbed **dose** ~50-100 times that of conventional x-ray. Significant **scattered** intensity.

Current CAT scanner

CT Foundations I: determination of μ

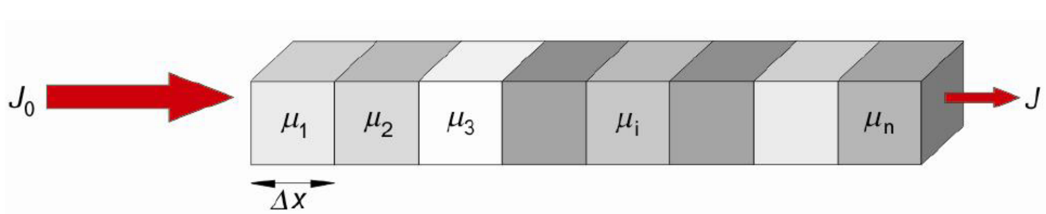
Objective: to determine the attenuation coefficient (μ_x) of the individual volume elements (voxels)





$$J_j = J_0 e^{-(\mu_{j1}\Delta x + \mu_{j2}\Delta x + \cdots + \mu_{ji}\Delta x + \cdots + \mu_{jn}\Delta x)}$$

$$D_j = lg\frac{J_0}{J_j} = (\mu_{j1}\Delta x + \mu_{j2}\Delta x + \cdots + \mu_{jn}\Delta x) \cdot lge$$

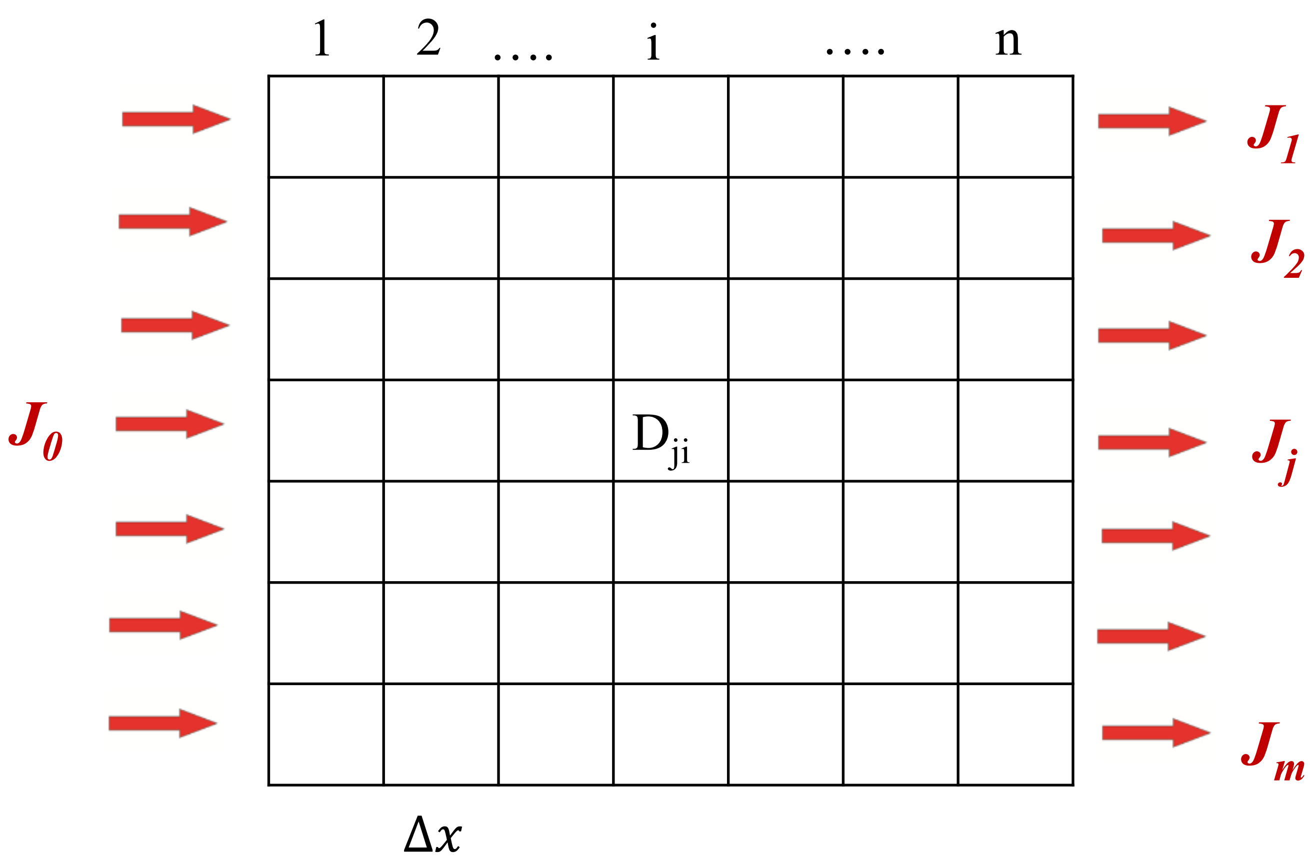


nr. of unknown **m x n**

nr. of linear equations: **m x n**

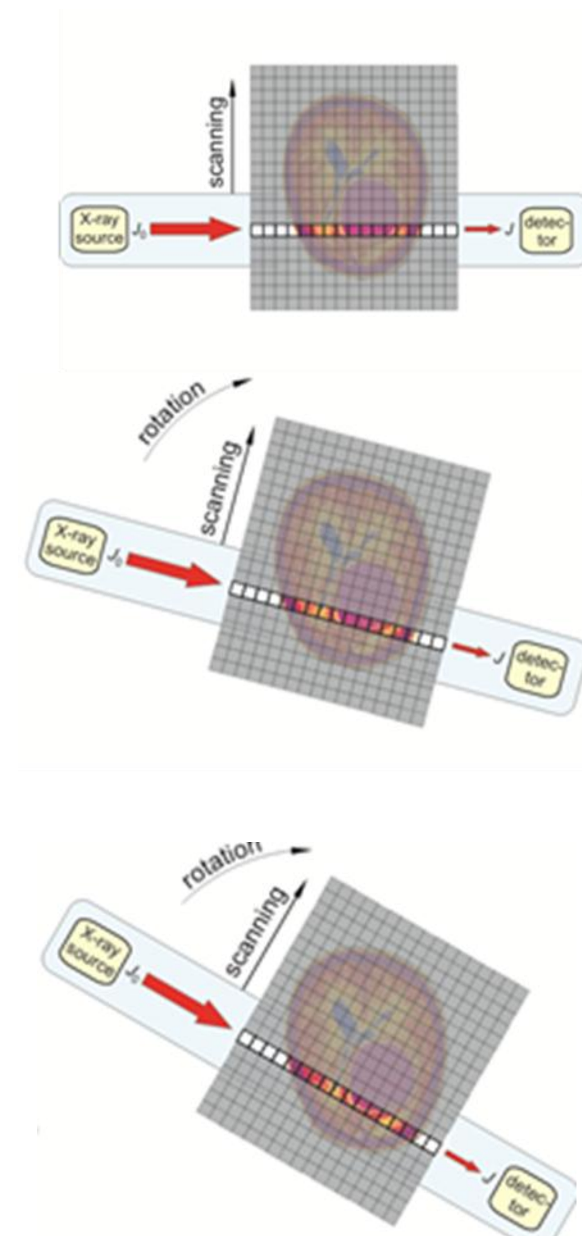
CT Foundations I: determination of μ

Objective: to determine the attenuation coefficient (μ_x) of the individual volume elements (voxels)

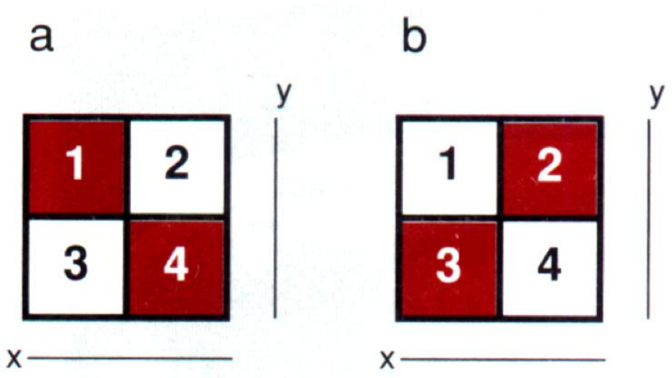


nr. of unknown: **m x n**

nr. of linear equations: **m x n**

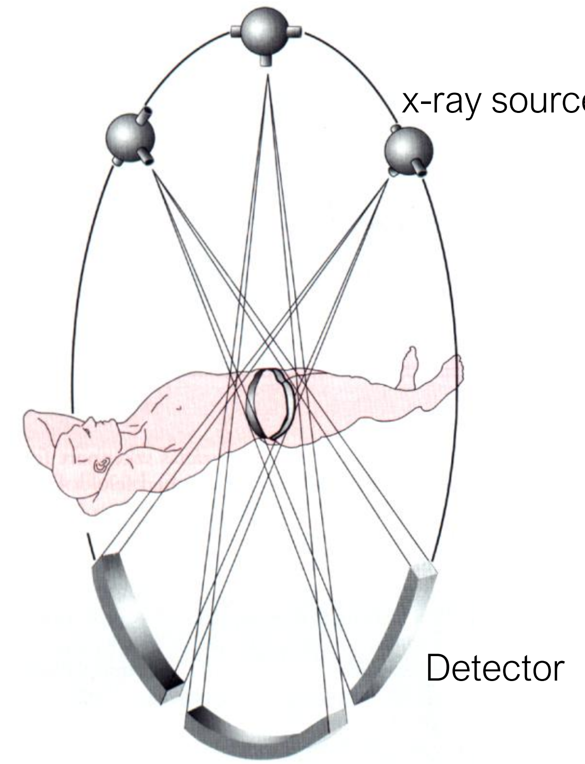


CT foundations II. scanninc

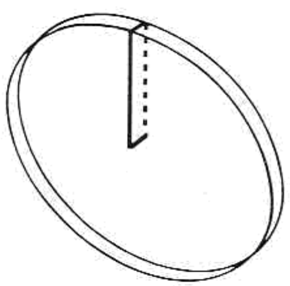


Problem: It is not possible to distinguish **a** from **b** in a bi-directional image

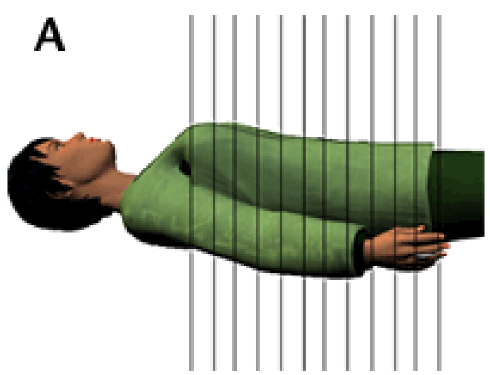
Solution: transaxial scanning along as large angular resolution as possible.



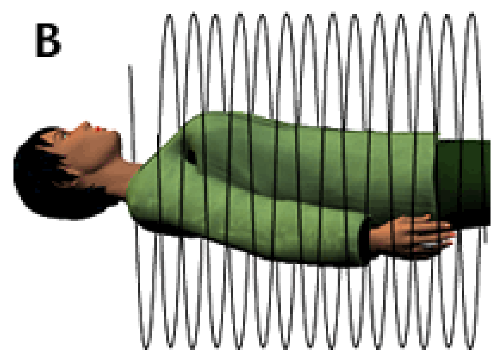
Conventional CT slice



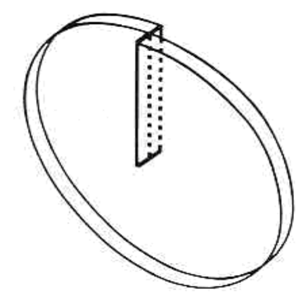
A

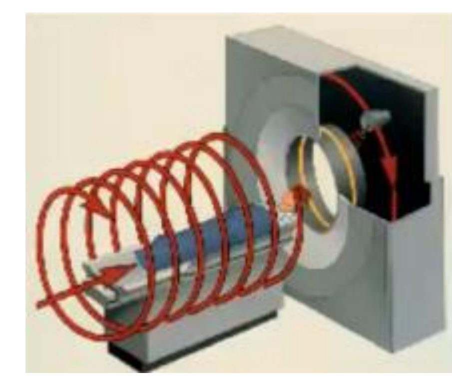


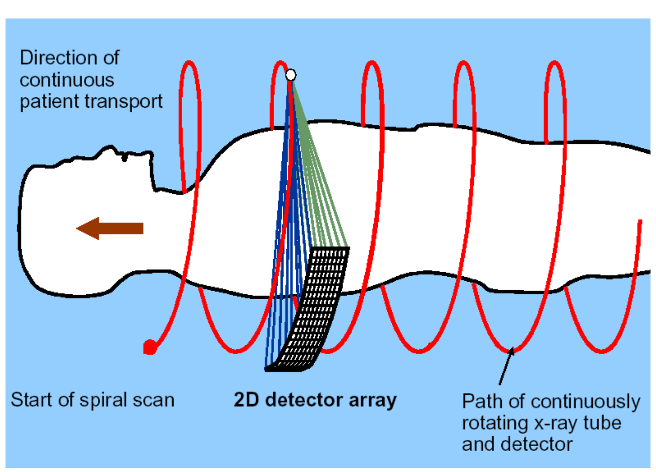
B



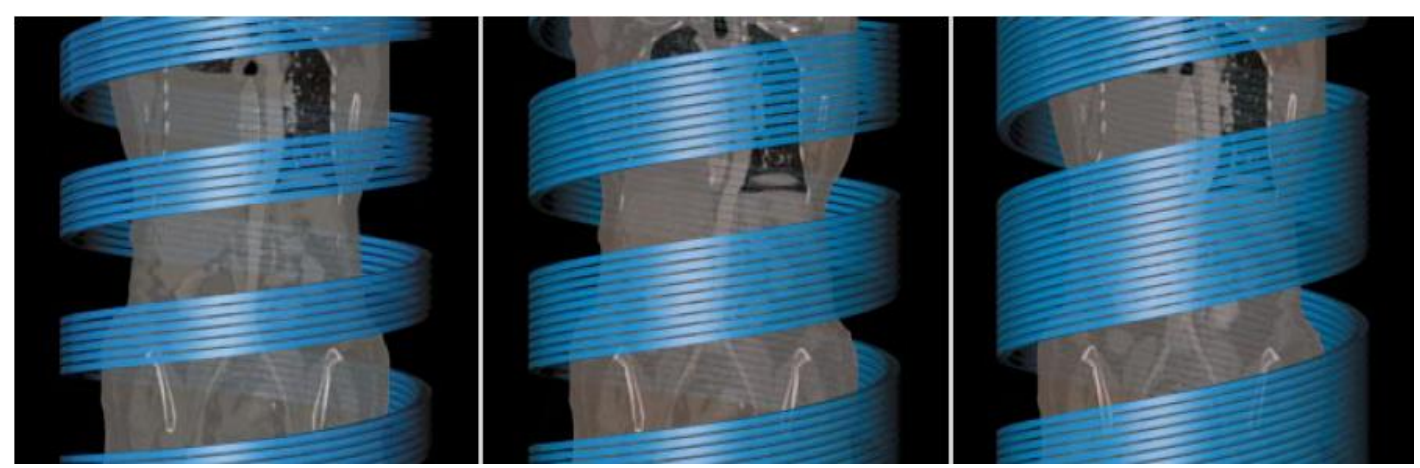
Spiral CT slice







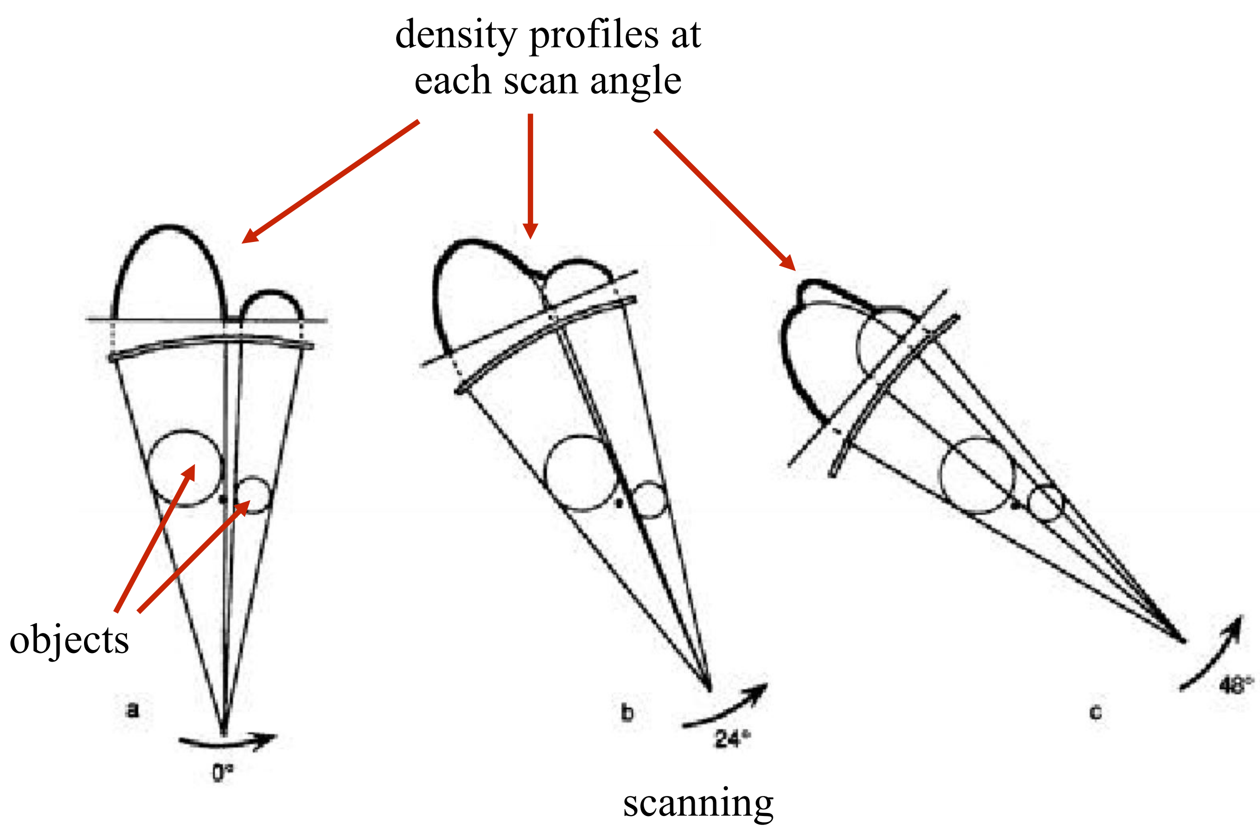
Multi-detector CT (MDCT)

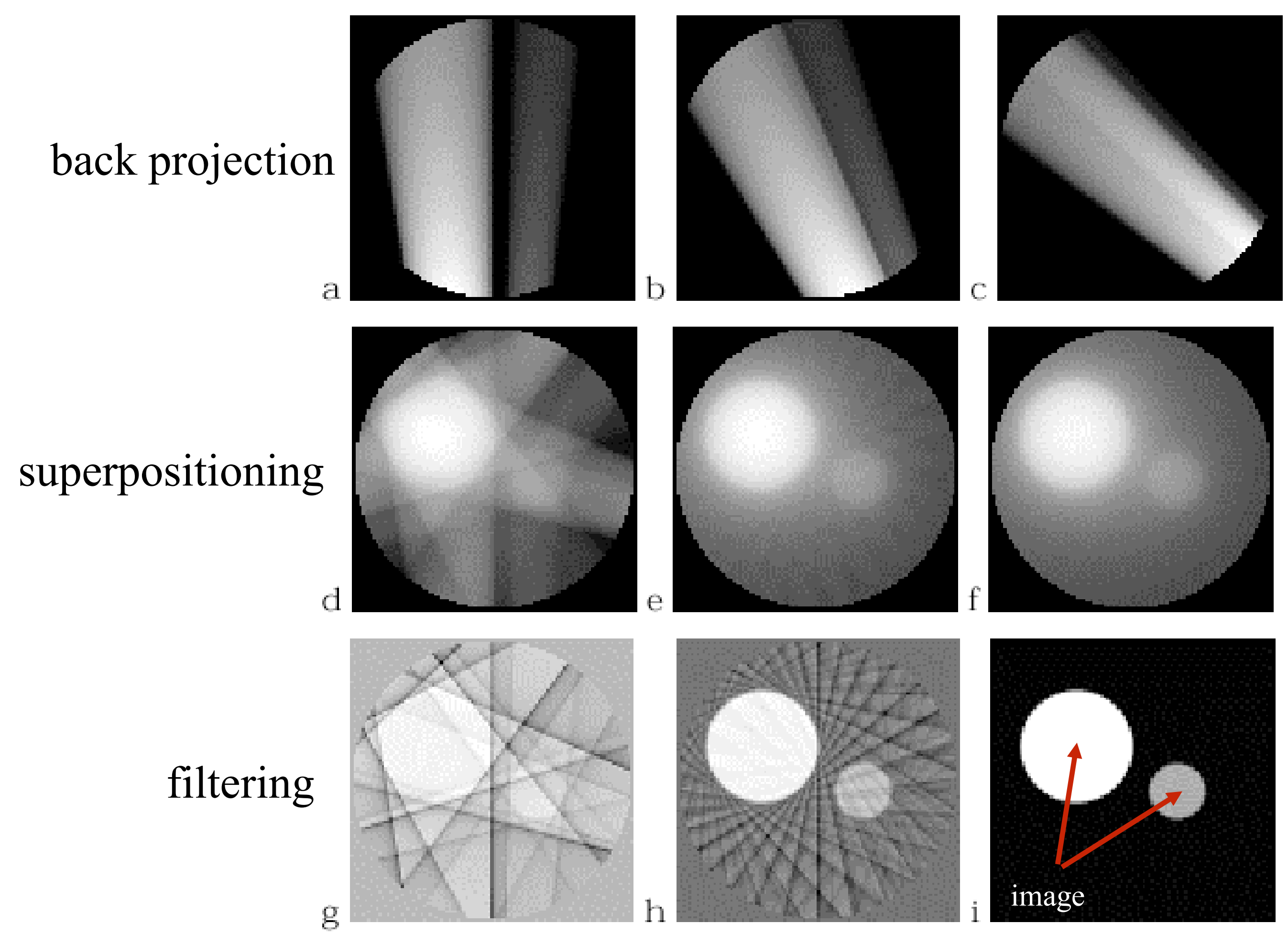


Multi-slice CT (MSCT)

CT foundations III: Image Reconstruction

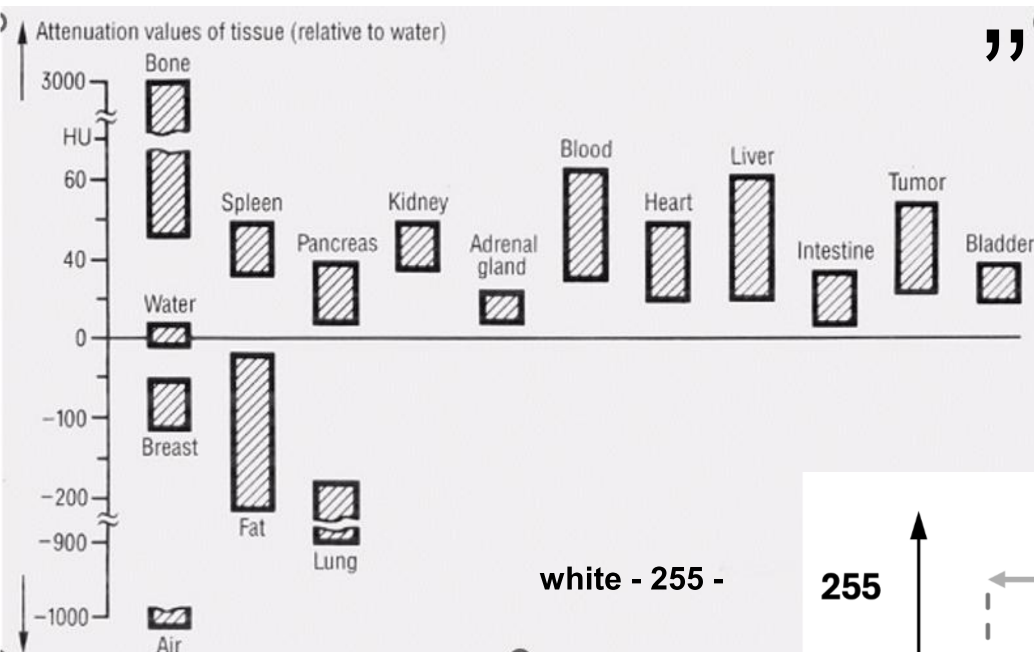
1. Algebraic reconstruction techniques
2. Direct Fourier reconstruction
3. „Filtered Back Projection” (current method)



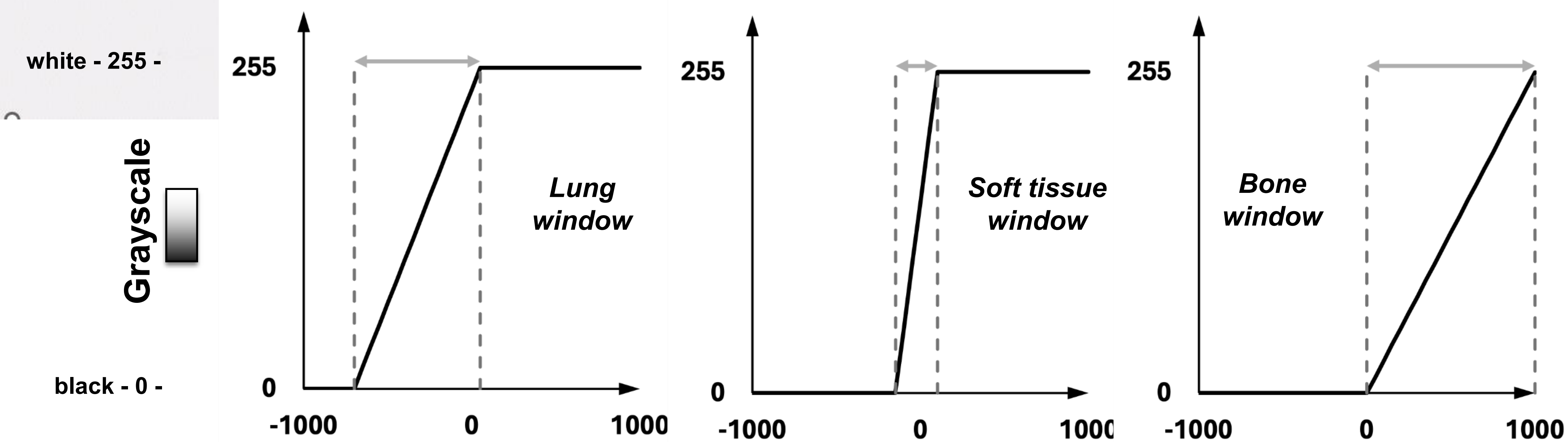


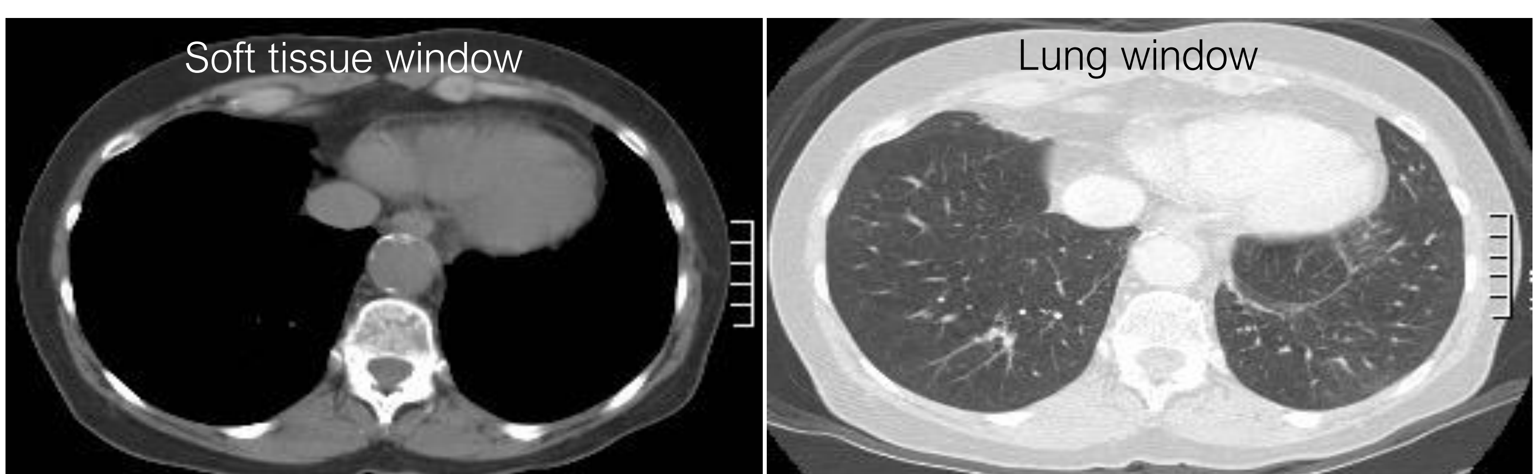
https://itc.semmelweis.hu/moodle/mod/kalvidres/view.php?id=266573

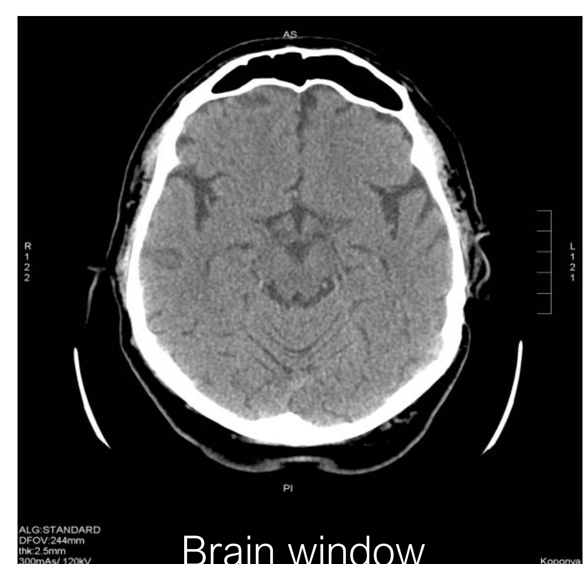
CT foundations IV: Contrast manipulation „Windowing”

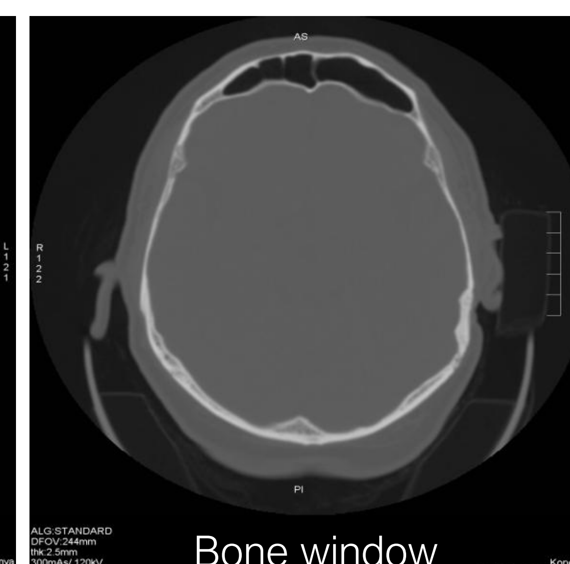


$$HU = \frac{\mu - \mu_{water}}{\mu_{water}} 1000$$





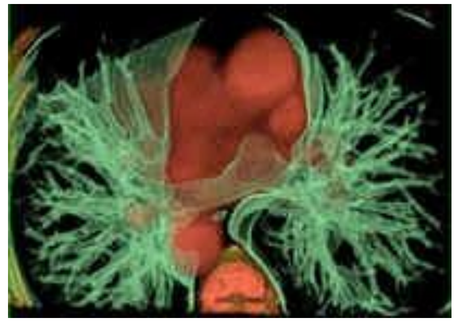


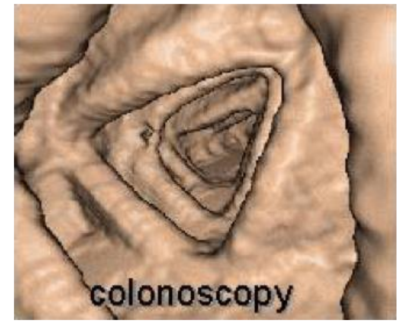


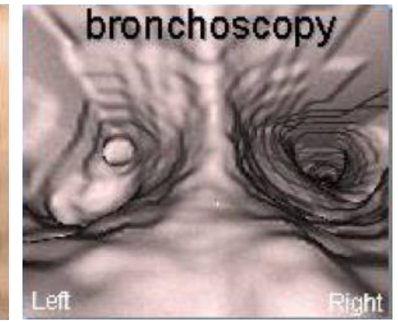
Same images with different windowing

Modern CAT scanning

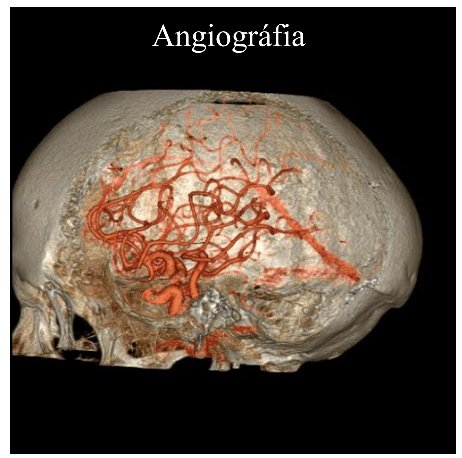
3D reconstruction, Virtual endoscopy

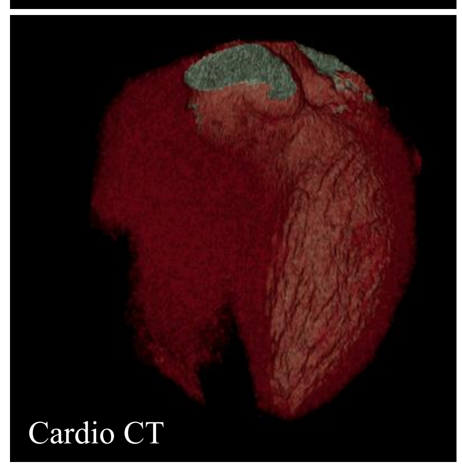




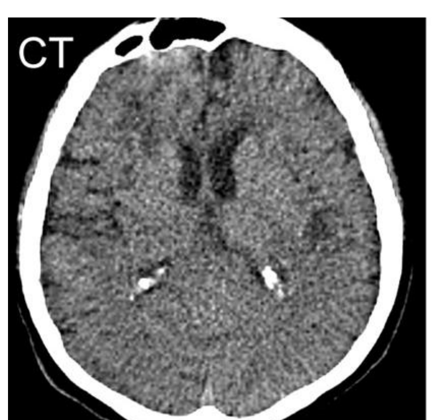


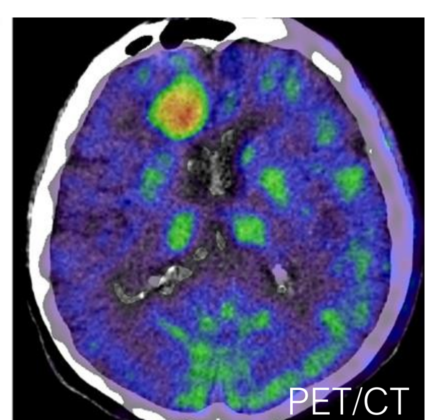
Increasing speed and resolution

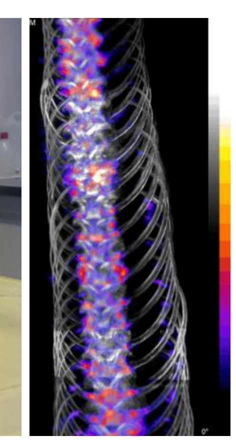




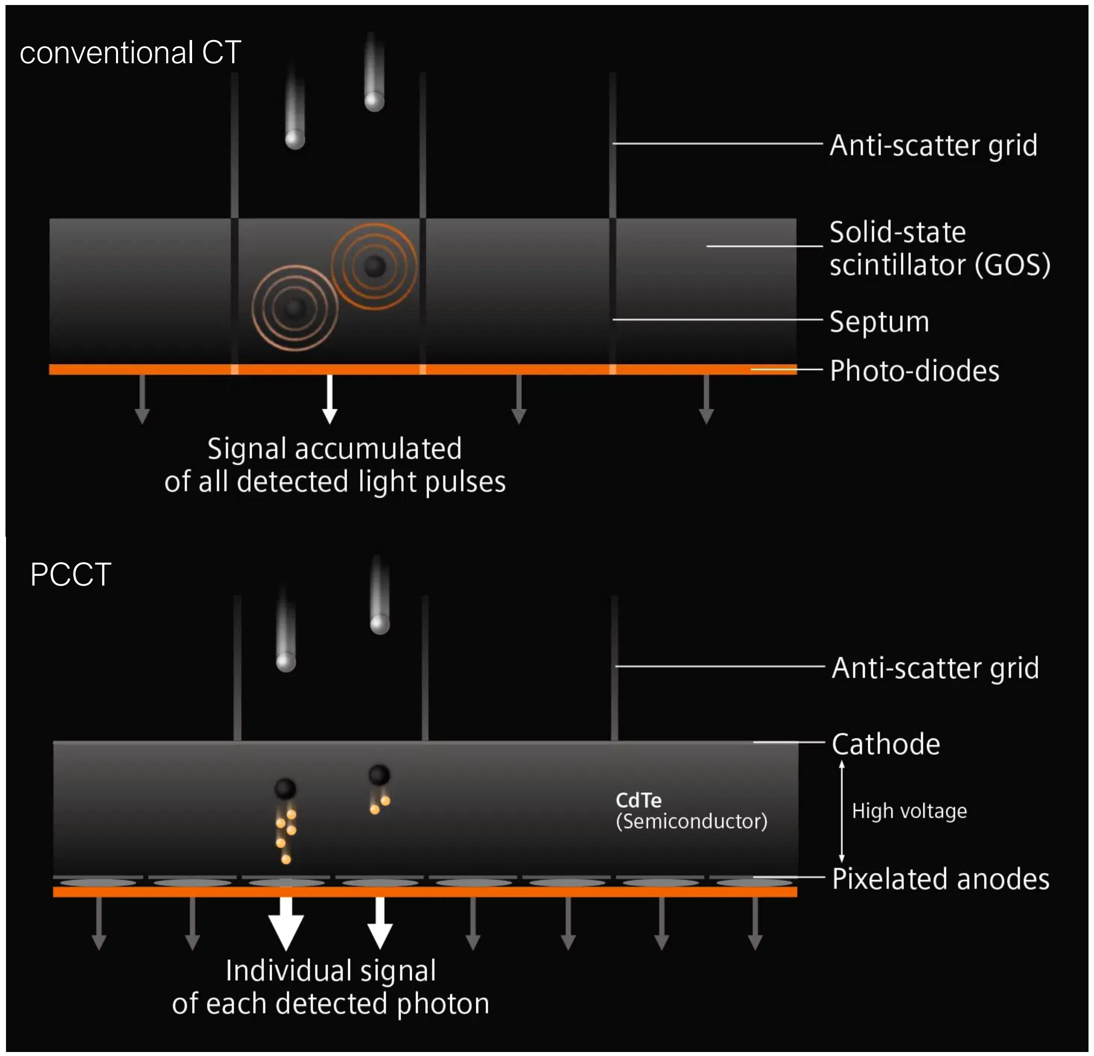
Combination with other modalities



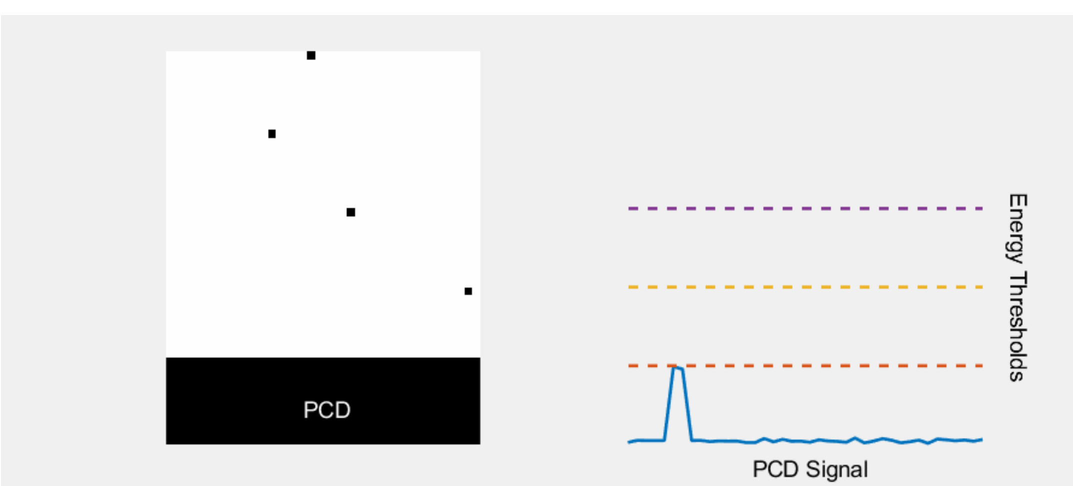


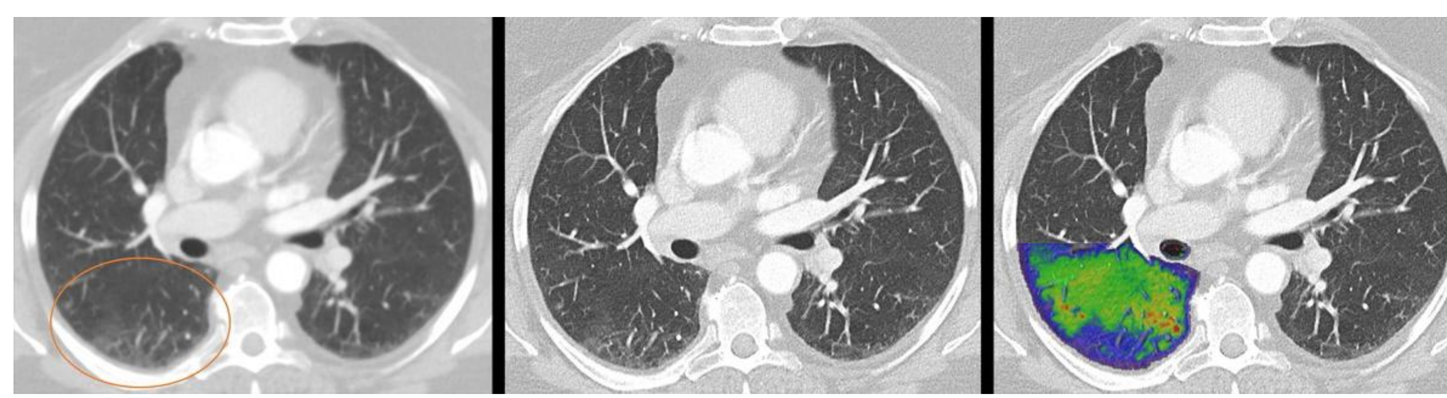


Photon Counting CT (PCCT)



- PCD: Photon Counting Detector (cadmium telluride crystal, CdTe)
- PCD keeps track of the energy of incoming photons
- PCD provides x-ray energy spectrum
- increased sensitivity (lower x-ray dose, lower contrast-agent dose)
- functional imaging possibility





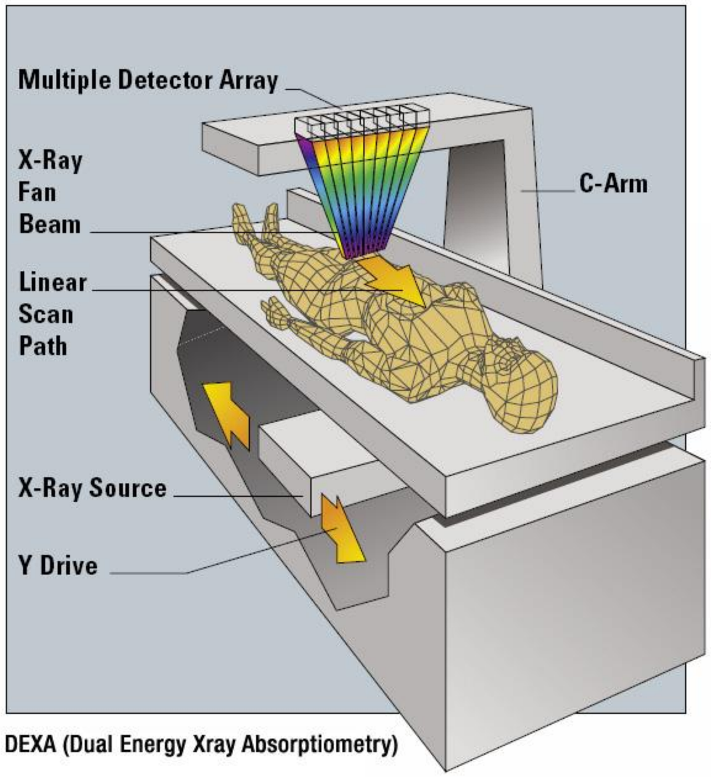
conventional CT

PCCT (increased detail)

PCCT (superimposed functional information)

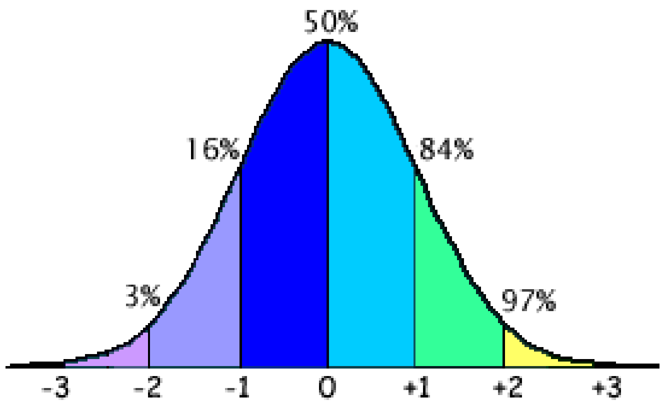
Application II. Absorptiometry

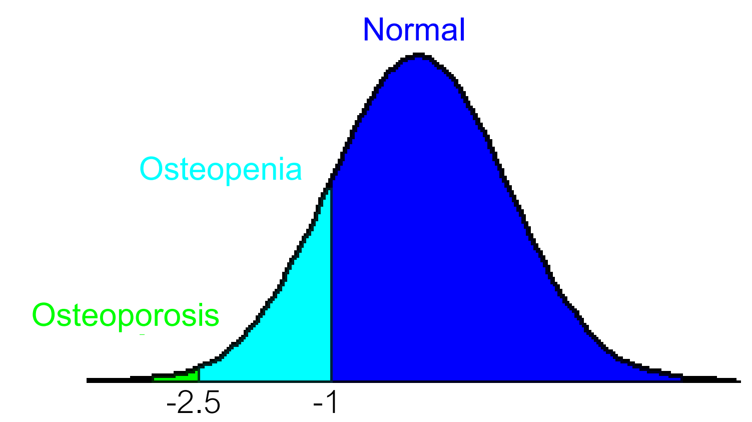
Dual-energy X-ray absorptiometry (DXA or DEXA)



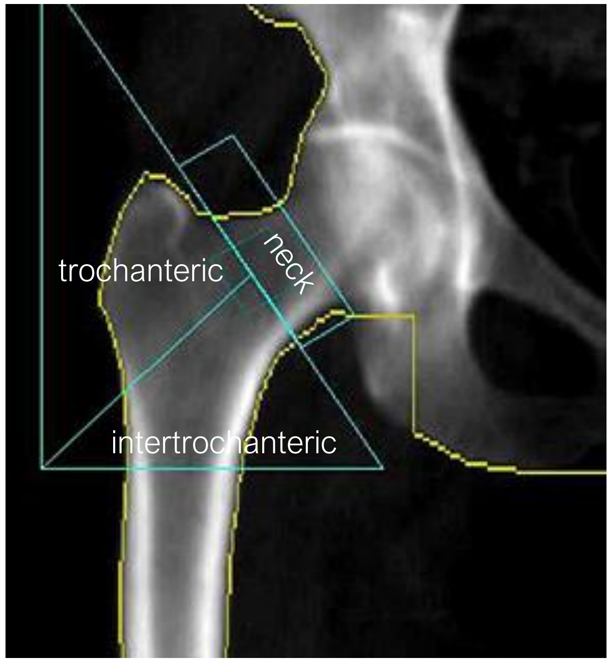
- Most important method for measuring bone density
- Characteristic X-ray is used as source
- Two different photon energies are employed (so that bone vs. soft-tissue absorption can be differentiated)
- Low dose is applied
- Whole-body scan is recorded
- Densities of distinct areas (e.g., femur, spine) are compared with reference databases
- Bone Mineral Density (BMD) calculated
- T-score is established

T-score: number of standard deviations below the average for a young adult at peak bone density.

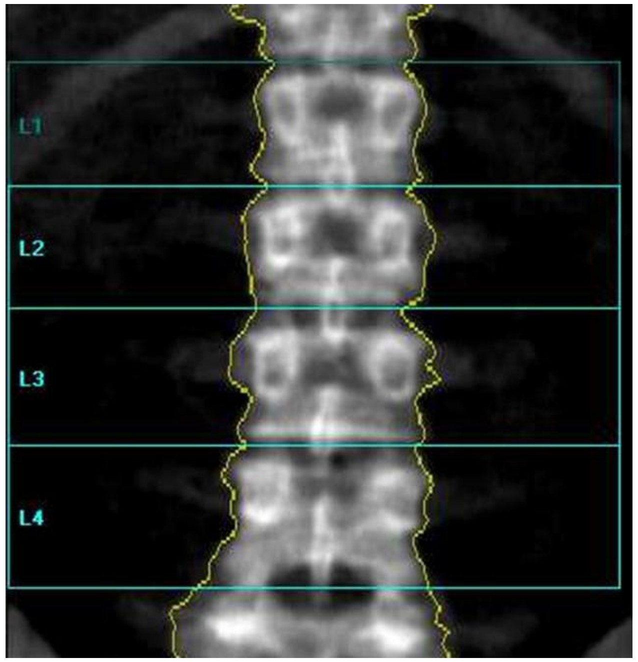




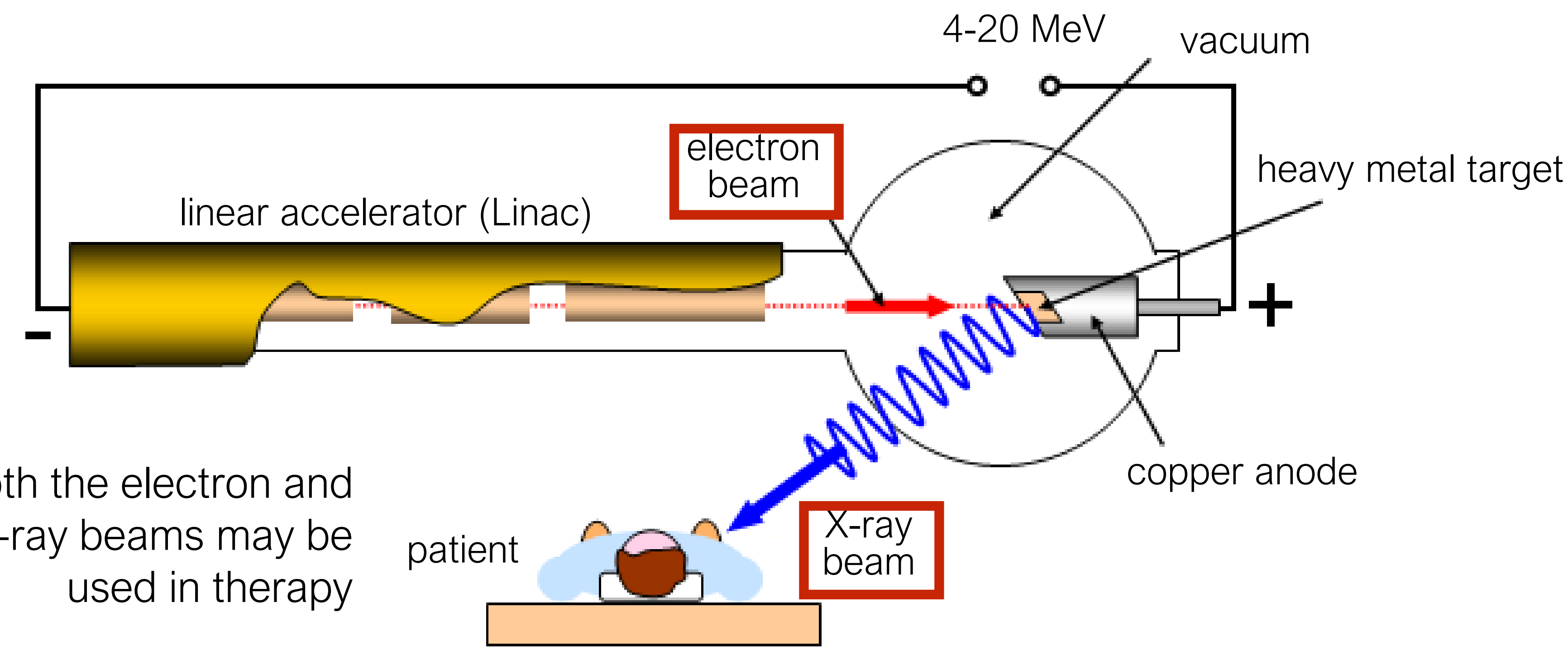
femur region



lumbar spine



Application III. Radiation therapy



Both the electron and X-ray beams may be used in therapy

First patient (Gordon Isaacs) treated with Linac radiation therapy (electron beam) for retinoblastoma (1955)

Modern hospital Linac

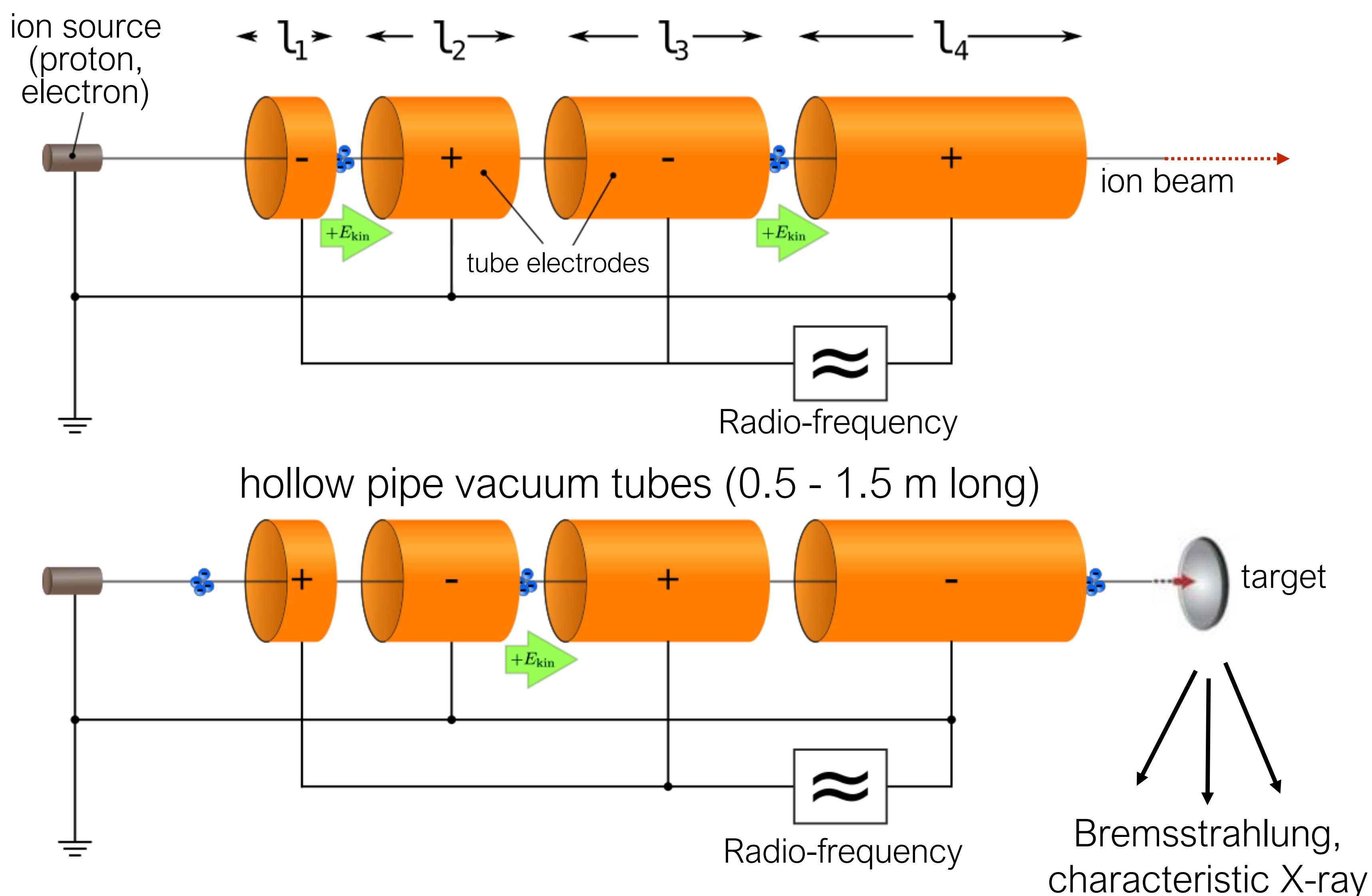
Advantages:

- Radiation may be turned on and off
- No contaminating radioactivity

Generating high-energy X-ray

Linear accelerator (Linac)

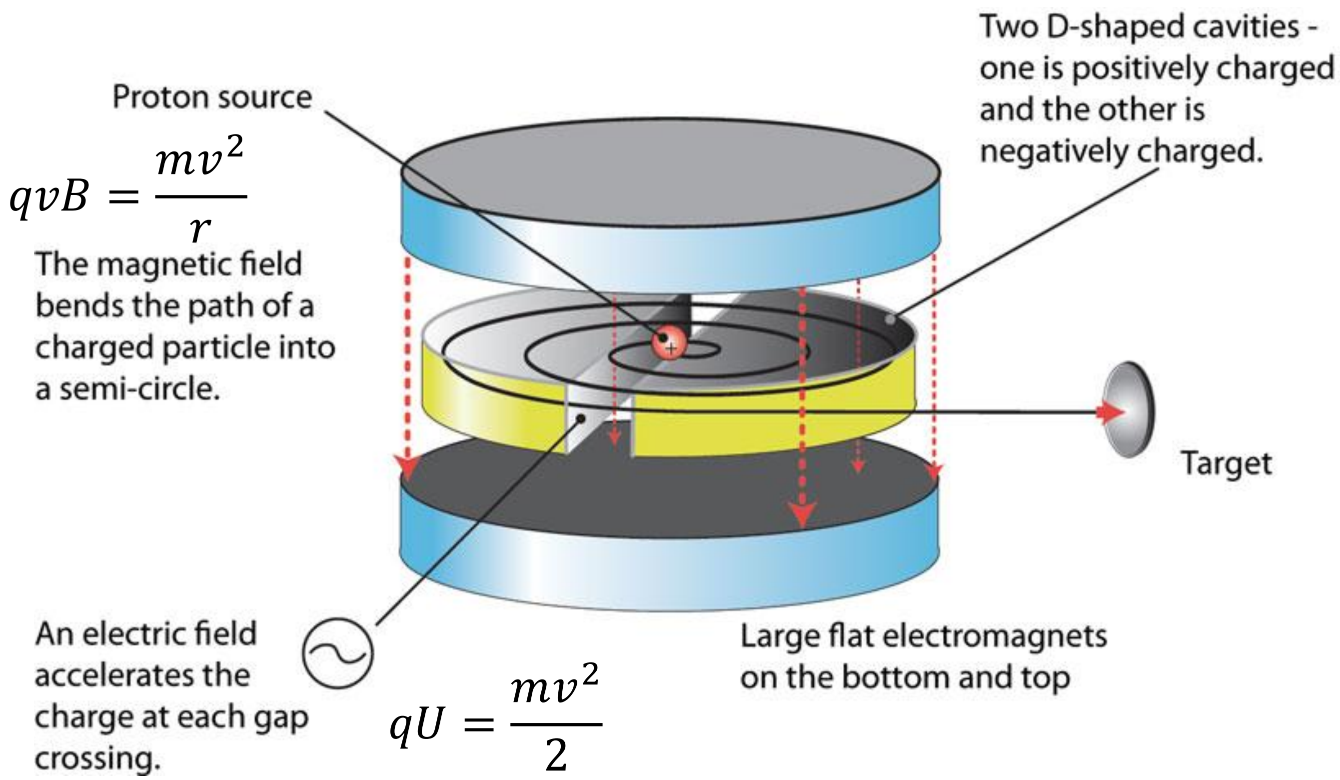
- Charged particle (electron, proton) accelerated between electrodes (but not inside the electrode).
- Velocity of particle increases in steps.
- Electrode polarity is alternating.
- Electrodes are gradually longer (l_n increases) in order to maintain synchrony.
- Accelerated particles are directed at suitable target material (to generate X-ray).



$$qU = \frac{mv^2}{2}$$

Ring-shape particle accelerators

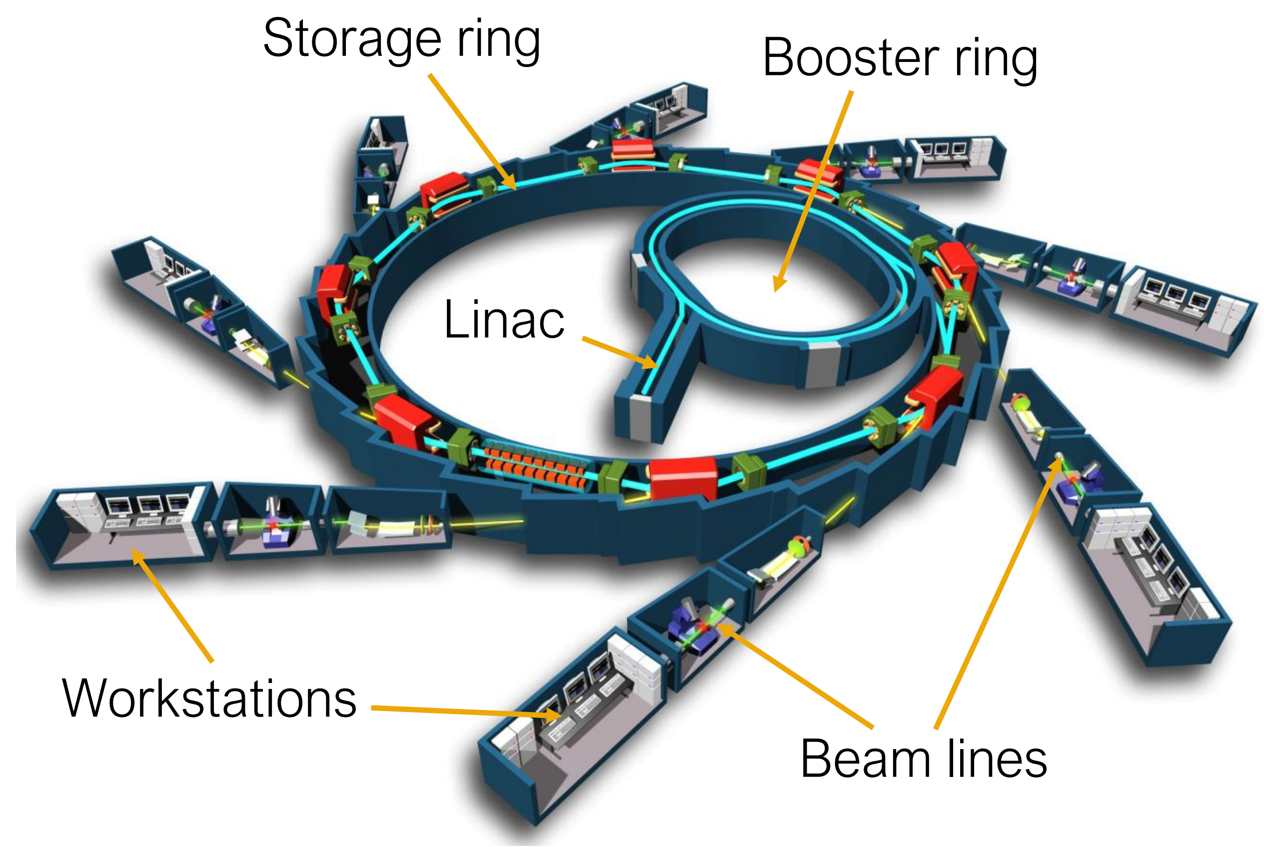
Cyclotron



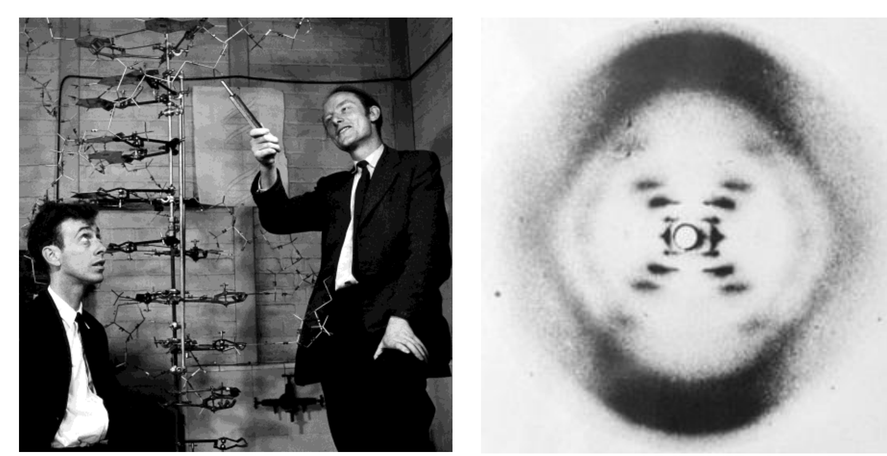
- Lorentz forces keep particles on circular path (causes limitations)
- Few tens of MeV particles are generated
- Used for generating positron-emitting isotopes (PET)
- Clinical cyclotrons in PET centers

11 MeV medical cyclotron

Synchrotron



- Very high energy particles can be generated (GeV)
- Relativistic speeds can be achieved (near light speed)
- X-rays used for high-resolution structural research
- Few facilities around the world (Grenoble, Chicago, etc.)



J.D. Watson and C.F. Crick, and the first x-ray image of DNA (1953)