X-ray

Attenuation mechanisms

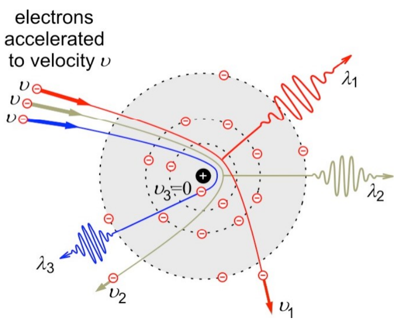
X-ray

Wilhelm Konrad Röntgen
(1845-1923)
Nobel prize in physics, 1901

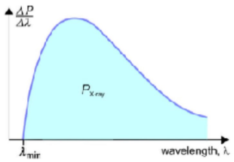
Hand mit Ringen (Hand with Ring): print of Wilhelm Röntgen's first "medical" X-ray, of Anna Bertha Ludwig

Mechanisms of X-ray generation

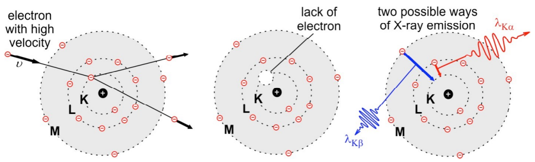
1. "Bremsstrahlung"
Breaking radiation
Deceleration radiation



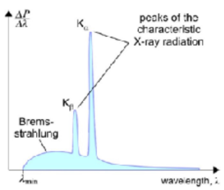
Continuous energy spectrum



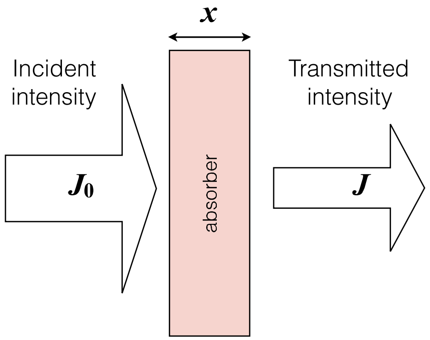
2. Characteristic radiation (X-ray fluorescence)



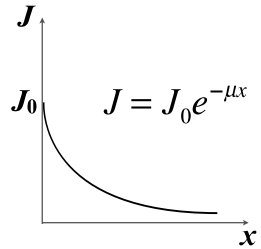
Linear energy spectrum



X-ray intensity atteunates when passing through an absorber



Exponential attenuation principle

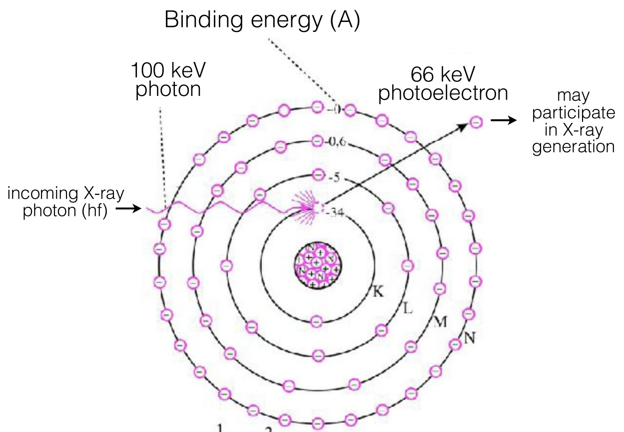


$$\mu = \mu_m \rho$$

μ : attenuation coefficient
μ_m : mass attenuation coefficient (cm²/g)
ρ : density (g/cm³)

μ_m is the sum of the mass attenuation coefficients of the different absorption mechanisms.

X-ray photoeffect



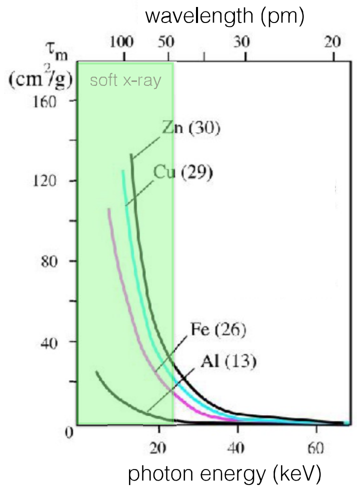
$$h \cdot f = A + \frac{1}{2}mv^2$$

Main effect in diagostic X-ray!

Photoeffect attenuation coefficient:

$$\tau = \tau_m \rho$$

Photoeffect attenuation depends strongly on the atomic number



Soft x-ray may be removed out with Al filters

$$\tau_m = const \cdot \frac{Z^3}{\varepsilon^3} = C \cdot \lambda^3 \cdot Z^3$$

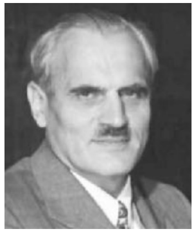
For multi-component system: "effective atomic number" (Z_{eff})

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

ε=photon energy
Z=atomic number
w=mole fraction
n=number of components

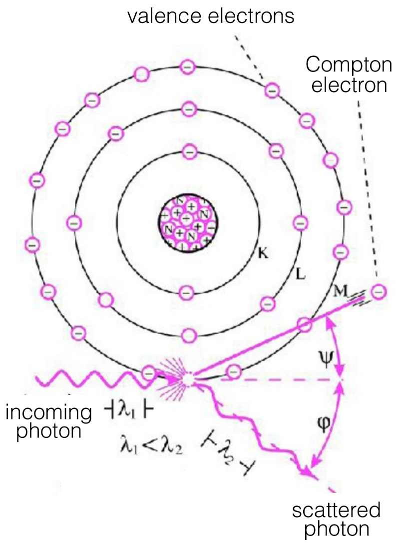
Material	Z_{eff}
Air	7,3
Water	7.7
Soft tissue	7.4
Bone	13.8

Compton scatter

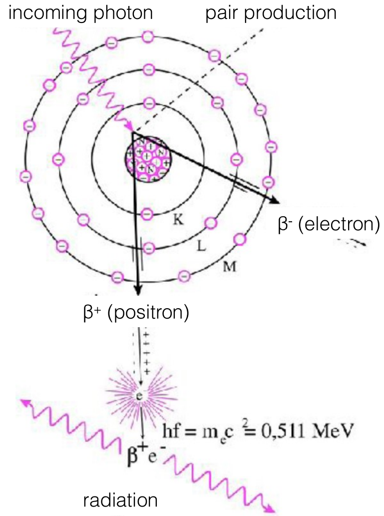


Arthur Holly Compton (1892-1962)

$$hf = A + hf_{scatt} + E_{kin}$$



Pair production



(relevant only in therapeutic x-ray)

Energy balance:

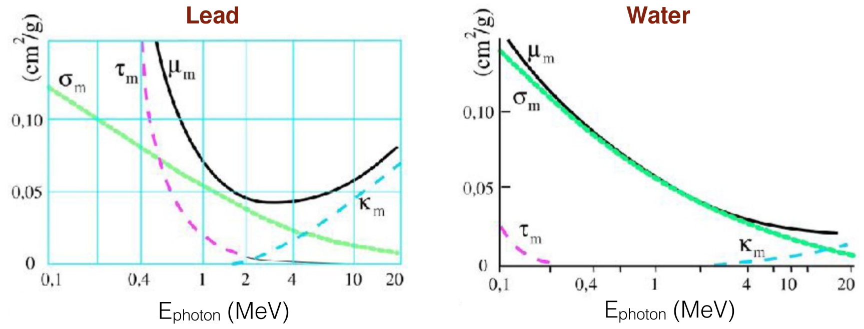
$$hf = 2m_e c^2 + 2E_{kin}$$

m_e=mass of electron
c=speed of light

Pair production relevant in high-energy X-ray photons, γ-radiation.

Attenuation mechanisms

Dependence on photon energy and material



$$\mu = \tau + \sigma + \kappa$$

μ_m=mass attenuation coefficient

σ_m=Compton effect mass attenuation coefficient

τ_m=photoeffect mass attenuation coefficient

κ_m=pair production mass attenuation coefficient

Summary of attenuation mechanisms

Mechanism	Photon energy (ε) dependence of the mass attenuation coefficient	Atomic number (Z) dependence of the mass attenuation coefficient	Relevant energy range in soft tissue
Rayleigh scatter	$\sim 1/\varepsilon$	$\sim Z^2$	1 - 30 keV
Photoeffect	$\sim 1/\varepsilon^3$	$\sim Z^3$	10 - 100 keV
Compton scatter	falls gradually with ε	~Z/A (A: mass number)	0.5 - 5 MeV
Pair production	rises slowly with ε	$\sim Z^2$	> 5 MeV

Diagnostic X-ray:
1. Contrast mechanism between soft tissue and bone: photoeffect ($\sim Z^3$)
2. Contrast mechanism within soft tissue: Compton-scatter ($\sim \rho$)

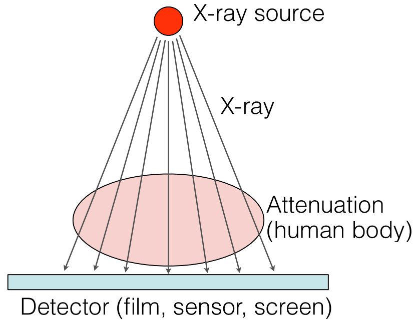
X-ray

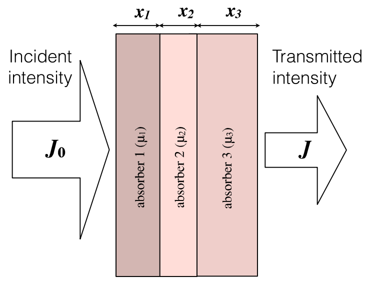
Applications

X-ray applications

- Diagnostic imaging
  The X-ray image
  Improvements of X-ray imaging
  CAT scanning
- Absorptiometry
  Bone density testing
- Therapy
  Generation of high-energy X-ray
  Tumor irradiation

Principles of X-ray imaging



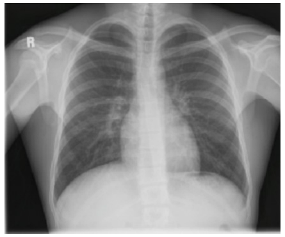


$$J = J_0 e^{-(\mu_1 x_1 + \mu_2 x_2 + \mu_3 x_3 + ...)}$$

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

μ_n : n[th] absorber's attenuation coefficient
x_n : n[th] absorber's thickness

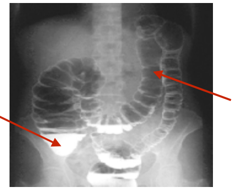
The X-ray image is a **summation image** ("X-ray image", "radiographic image", "roentgenogram"). Contrast arises due to spatially varying attenuation.



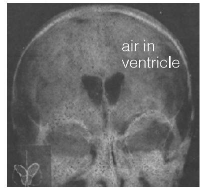
Improving X-ray imaging I.

Increasing contrast: contrast agents

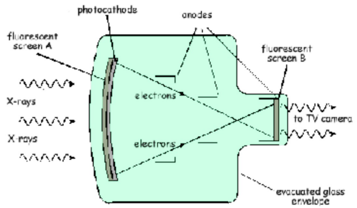
Positive contrast (large Z, e.g., Ba)



Negative contrast (small effective Z, e.g., air)

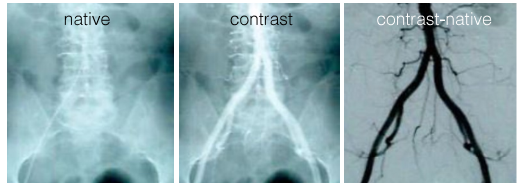


Enhancing sensitivity: intensifier



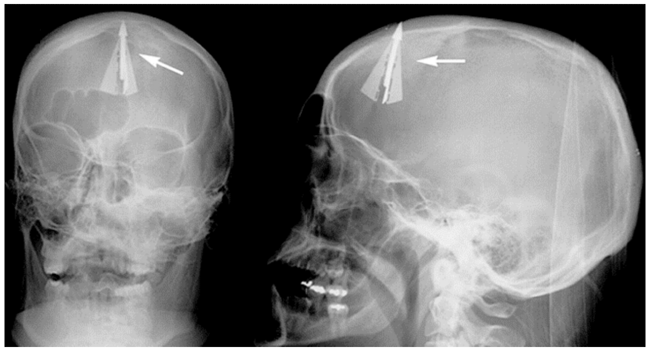
"C-arm"

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.

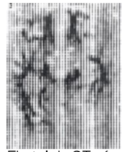
Improving X-ray imaging: the CAT scanner

History

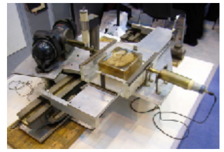
- Röntgen, Hounsfield and Cormack
- 1967: first CAT scan
- 1972: prototype
- 1974: first clinical CAT image (head)
- 1976: whole body CAT scan
- 1979: Nobe-prize
- 1990: spiral CAT scanner
- 1992: multislice CAT scanner
- 2006: 64 slice (and more…)
- multiple and hybrid modes: SPECT-CT, PET-CT, Dual-source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

Godfrey Hounsfield

Allan Cormack



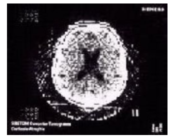
First, lab CT of a brain slice



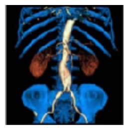
Prototype CAT scanner (EMI)

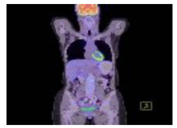
„Siretom" head scanner (1974)

128x128 pixel image (1975)



Multi-modal (combined) images

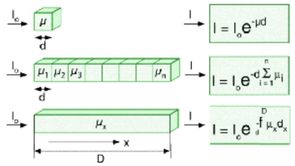




Current CAT scanner

Foundations and steps of CAT

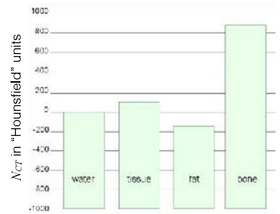
Objective: to determine the attenuation coefficient (μ_x) of the individual volume elements (voxels)



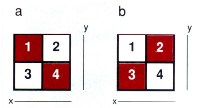
Based on μ the voxel "density" ("CT-number, N_{CT}) can be determined:

$$N_{CT} = 1000 \frac{\mu - \mu_w}{\mu_w}$$

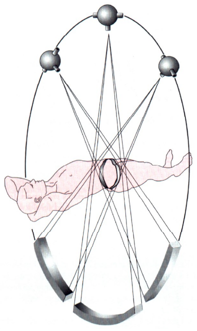
μ: voxel attenuation coefficient
μ_w: water attenuation coefficient



Scanning in transaxial tomographic slices ("*tomos*") is needed

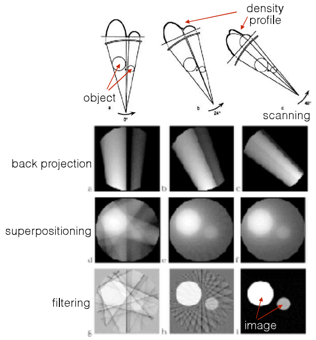


It is not possible to distinguish **a** from **b** in a bi-directional image

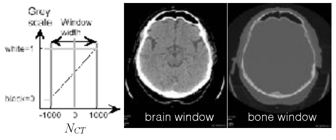


Scanning along as large angular resolution as possible is necessary

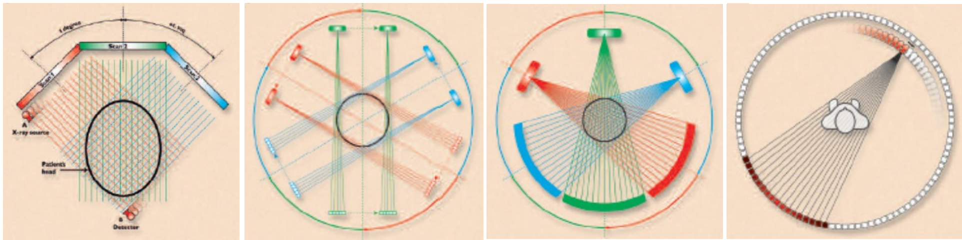
Image reconstruction and manipulation



The CAT scan is a density matrix, the color scale of which can be manipulated ("windowing") to increase specific local contrast



Scanning techniques evolved through generations



I. Generation.
There is a single moving source and a single moving detector, each translating linearly, then rotated.

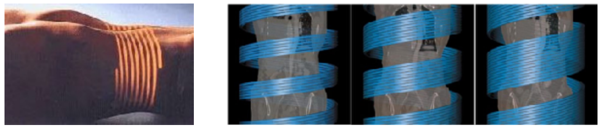
II. Generation.
There are a small number of beams (approximately 8 to 30) in a narrow fan configuration with the same translate-rotate motion used in first generation machines. Each linear traverse produces several projections at differing angles, one view for each X-ray beam.

III. Generation.
There are a large number of X-ray beams (approximately 500 to 700) in a wide fan configuration. Both the X-ray tube and the detectors rotate.

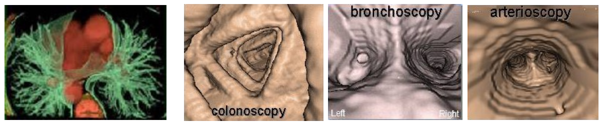
III. Generation.
There are an intermediate number of X-ray beams (approximately 50 to 200) in a wide fan configuration with a rotating X-ray tube and a stationary circular array of approximately 600 to 2,400 detectors surrounding the patient.

Modern CAT scanning

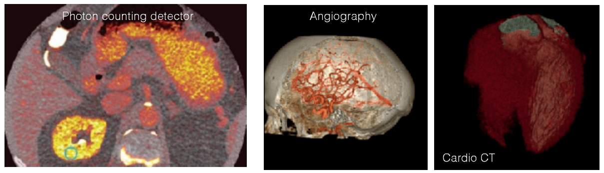
Spiral and multislice CAT



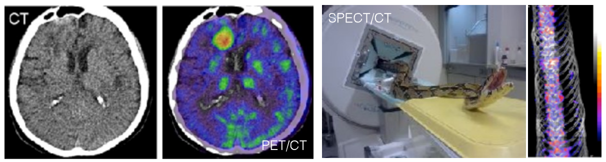
3D reconstruction, virtual endoscopy



Icreasing sensitivity and resolution

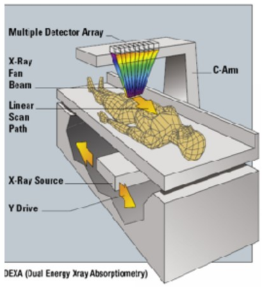


Combination with other modalities



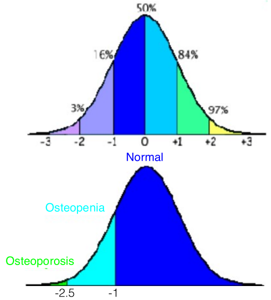
Absorptiometry

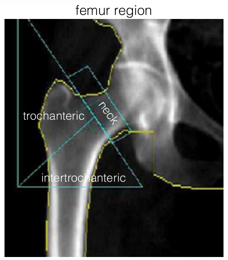
Dual-energy X-ray absorptiometry (DXA or DEXA)

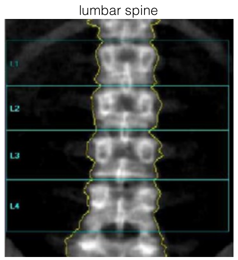


- Most important method for measuring bone density
- Characteristic X-ray is used as source
- Two different photon energies are employed
- Low dose is applied
- Whole-body scan is recorded
- Densities of distinct areas (e.g., femur, spine) are compared with reference databases
- Bone Mineral Density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

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



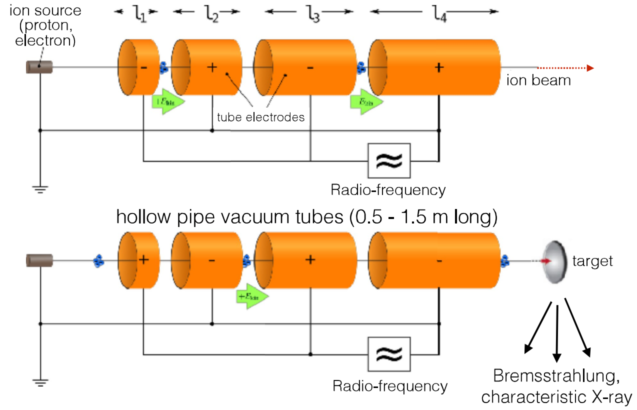




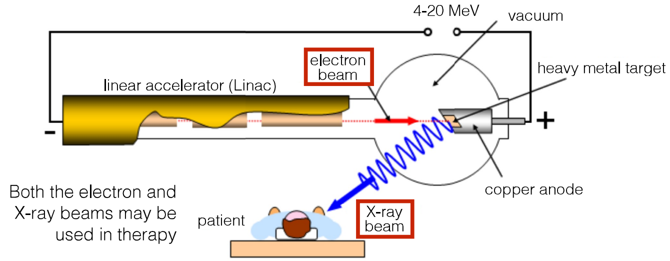
Generating high-energy X-ray

Linear accelerator (Linac)

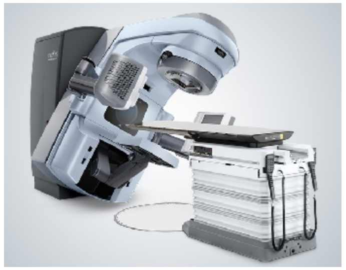
- Charged particle (electron, proton) accelerated between electrodes (but not inside the electrode).
- Velocity of particle increases in steps.
- Electrode polarity is alternating.
- Electrodes are gradually longer (l_n increases) in order to maintain synchrony.
- Accelerated particles are directed at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



Linac-based radiation therapy



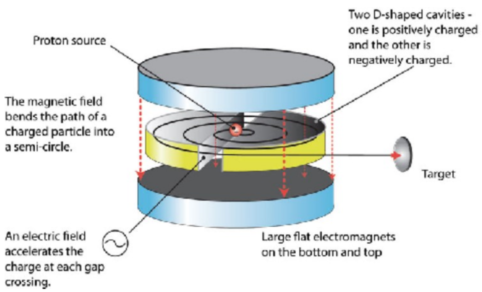

First patient (Gordon Isaacs) treated with Linac radiation therapy (electron beam) for retinoblastoma (1955)


Modern hospital Linac

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

Ring-shape particle accelerators

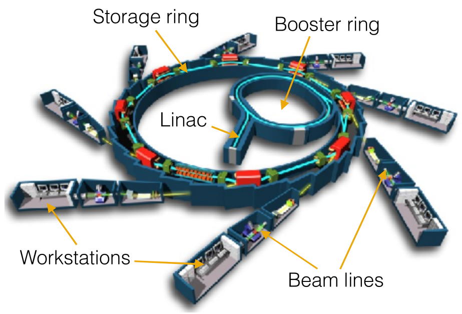
Cyclotron



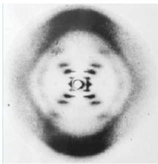
- Lorentz forces keep particles on circular path (causes limitations)
- Few tens of MeV particles are generated
- Used for generating positron-emitting isotopes (PET)
- Clinical cyclotrons in PET centers


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)