

X-ray Applications

Medical Biophysics II. 19 February, 2025

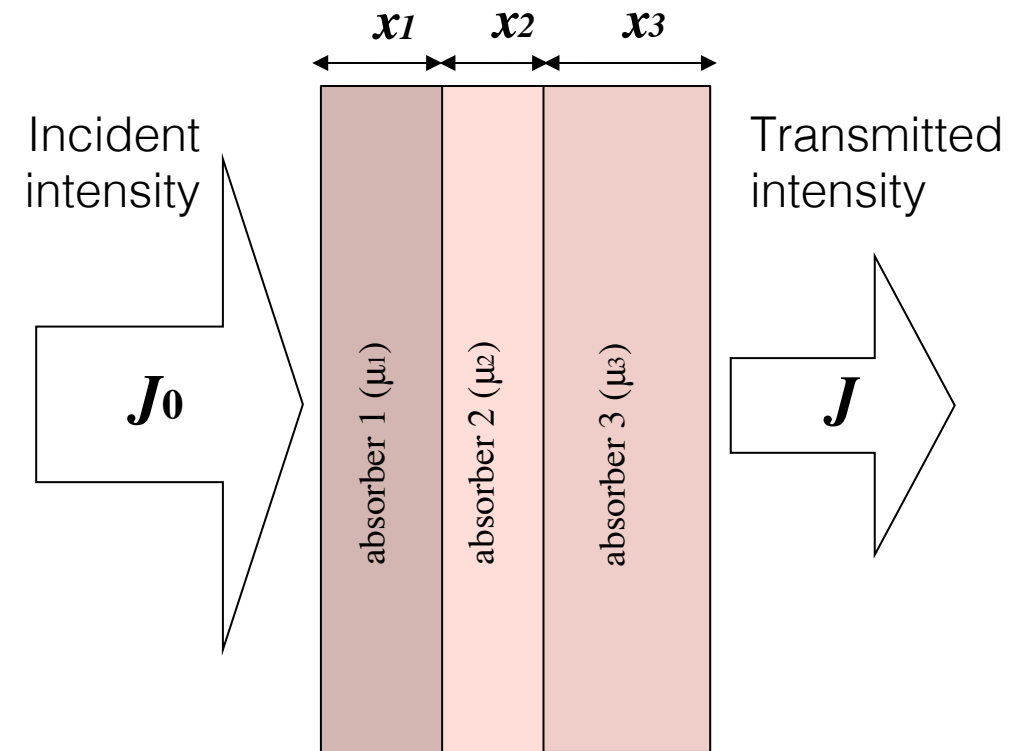
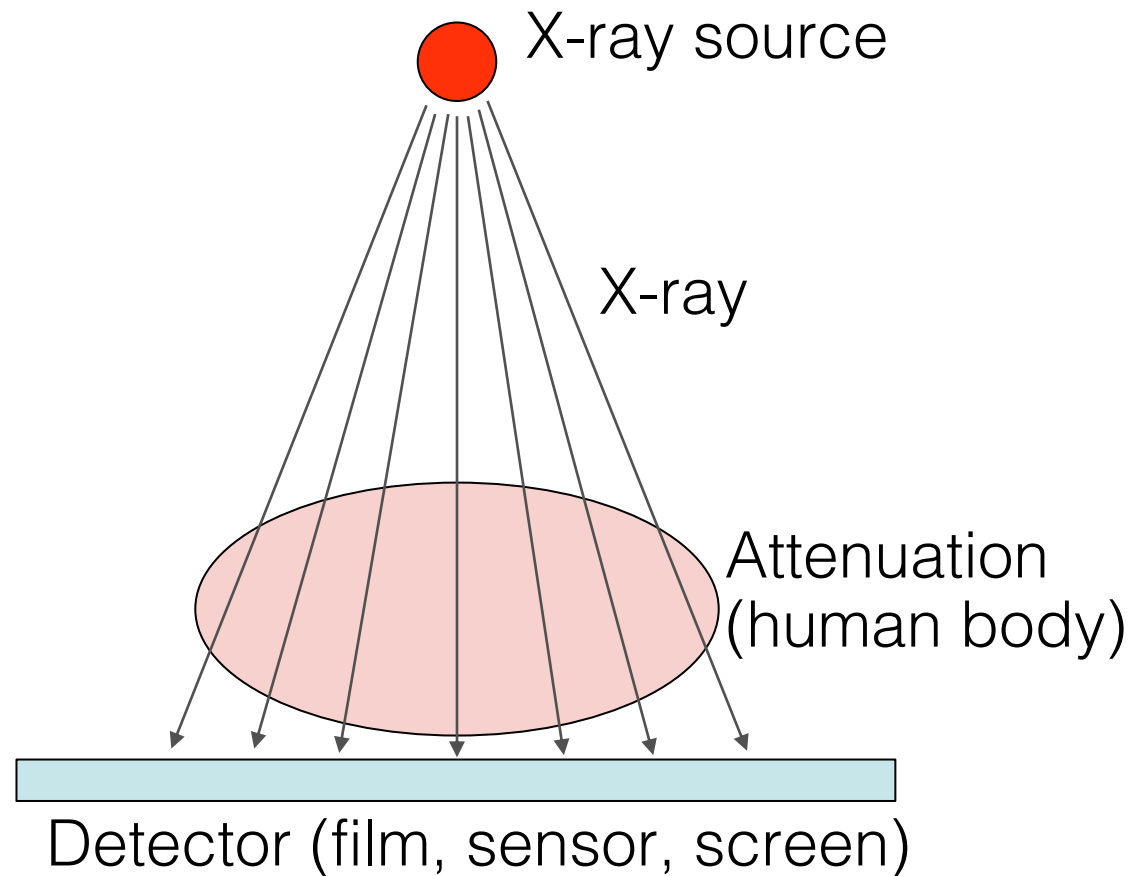
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SEMMELWEIS
EGYETEM 1769

Application I. X-ray imaging

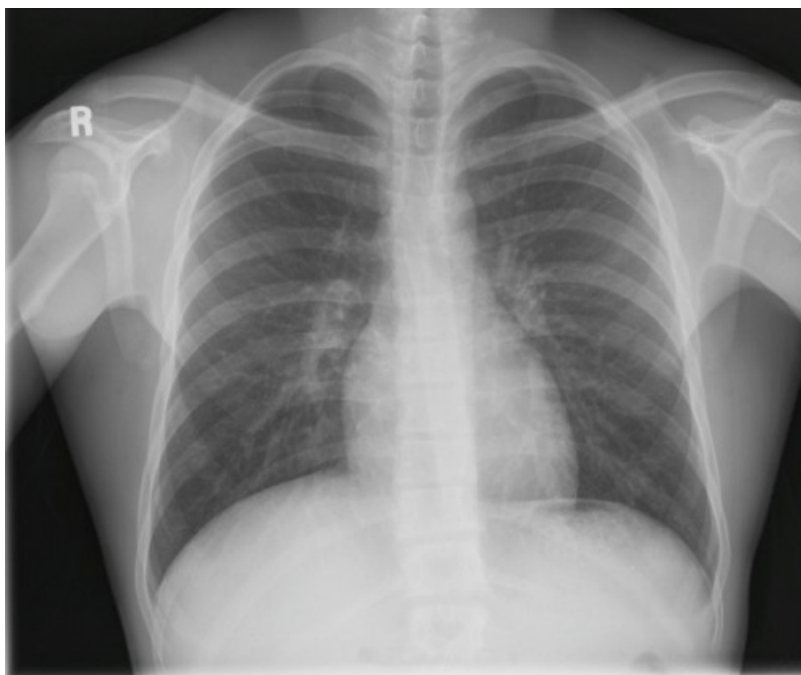


$$J = J_0 e^{-(\mu_1 x_1 + \mu_2 x_2 + \mu_3 x_3 + \dots)}$$

$$\lg \frac{J_0}{J} = (\mu_1 x_1 + \mu_2 x_2 + \mu_3 x_3 + \dots) \cdot \lg e$$

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

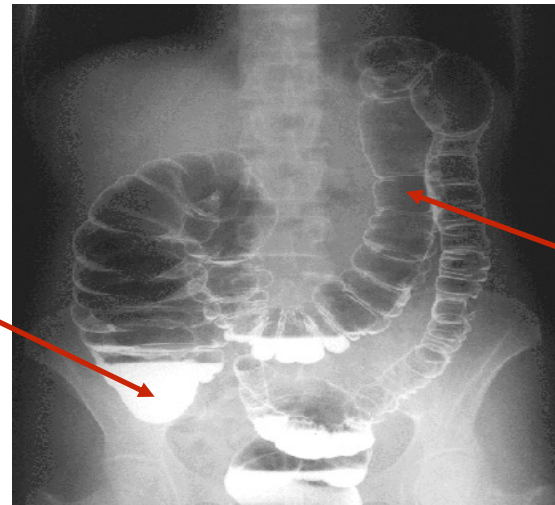
The X-ray image is a summation image ("X-ray image", "radiographic image", "roentgenogram"). Contrast arises due to spatially varying attenuation.



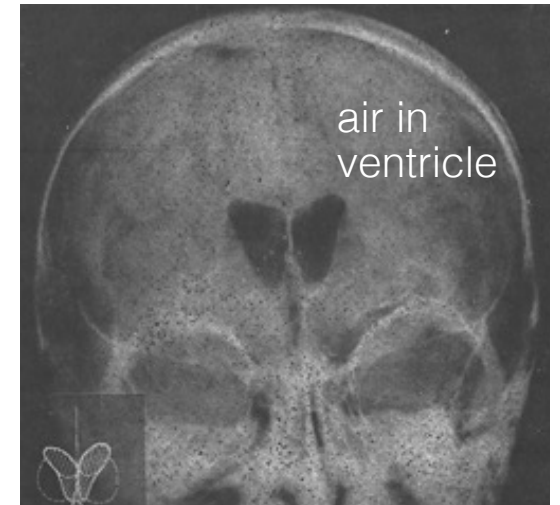
Improving X-ray imaging I.

Increasing contrast:
contrast agents

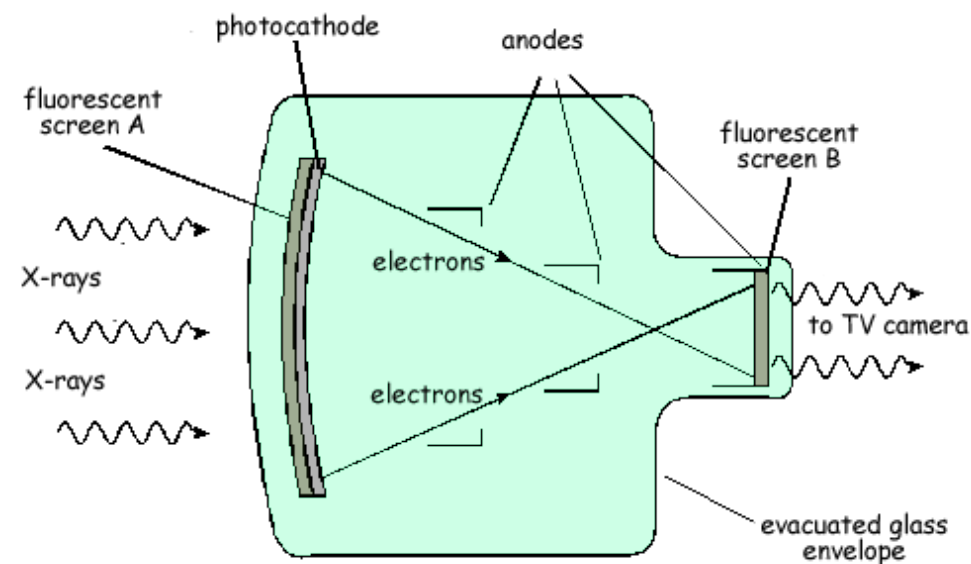
Positive contrast
(large Z,
e.g., Ba)



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



Enhancing sensitivity:
intensifier



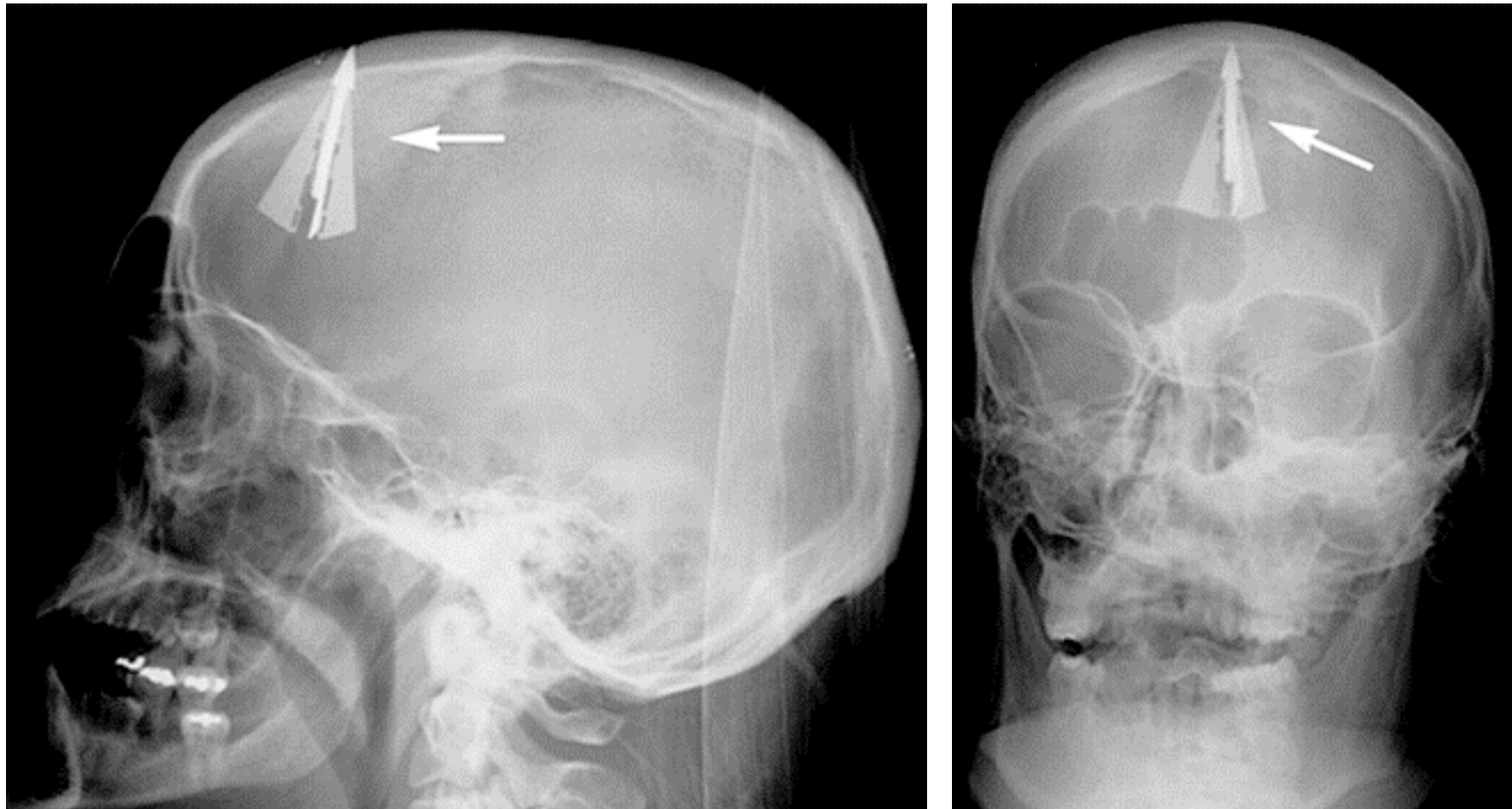
Background subtraction:
"Digital Subtraction Angiography" (DSA)



Improving X-ray imaging II.

Spatial resolution

Bi-directional X-ray imaging

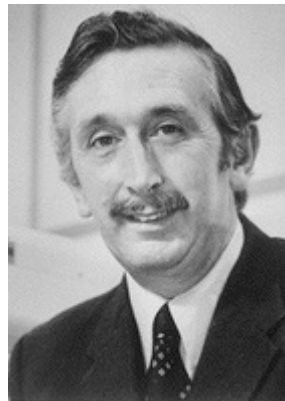


Bi-directional cranial X-ray of an individual who tried to commit suicide with a crossbow.

Improving X-ray imaging: the CAT scanner

History

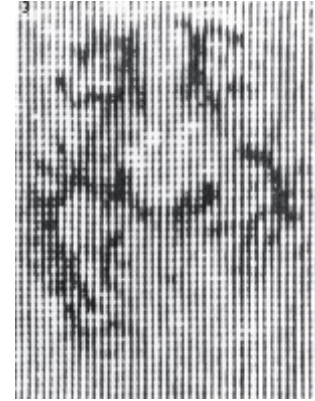
- Röntgen, Hounsfield and Cormack
- 1967: first CAT scan
- 1972: prototype
- 1974: first clinical CAT image (head)
- 1976: whole body CAT scan
- 1979: Nobel-prize
- 1990: spiral CAT scanner
- 1992: multislice CAT scanner
- 2006: 64 slice (and more...)
- multiple and hybrid modes: SPECT-CT, PET-CT, Dual-source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



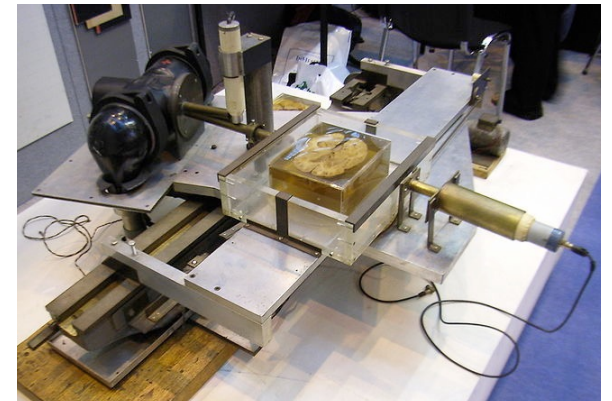
Godfrey Hounsfield



Allan Cormack



First, lab CT of a brain slice

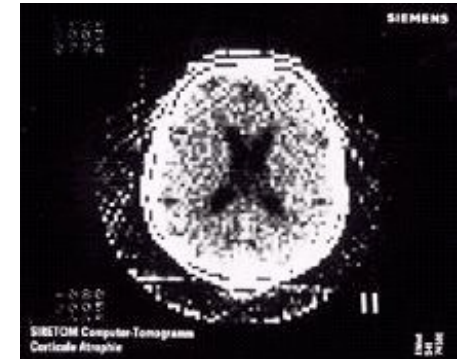


Prototype CAT scanner (EMI)

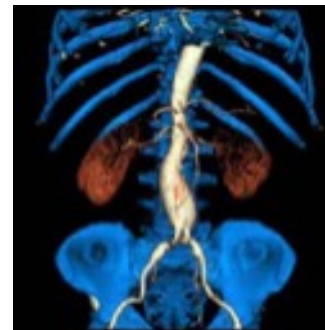


„Siretom” head scanner (1974)

128x128 pixel image (1975)



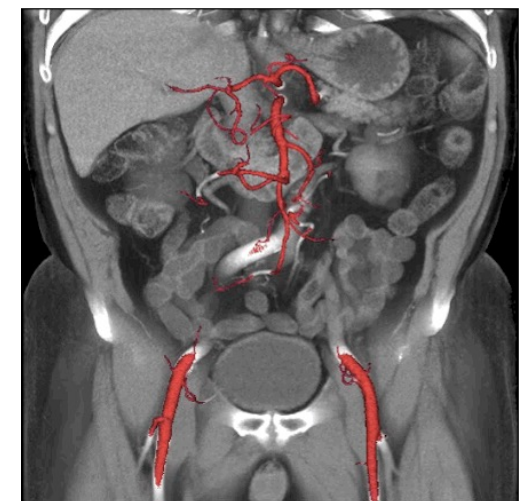
Multi-modal (combined) images



Summary

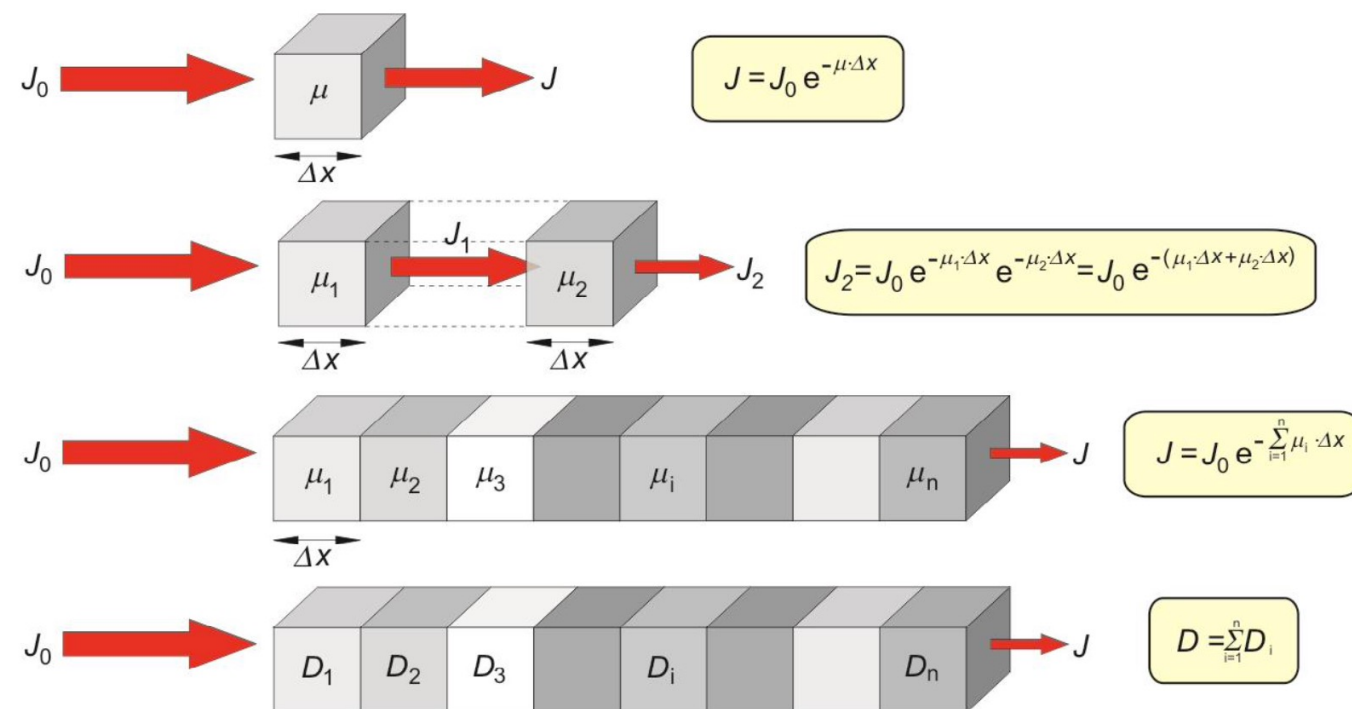
- Tomographic digital imaging method that uses **x-rays**: displays x-ray **absorbance** by the different points of the tomographic slice.
- **Multidetector** spiral CT (4-64 detector array): one slice 0.4-1 s; entire examination 5-15 s.
- **Ionizing** radiation. Absorbed **dose** ~50-100 times that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



μ_x : linear attenuation coefficient
 Δx : size of the voxel

$$\text{Density: } D = \lg \left(\frac{J_0}{J} \right) = \lg e \cdot \mu \cdot \Delta x$$

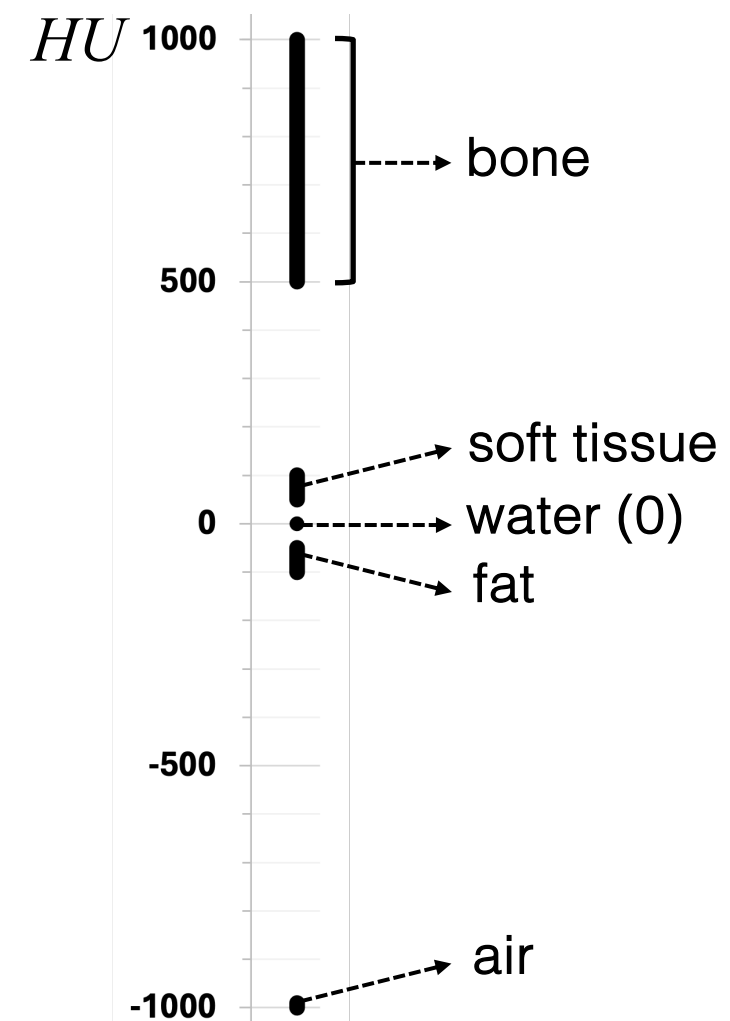
CT Image: density matrix

$$HU = 1000 \frac{\mu - \mu_w}{\mu_w}$$

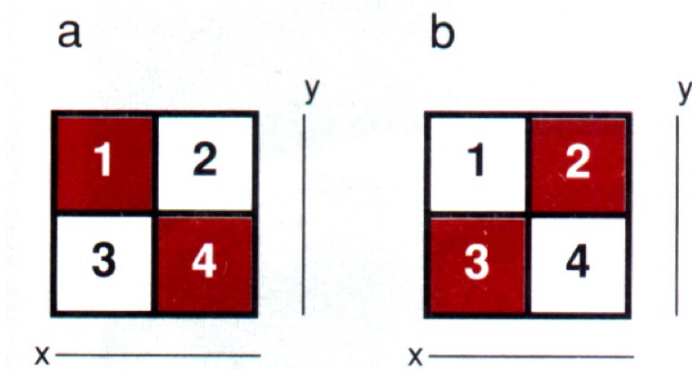
HU : Hounsfield units

μ : attenuation coefficient of voxel

μ_w : attenuation coefficient of water

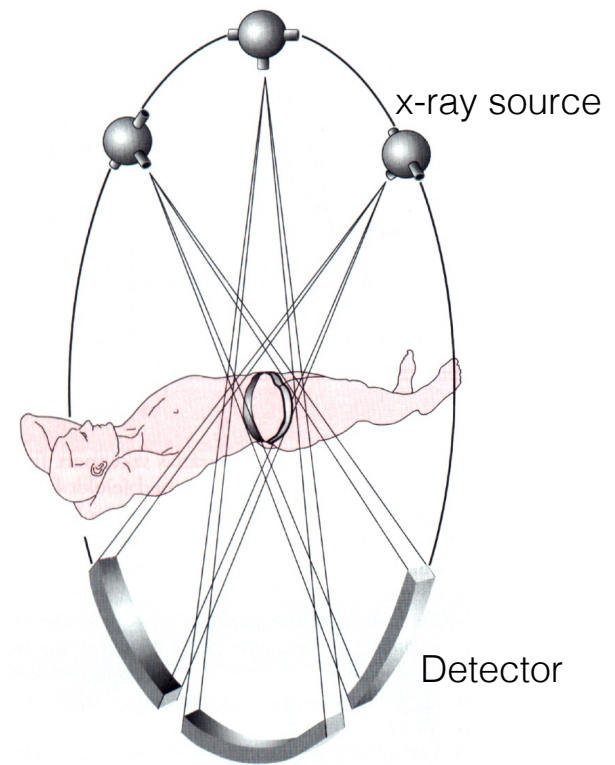


CT foundations II. scanning

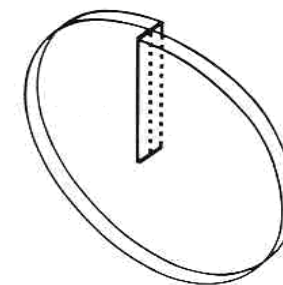
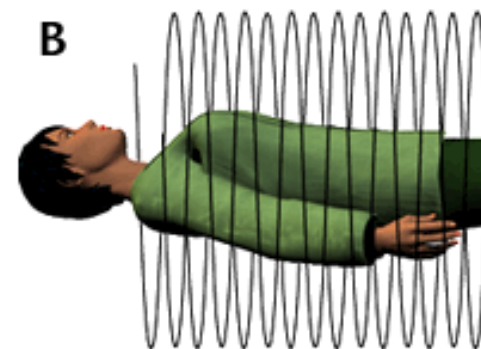
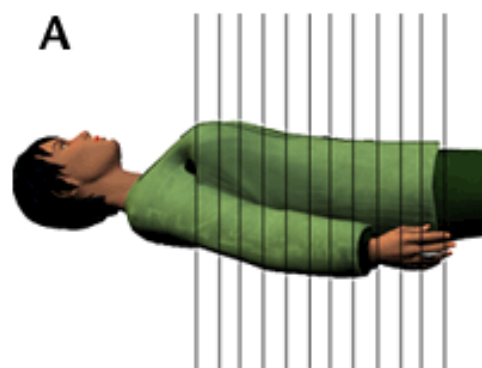
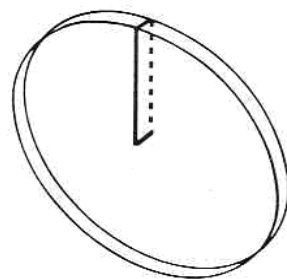


Problem: It is not possible to distinguish **a** from **b** in a bi-directional image

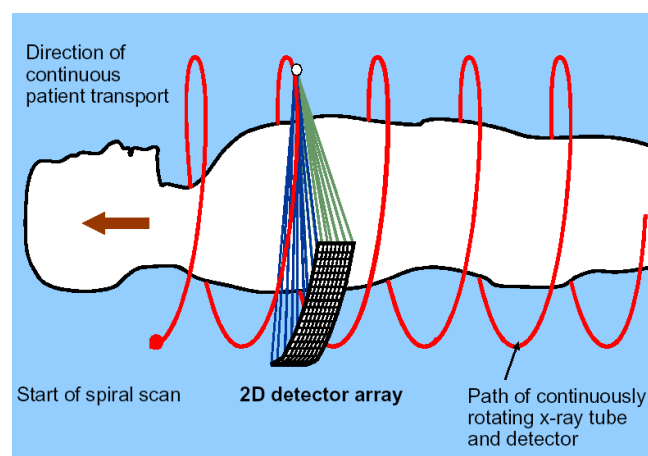
Solution: transaxial scanning along as large angular resolution as possible.



Conventional CT slice



Spiral CT slice



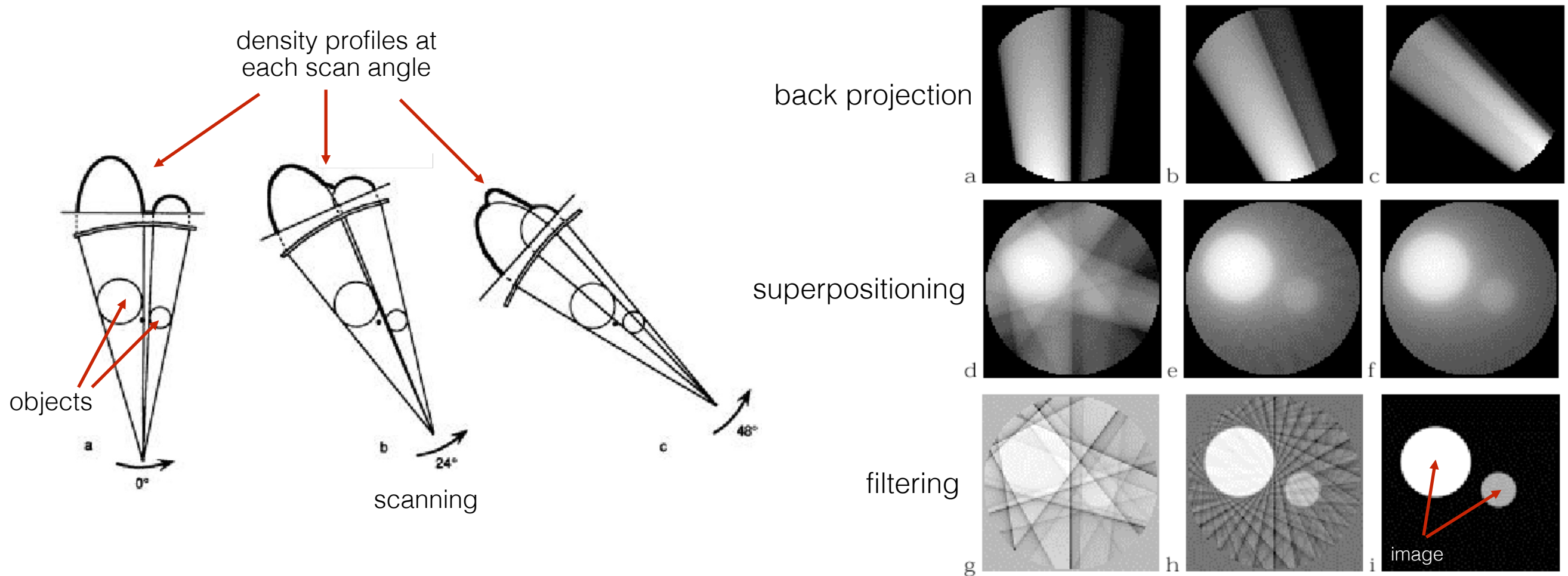
Multi-detector CT (MDCT)



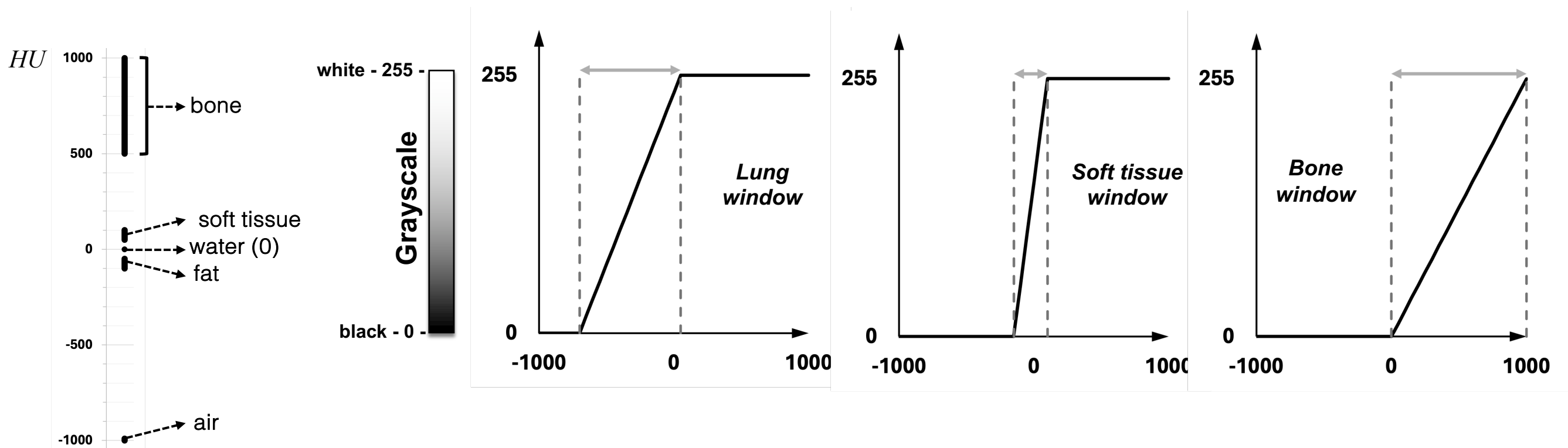
Multi-slice CT (MSCT)

CT foundations III: Image Reconstruction

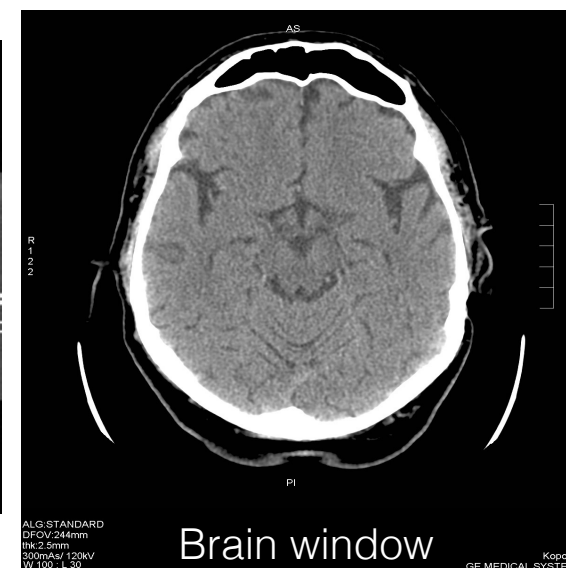
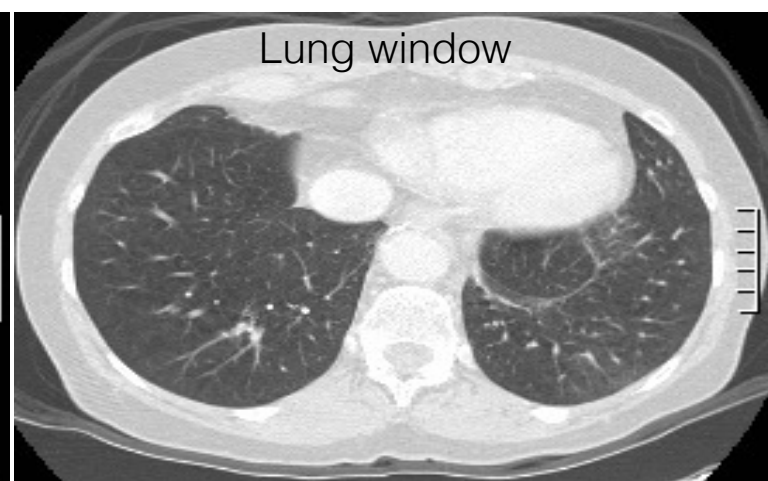
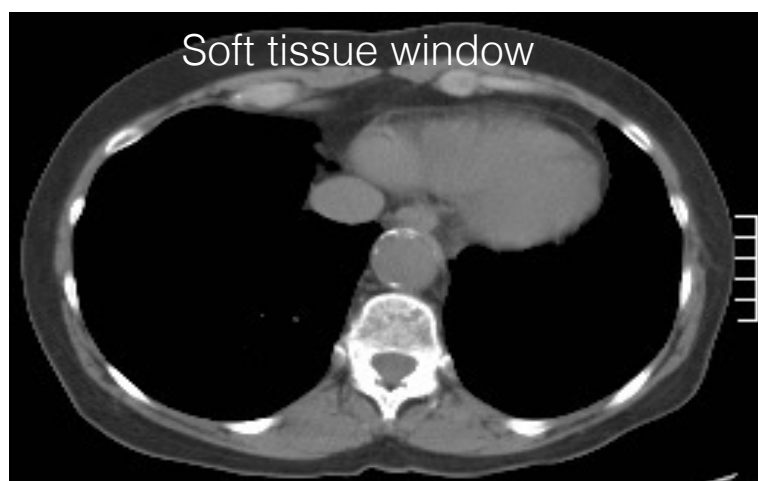
1. Algebraic reconstruction techniques
2. Direct Fourier reconstruction
3. „Filtered Back Projection” (current method)



CT foundations IV: Contrast manipulation „Windowing”

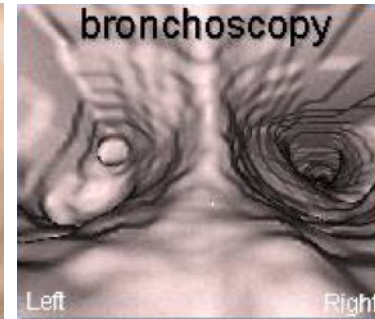
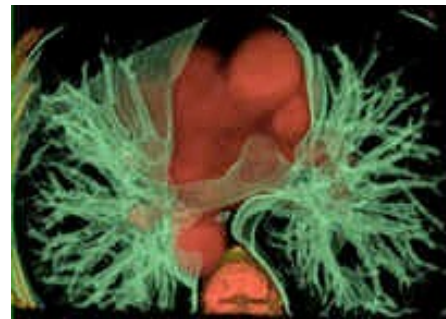


Same images with different windowing (different contrast transfer function)

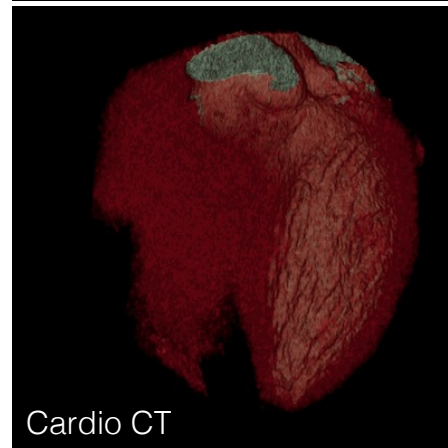
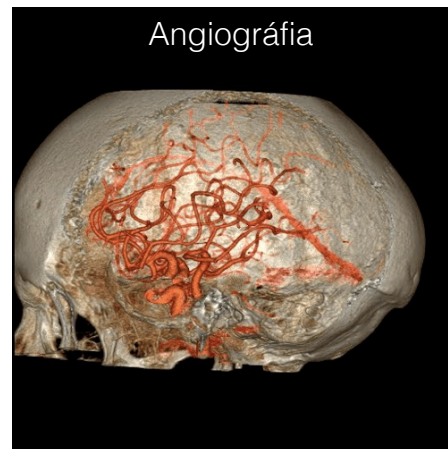


Modern CAT scanning

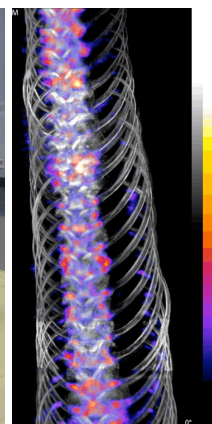
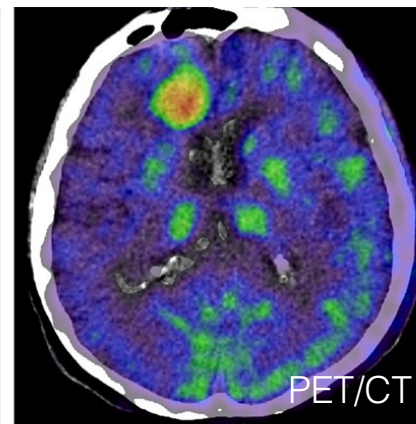
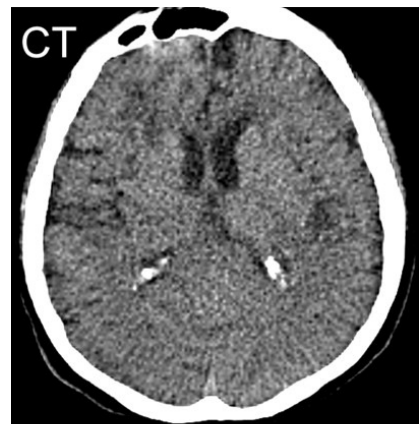
3D reconstruction,
Virtual
endoscopy



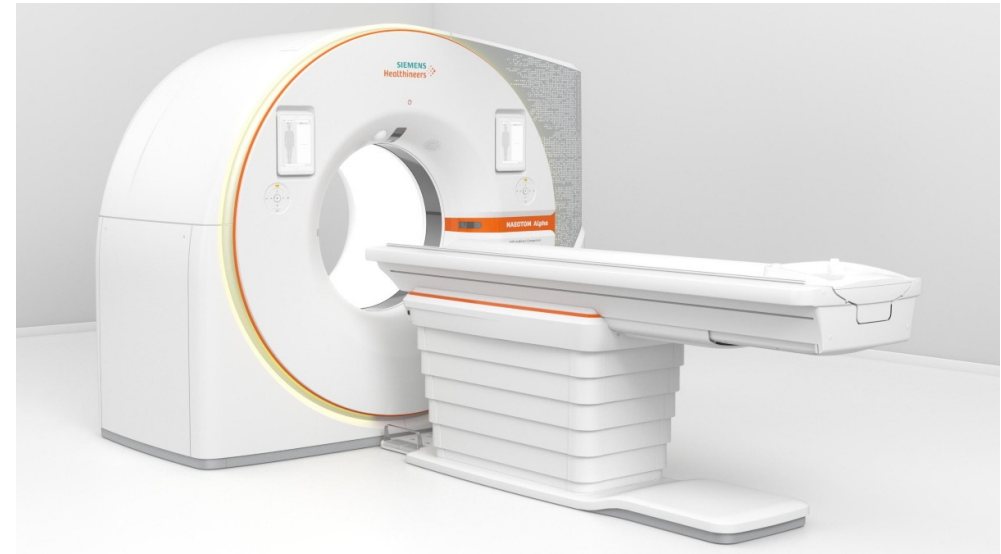
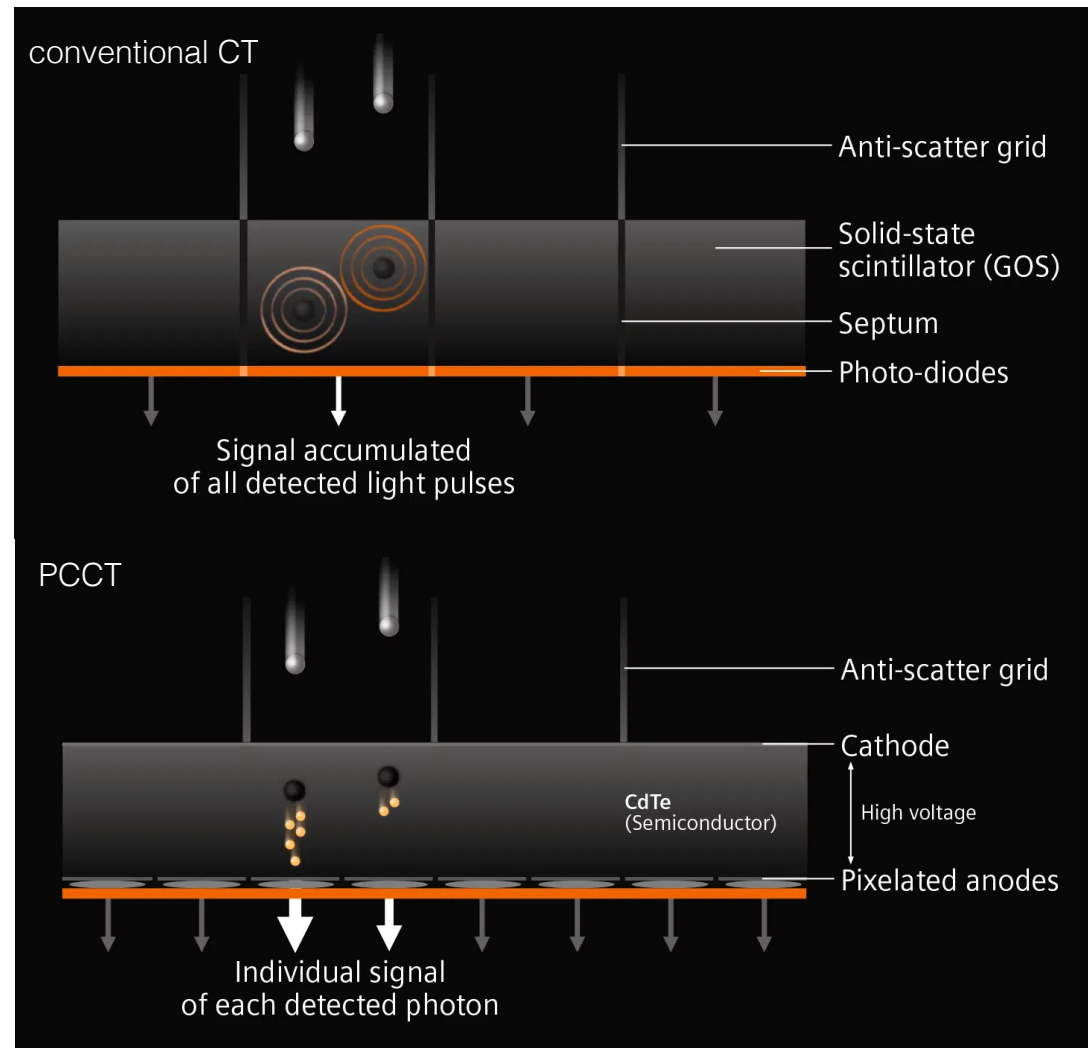
Increasing speed
and resolution



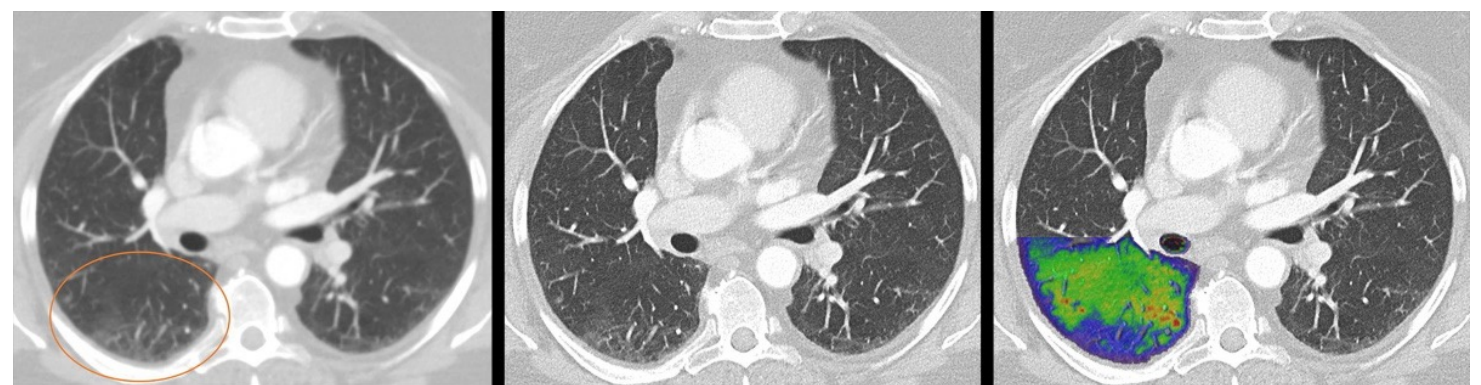
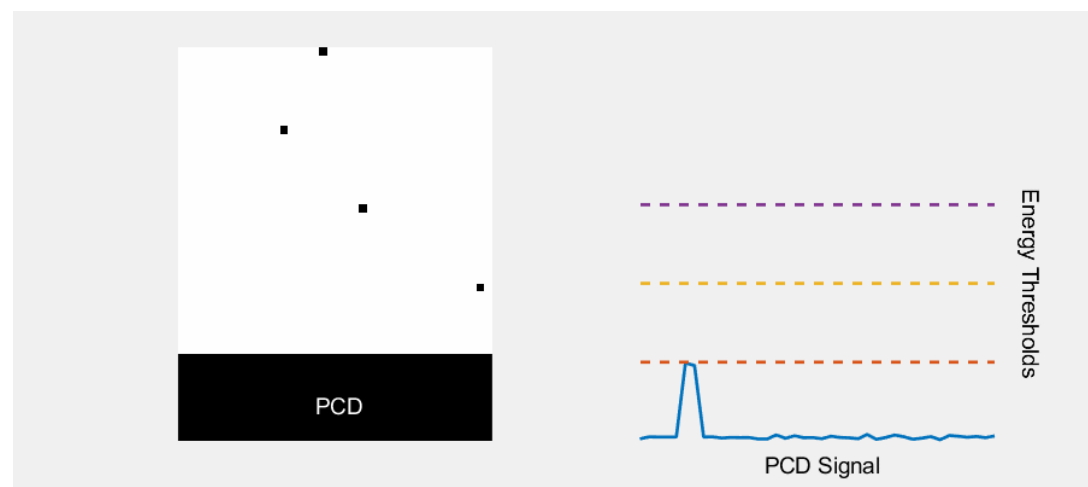
Combination with
other modalities



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



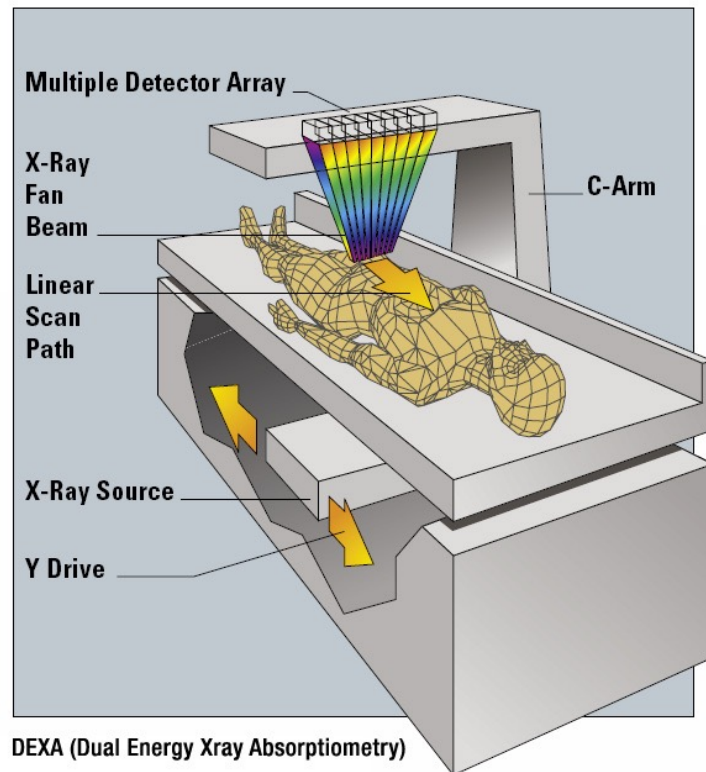
conventional
CT

PCCT
(increased
detail)

PCCT
(superimposed functional
information)

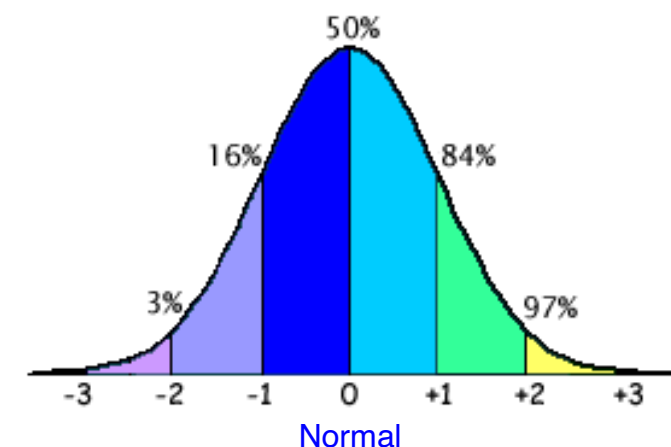
Application II. Absorptiometry

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

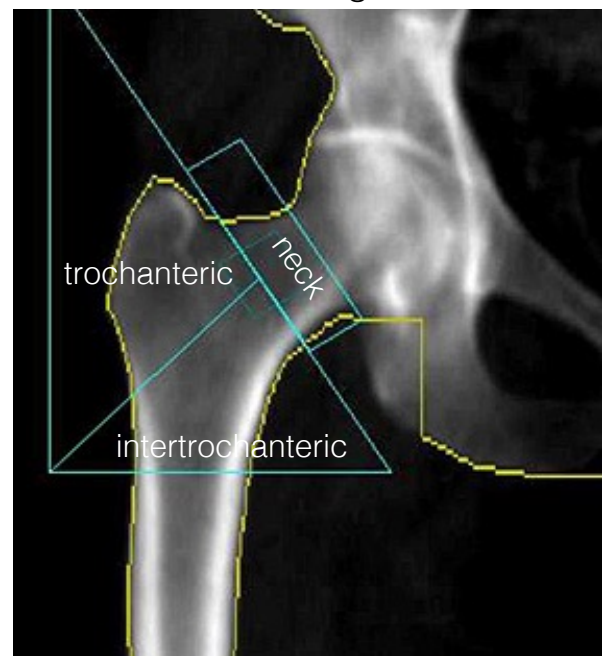


- Most important method for measuring bone density
- Characteristic X-ray is used as source
- Two different photon energies are employed (so that bone vs. soft-tissue absorption can be differentiated)
- Low dose is applied
- Whole-body scan is recorded
- Densities of distinct areas (e.g., femur, spine)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

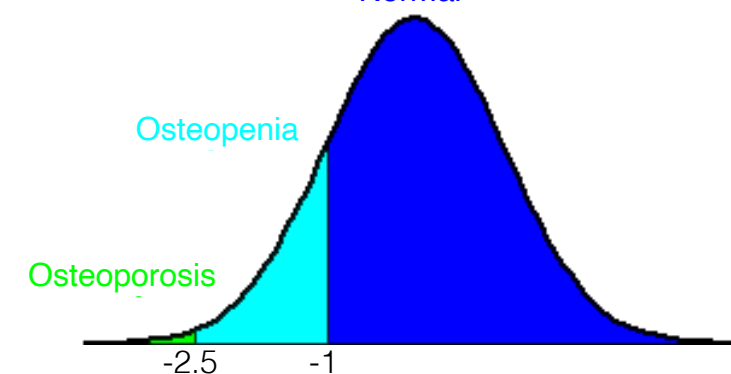
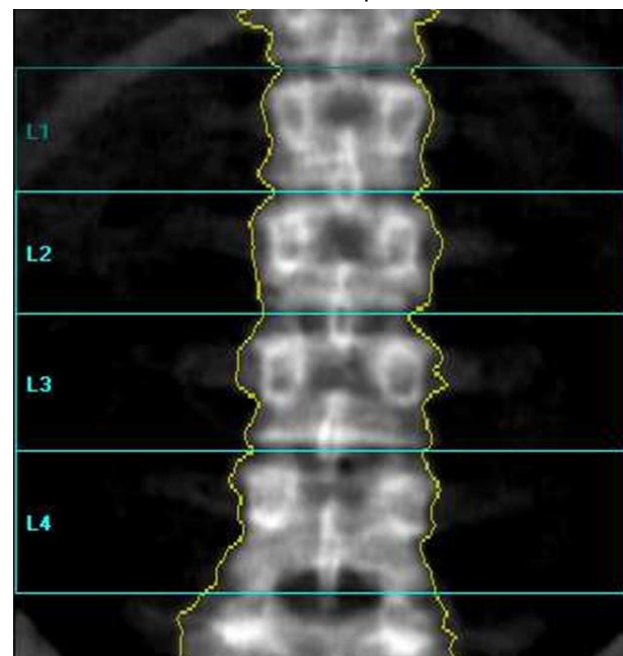
T-score:
number of standard deviations below the average for a young adult at peak bone density.



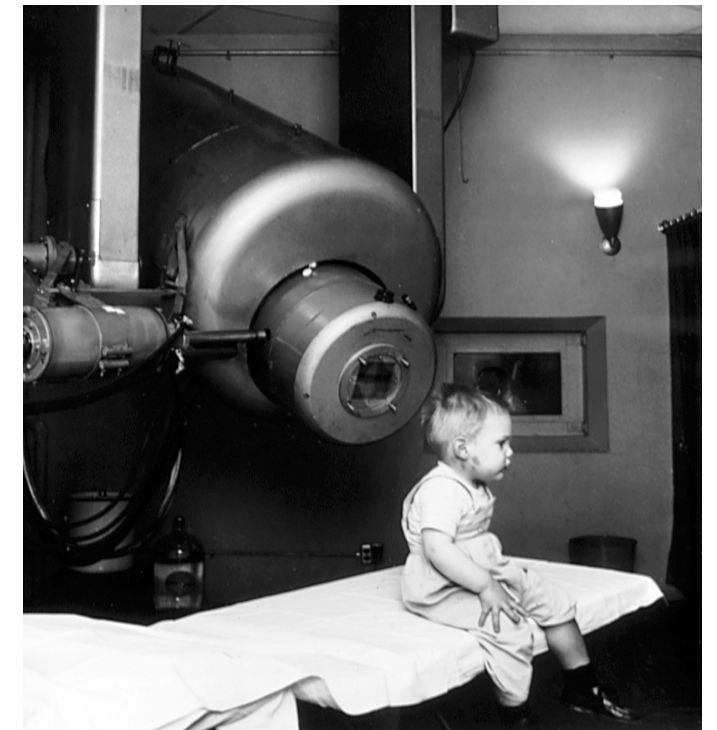
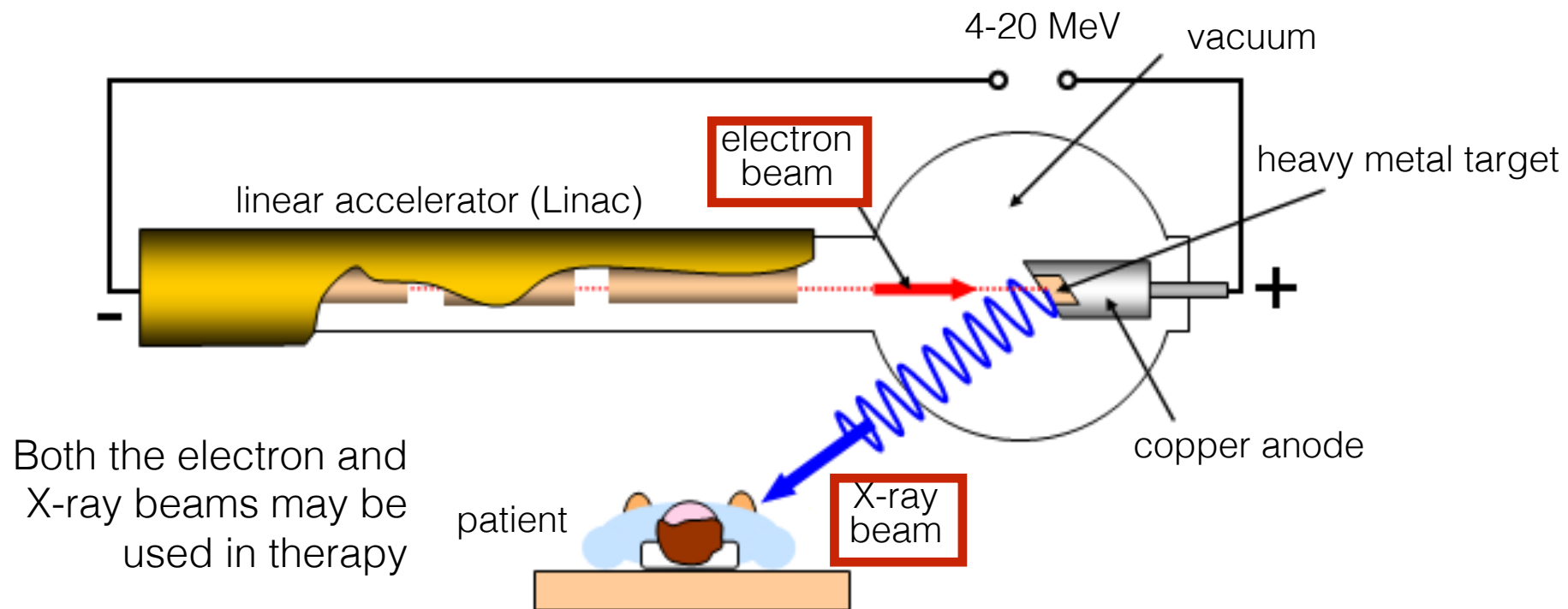
femur region



lumbar spine



Application III. Radiation therapy



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



Modern hospital Linac

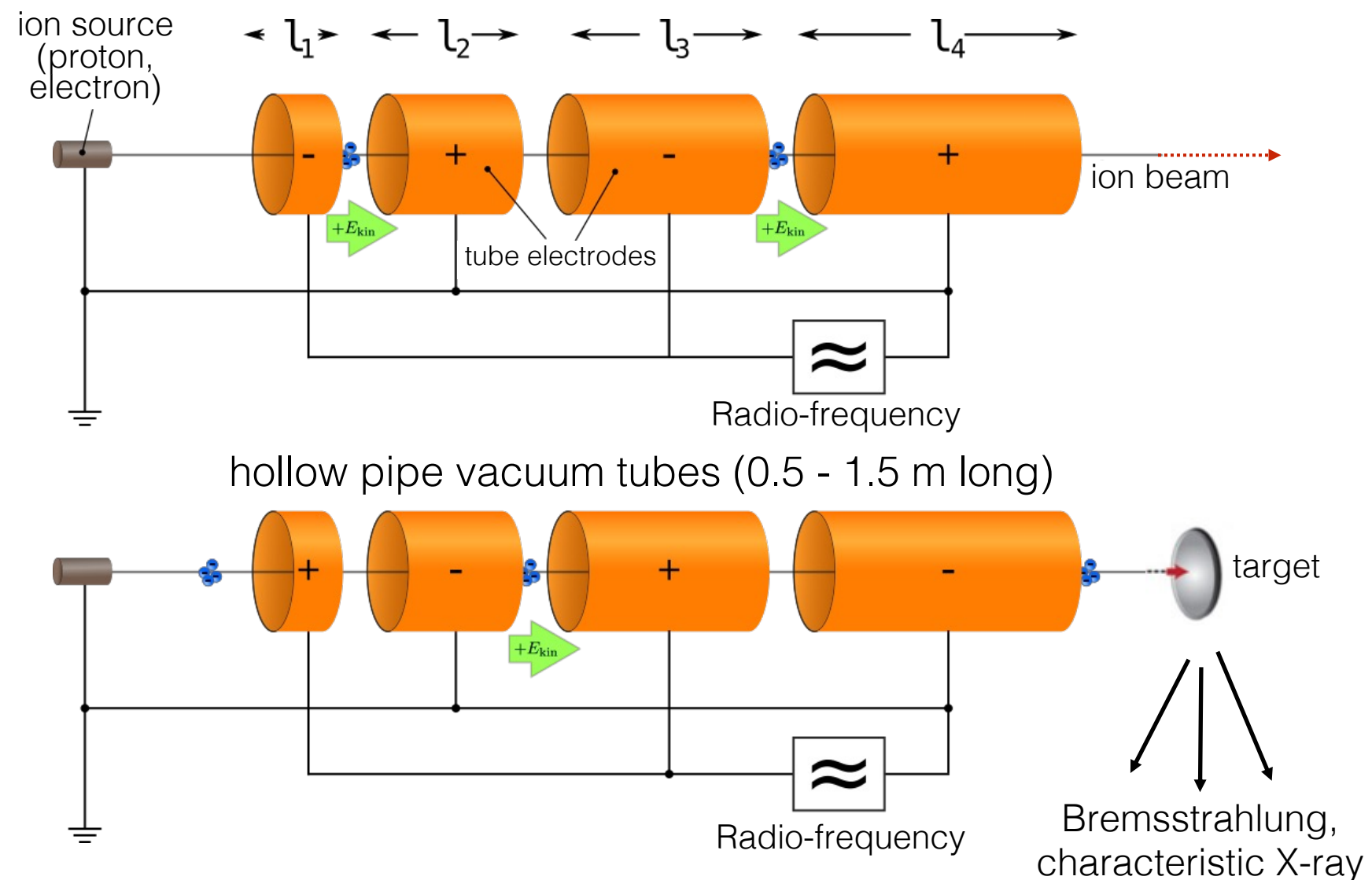
Advantages:

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

Generating high-energy X-ray

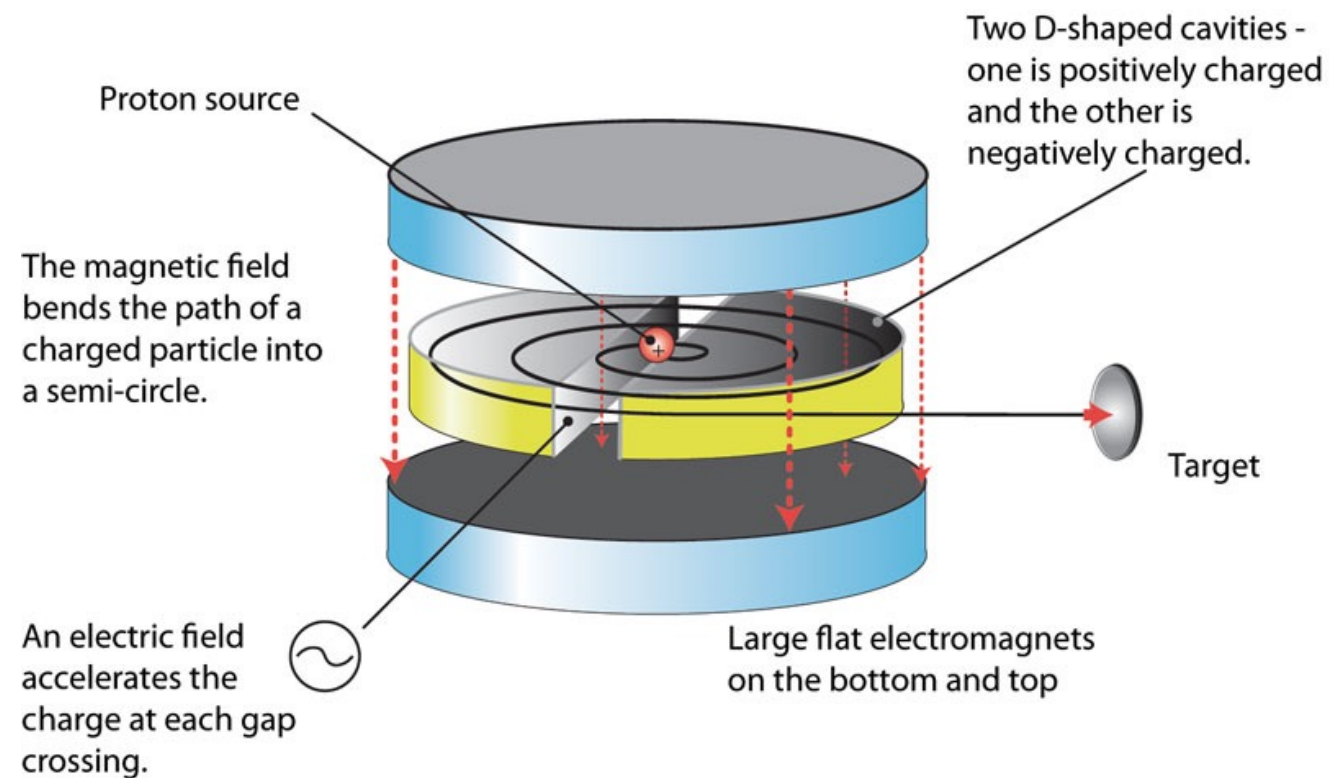
Linear accelerator (Linac)

- 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).



Ring-shape particle accelerators

Cyclotron

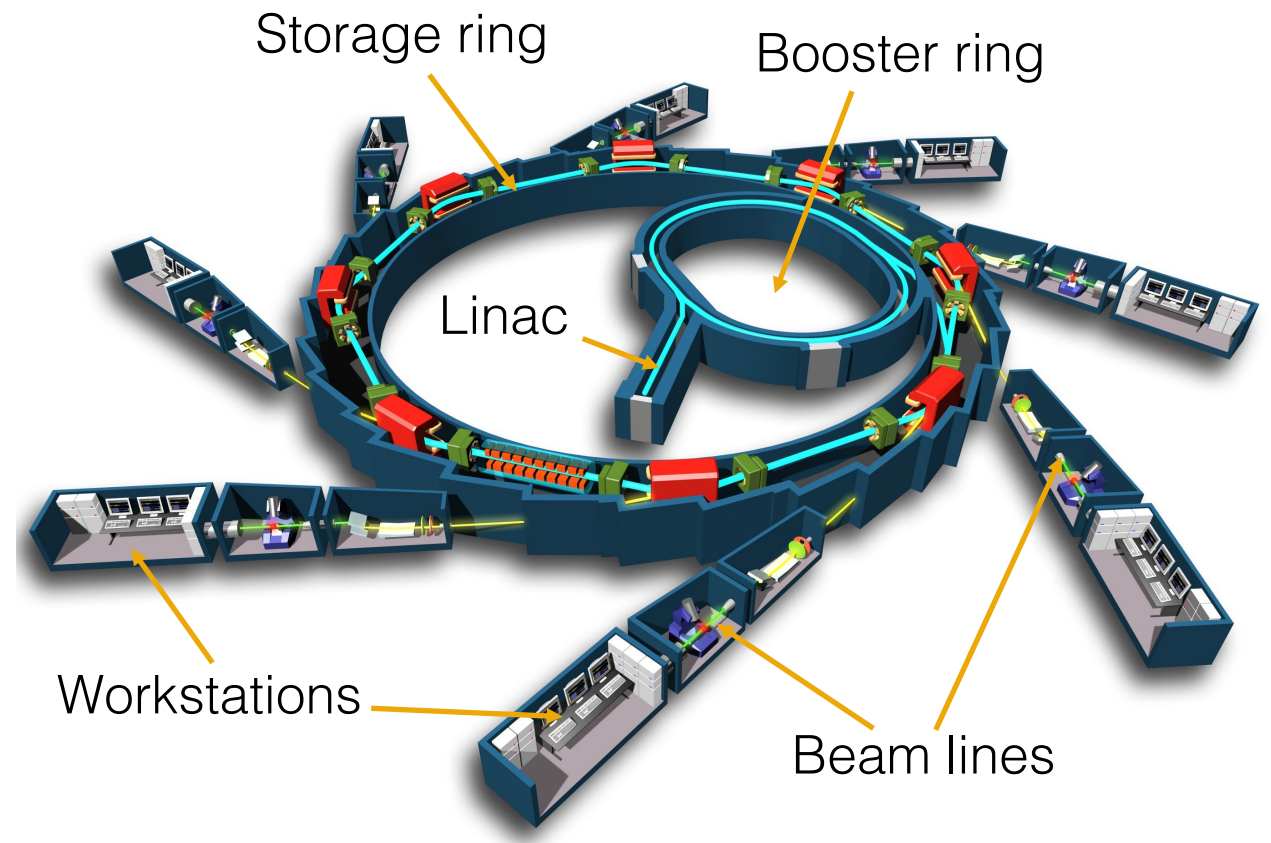


- Lorentz forces keep particles on circular path (causes limitations)
- Few tens of MeV particles are generated
- Used for generating positron-emitting isotopes (PET)
- Clinical cyclotrons in PET centers

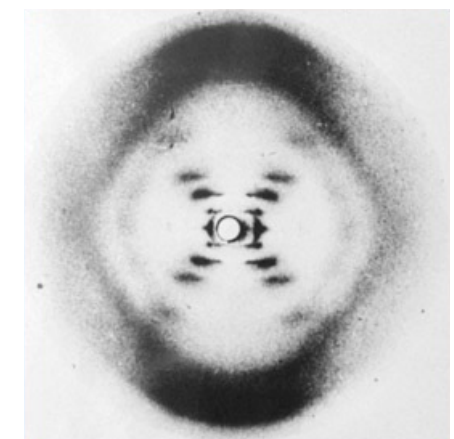
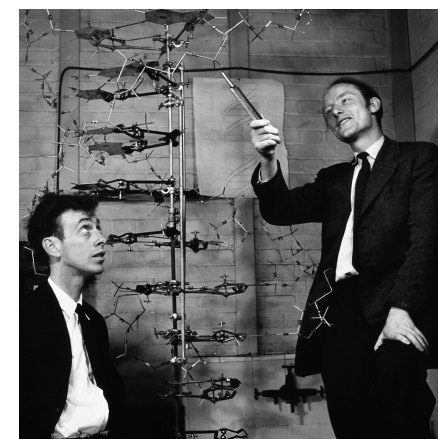


11 MeV medical cyclotron

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)