X-Rays

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Overview

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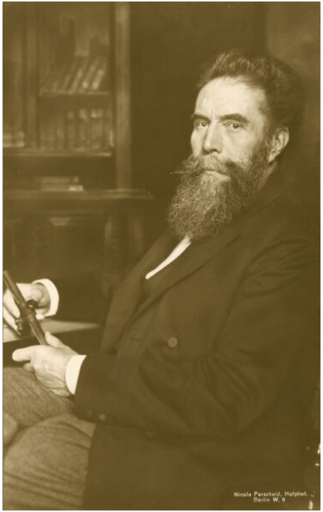
- Fundamentals of X-rays
  - Invention
  - Electromagnetic spectrum
  - Particles and waves
  - Chest X-rays radiography machine
- Generation of X-rays
  - X-ray source
  - Beam focusing
  - Penumbra
  - X-ray tube
  - X-ray parameters / spectrum
- Interaction of X-rays with mstter
  - Coherent scattering
  - Photoelectric effect
  - Compton scattering
  - Attenuation
- Detection of X-rays
  - Collimator
  - Antiscatter grid
  - Intensifier screen
  - Film
  - Charge Coupled Device (CCD)
  - Medipix/Timepix (MPX/TPX)
- Imaging and diagnostic methods
  - X-ray image characteristics
  - X-ray contrast agents
  - X-ray angiography
  - Digital Subtraction Angiography
  - Intra-operative imaging
  - Dual-Energy Imaging
  - Mamography
- Pros and Cons

Invention, Nobel Prize in Physics 1901



1895, W. Röntgen

B. Röntgen hand

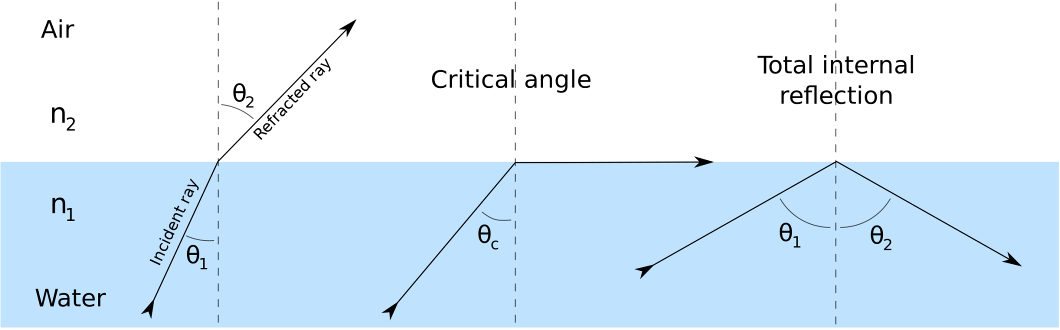
modern hand

Electromagnetic spectrum

Electromagnetic wave spectrum

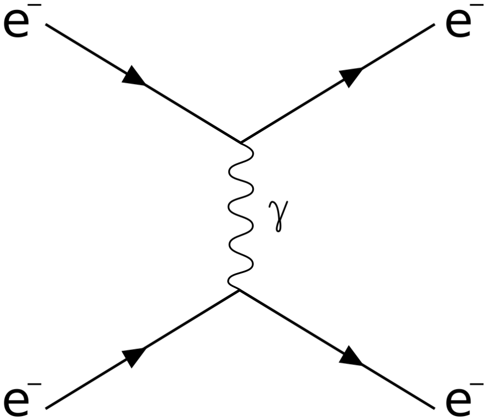
Energy (eV)	Frequency (Hz)		Wavelength (m)
4×10^{-11}	10^{4}		10^{4}
4×10^{-10}	10^{5}	AM radio waves	10^{3}
4×10^{-9}	10^{6}		10^{2}
4×10^{-8}	10^{7}	Short radio waves	10^{1}
		FM radio waves and TV	
4×10^{-7}	10^{8}		10^{0}
4×10^{-6}	10^{9}		10^{-1}
4×10^{-5}	10^{10}	Microwaves and radar	10^{-2}
4×10^{-4}	10^{11}		10^{-3}
4×10^{-3}	10^{12}	Infrared light	10^{-4}
4×10^{-2}	10^{13}		10^{-5}
4×10^{-1}	10^{14}	Visible light	10^{-6}
4×10^{0}	10^{15}	Ultraviolet light	10^{-7}
4×10^{1}	10^{16}		10^{-8}
4×10^{2}	10^{17}		10^{-9}
4×10^{3}	10^{18}	X-ray	10^{-10}
4×10^{4}	10^{19}		10^{-11}
4×10^{5}	10^{20}		10^{-12}
4×10^{6}	10^{21}	Gamma ray	10^{-13}
4×10^{7}	10^{22}	Cosmic ray	10^{-14}

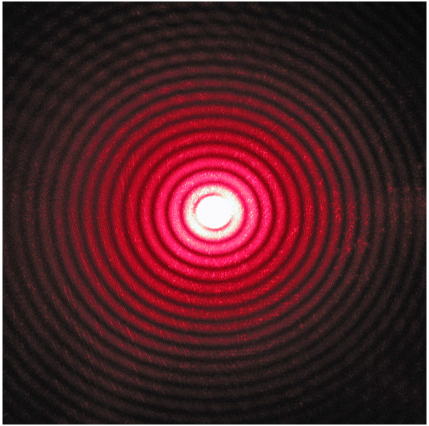
Particles and waves



- refraction, reflection = waves
- photoelectric effect, ionizing radiation (above 10 eV, $\lambda = 120\,\text{nm}$) = particles
- photons with energy $E = hf$, $h \approx 6.6 \cdot 10^{-34}\,\text{J} \cdot \text{s} \approx 4.1 \cdot 10^{-15}\,\text{eV} \cdot \text{s}$
  $1\,\text{eV} \approx 1.6 \cdot 10^{-19}\,\text{J}$
  $c = f\lambda \approx 3 \cdot 10^8\,\text{m/s} \qquad \lambda = 1\,\text{nm} \quad \approx \quad 1.2 \cdot 10^3\,\text{eV} = 1.2\,\text{keV}$

Particles and waves (2)

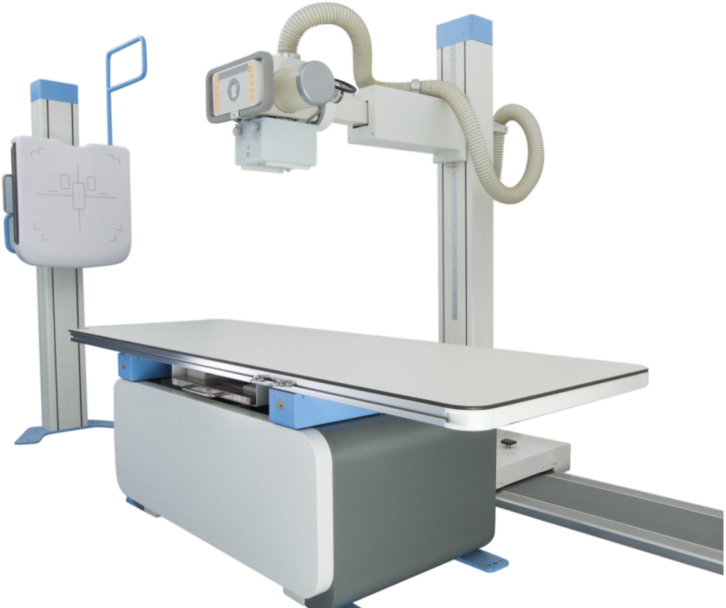




- electron scattering, light diffraction

Chest X-rays radiography machine

Chest X-rays radiography machine



Chest X-ray

Chest X-ray

X-ray scanner

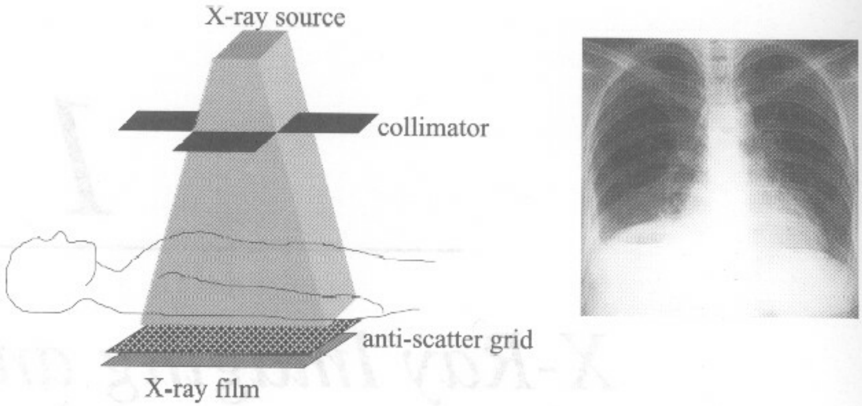


FIGURE 1.1. *(Left) The basic setup for X-ray imaging. The collimator restricts the beam of X-rays so as to irradiate only the region of interest. The antiscatter grid increases tissue contrast by reducing the number of detected X-rays that have been scattered by tissue. (Right) A typical planar X-ray radiograph of the chest, in which the highly attenuating regions of bone appear white.*

X-ray source

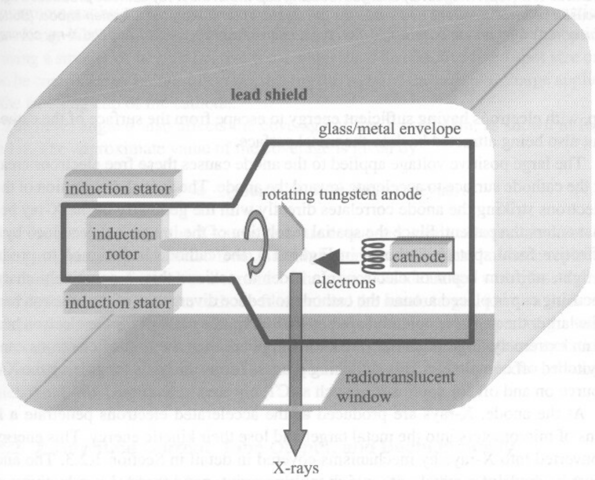
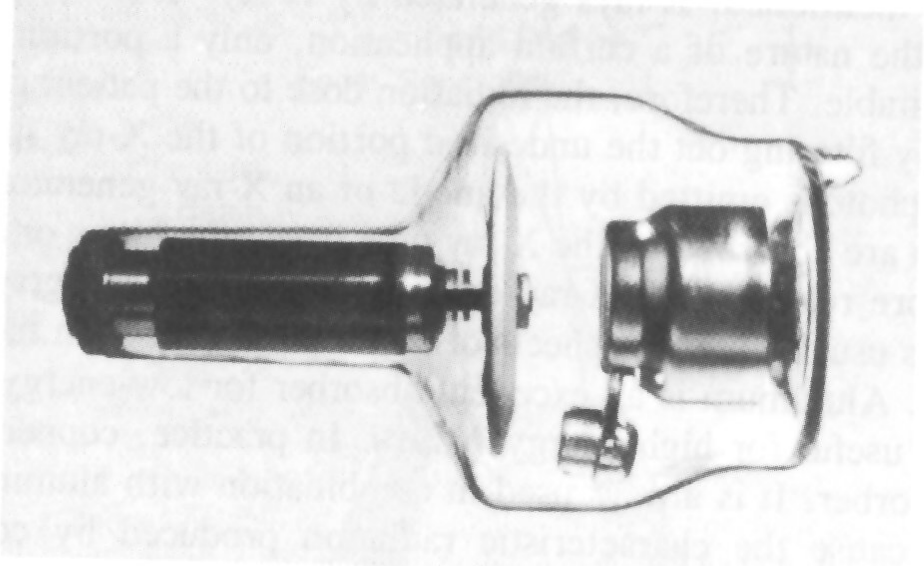


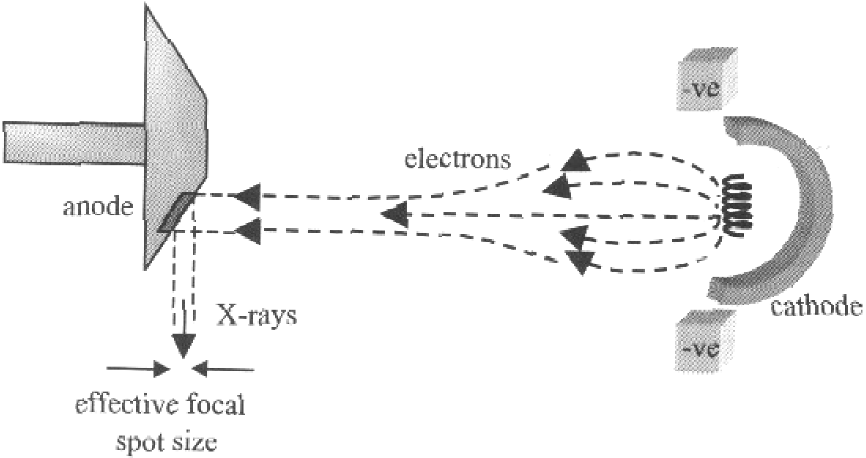
FIGURE 1.3. A schematic of an X-ray source used for clinical imaging.

- $15 \sim 150\,\text{kV}$, rectified AC
- $50 \sim 400\,\text{mA}$ anode current
- tungsten wire ($200\,\mu\text{m}$) cathode, heated to $\sim 2200^\circ\text{C}$
- anode rotates at 3000 rpm
- molybdenum or tungsten-rhenium anode
- thermoionic emission

X-ray tube

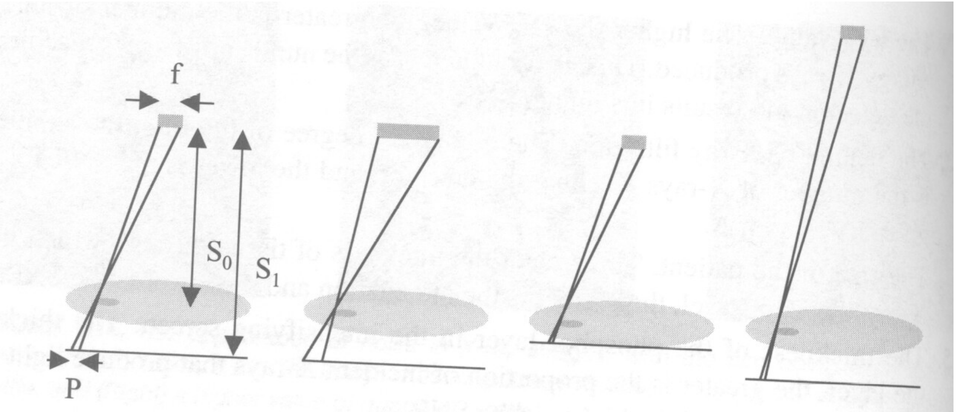


Beam focusing



- Focal spot size 0.3 mm $\sim$ 1.2 mm

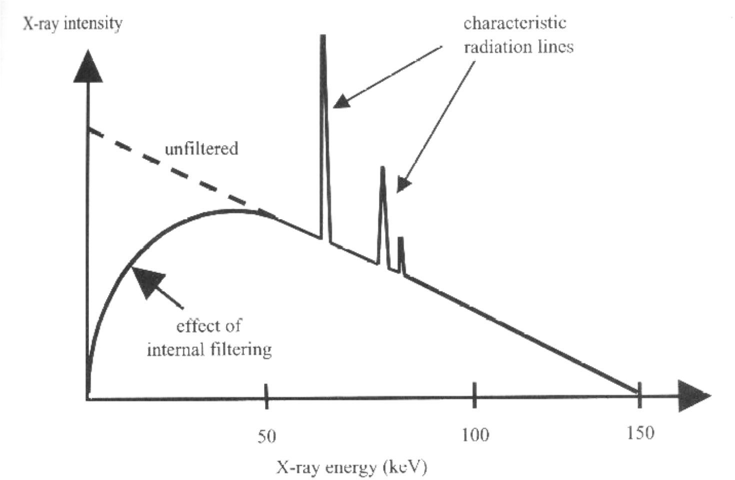
Penumbra (Latin paene "almost", umbra "shadow")



- geometric unsharpness
- small focal spot
- large distance

X-ray parameters

Intensity: $[W/m^2]$: $\propto U^2 I$
Spectrum: (150 kV)

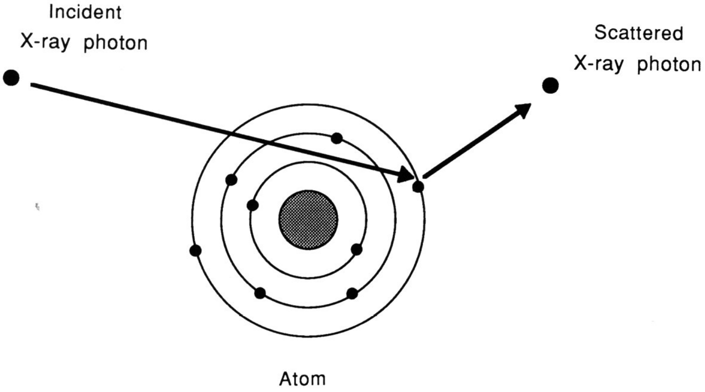


- Bremsstrahlung
- Characteristic radiation
- Filter low-energy rays that would not penetrate the patient — *Al* sheets. (skin dose reduced $80\times$)

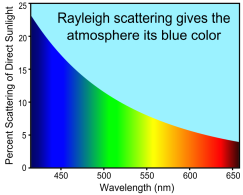
Interaction between X-rays and matter

- Coherent scattering
- Photoelectric effect
- Compton scattering
- *(Pair production)*
- *(Photodisintegration)*

Coherent (Rayleigh) scattering

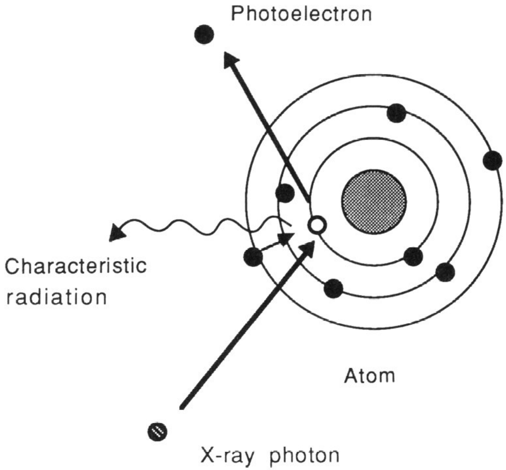


- Photon $\longrightarrow$ photon, almost same frequency
- Low-energy radiation
- Probability $\propto Z_{\text{eff}}^{8/3}$
  - Z_{eff} - effective atomic number
  - muscle $Z_{\text{eff}} \approx 7.4$, bone $Z_{\text{eff}} \approx 20$
- About $5 \sim 10\,\%$ of tissue interactions



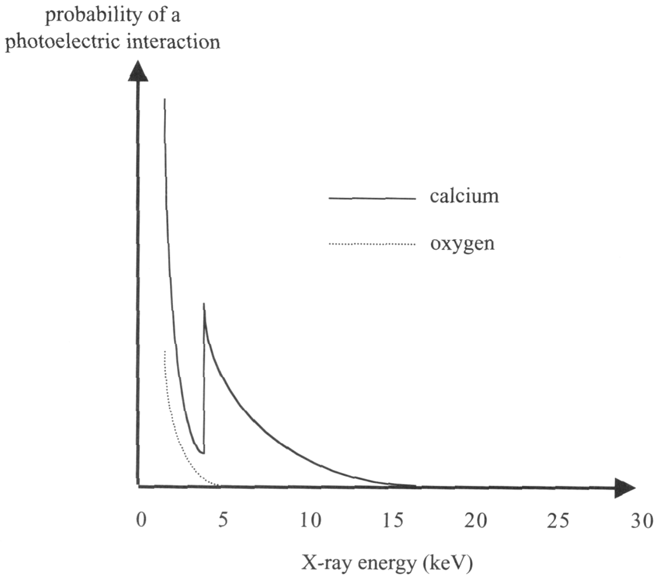
Photoelectric effect

A.Einstein Nobel Prize 1921 “for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect”

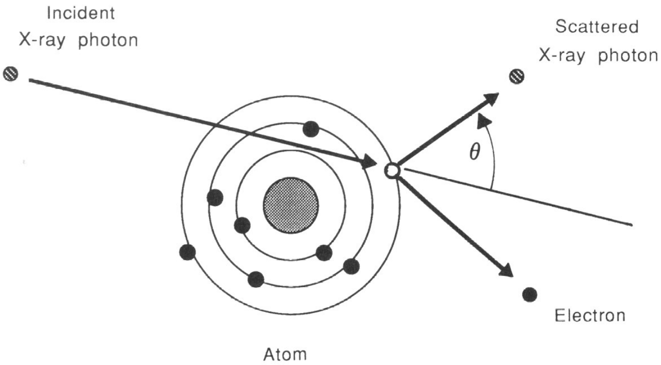


- High-energy radiation
- Photon $\longrightarrow$ characteristic radiation, photo-electron / Auger electron, positive ion
- $\longrightarrow$ ionization
- Desirable, X-ray photon completely absorbed

Photoelectric interaction wrt E



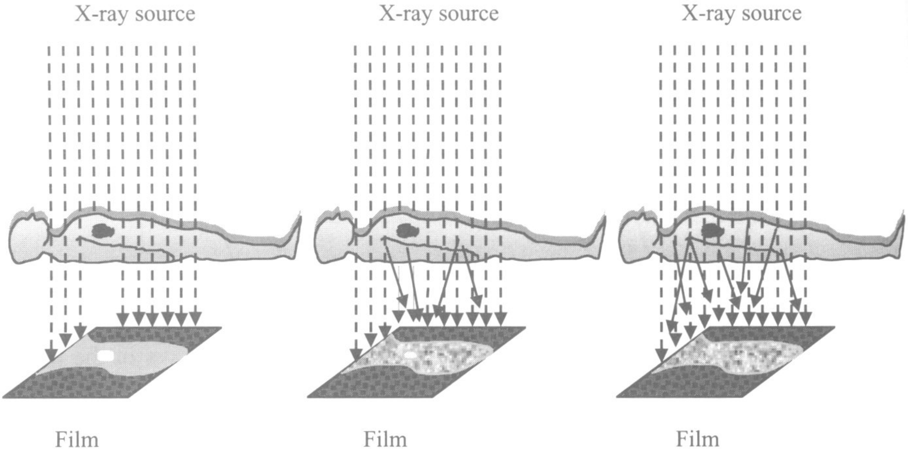
Compton scattering



$$E_{\text{scatt}} = \frac{E_{\text{inc}}}{1 + \frac{E_{\text{inc}}}{m_e c^2}(1 - \cos\theta)}$$

- photon $\longrightarrow$ photon + electron, ionization
- most frequent in X-ray imaging, especially for high E_{inc}
- independent to atomic number $\longrightarrow$ small contrast
- background noise, health hazard

Effects of Compton scattering



Attenuation

$$\mathrm{d}I = -\mu I \mathrm{d}x \qquad \mu = n\sigma$$
$$I_x = I_0 \mathrm{e}^{-\mu x}$$

μ — linear attenuation coefficient
Half-value layer $\log 2/\mu \approx 0.693/\mu$

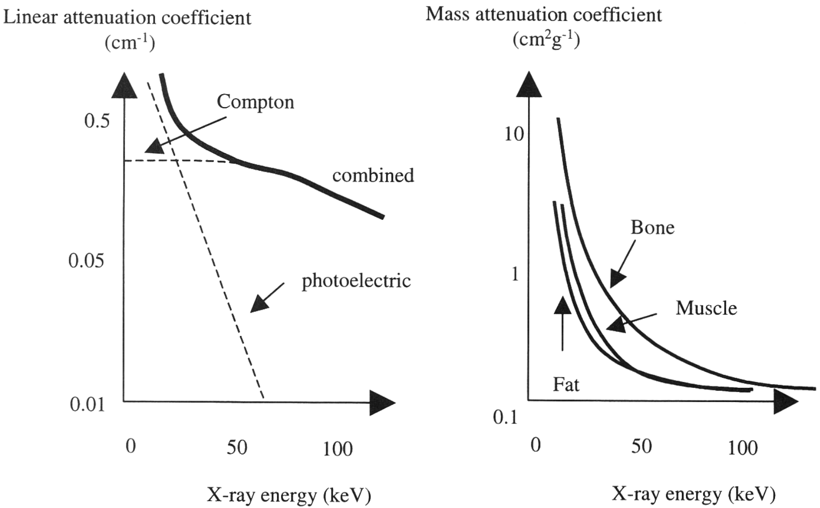
TABLE 1.2. The Half-Value Layer (HVL) for Muscle and Bone as a Function of the Energy of the Incident X-Rays

X-ray energy (keV)	HVL, muscle (cm)	HVL, bone (cm)
30	1.8	0.4
50	3.0	1.2
100	3.9	2.3
150	4.5	2.8

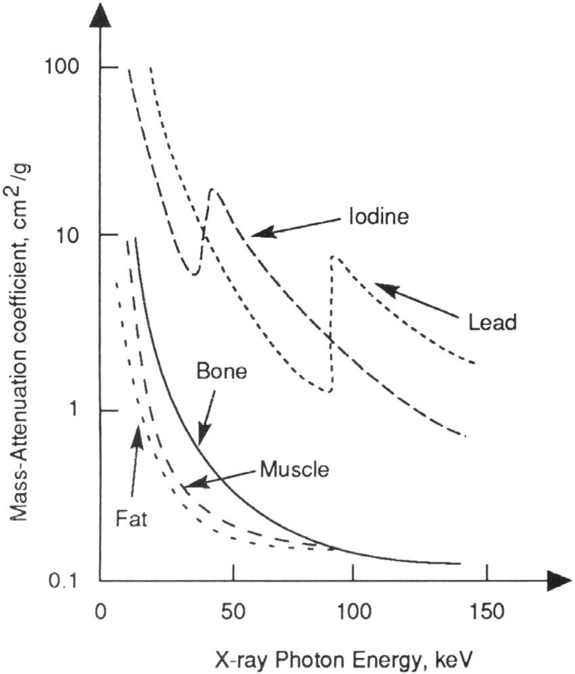
Mass attenuation coefficient μ/ρ
Attenuation decreases with energy, $\mu \propto E^{-3}$

Attenuation factors wrt E

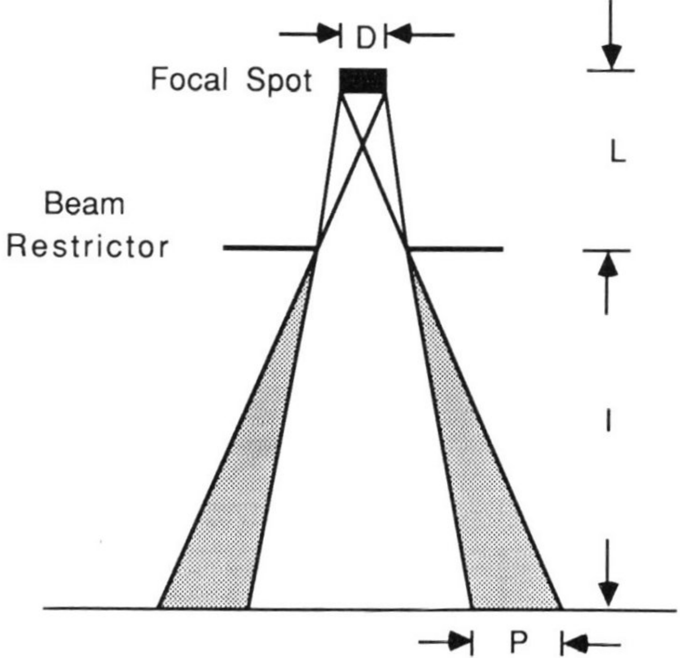
$$\mu = \mu_{\text{photoel}} + \mu_{\text{Compton}} + \mu_{\text{coherent}}$$



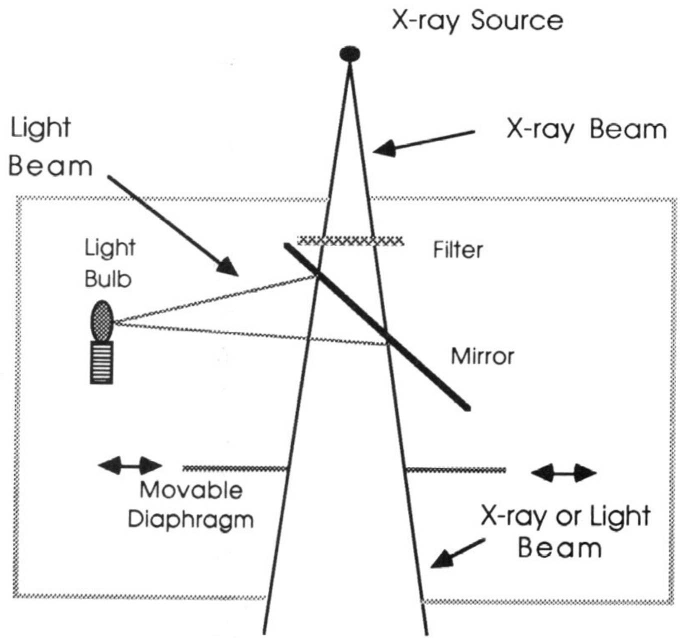
Attenuation wrt E (2)



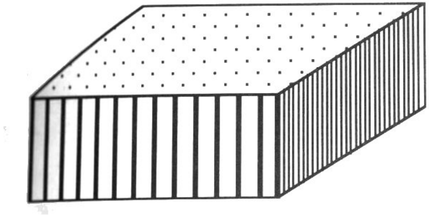
Beam restrictor / Collimator

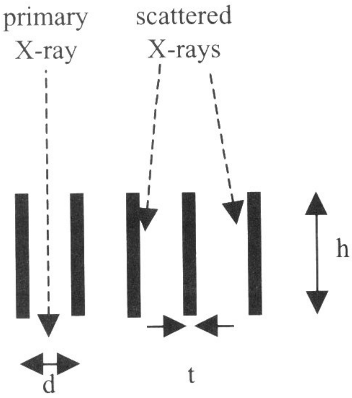


Beam restrictor / Collimator (2)



Antiscatter grid





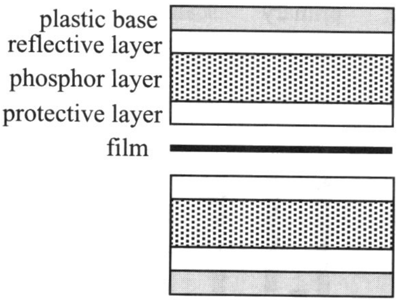
Bucky factor = dose increase

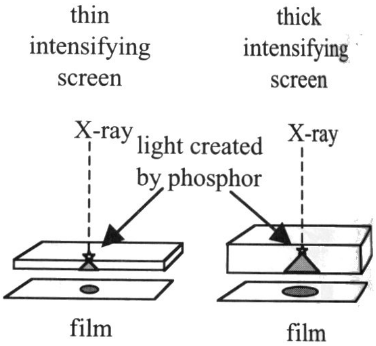
Antiscatter grid — example

3 mAs

antiscatter grid, 10 mAs

Intensifier screen

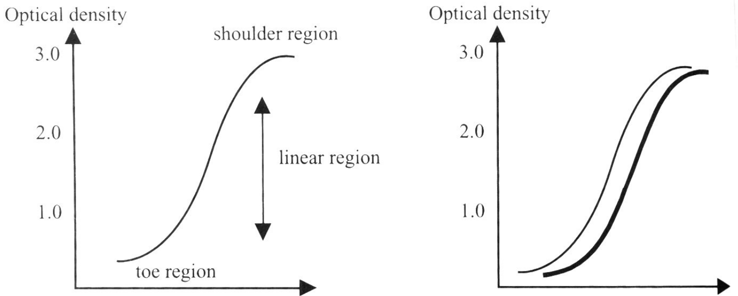




- 50× sensitivity increase
- thickness; trade-off resolution/sensitivity
- Gd — green, La – blue, CsI, ZnS
- efficiency 20 %

Film

- monochromatic (sensitive to blue), ortochromatic (sens. to green)
- double emulsion (10 μm), silver bromide in gelatin
- blackening, optical density (OD) $\log_{10}(I_i/I_t)$
- contrast $\gamma = \frac{OD_2 - OD_1}{\log_{10} E_2 - \log_{10} E_1}$, slope of the linear region
- latitude (dynamic range), range of useful exposure values
- grain size sensitivity/resolution trade-off
- mixed-particle size $\longrightarrow$ high contrast
- automatic exposure control, ionization chamber



Digital Sensors

- Computed radiography (CR)
  - Phosphor-based storage plate
  - chemical storage (oxidation of Eu)
  - laser scanning, light erasure

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- Digital radiography (DR)
  - flat-panel detectors (FPD)
  - thin-film transistor (TFT) array
  - CsI scintillator $\longrightarrow$ photo-diode/transistor
  - $41 \times 41\,\text{cm}$, 2048×2048 pixels
  - better dynamic range, quantum efficiency, and latitude wrt film

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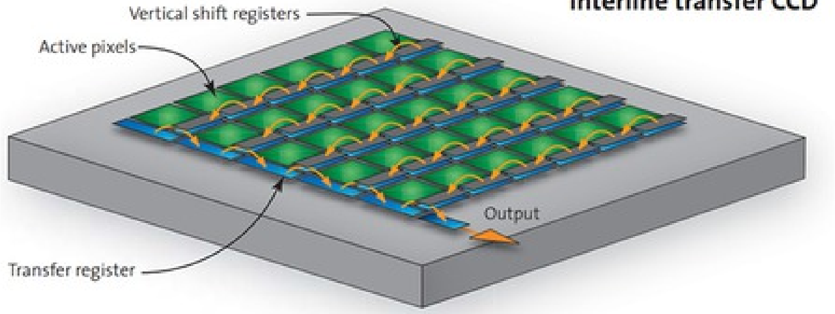
- Charge Coupled Device (CCD), Willard S. Boyle and George E. Smith, Nobel Prize 2009 "for the invention of an imaging semiconductor circuit – the CCD sensor"
  - Phosphor screen, fiber-optic cables, CCD sensor
  - good sensitivity, low noise
  - CCD X-ray detectors have replaced photographic film as the detector of choice for diagnostic imaging, allowing digital copies of images to be captured and stored much more quickly.

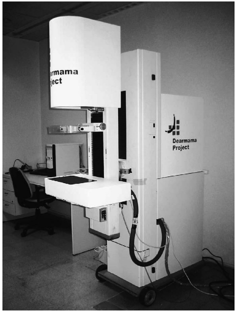
CCD detectors

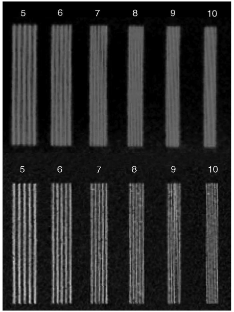
Interline transfer CCD

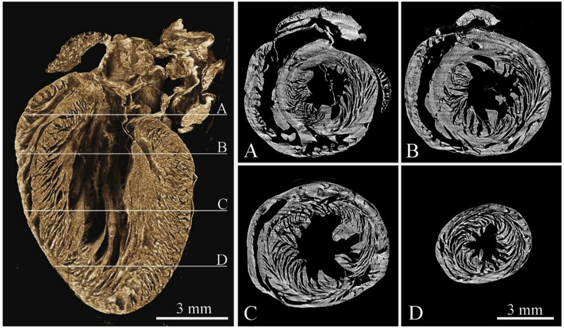


Medipix/Timepix detectors Radiation Measurements,https://doi.org/10.1016/j.radmeas.2019.04.007

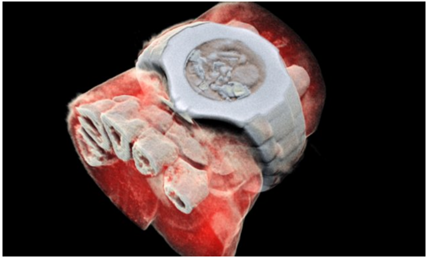
- direct detection (no light conversion), on-chip processing, since 1990 in CERN
- pixel counters, energy measurement, arrival time, particle trace (type)
- good spatial resolution (55 μm), 256×256 pixels, up to 10×10 chips
- new imaging methods (e.g. Compton camera - two stacked detectors)
- high-price

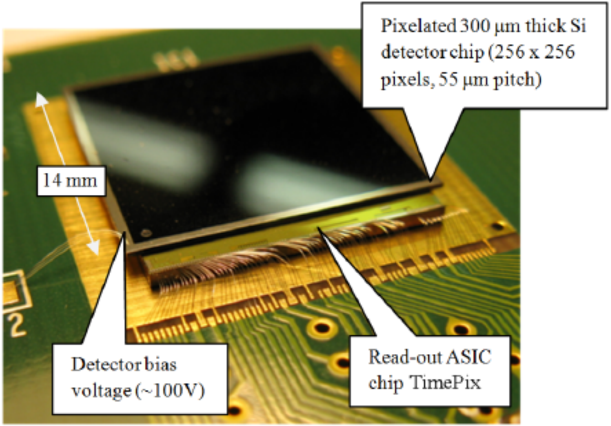






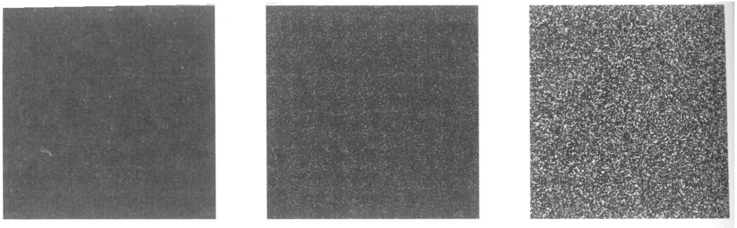
Medipix/Timepix detectors (2)





CERN, Mars Bioimaging, medipix-3
sensor measures attenuation of specific wavelengths of the X-rays as they pass through different materials.

X-ray image characteristics



- **Signal-to-noise ratio (SNR)**
  - Discrete photons, Poisson distribution
  - $\mu = \lambda$, $\sigma^2 = \lambda$
  - SNR $\propto \sqrt{\lambda}$, λ — intensity/photons per area/pixel
  - exposure time and current, SNR $\propto \sqrt{TI}$
  - higher U $\longrightarrow$ more high-energy rays $\longrightarrow$ more incident photons $\longrightarrow$ better SNR
  - X-ray filtering $\longrightarrow$ smaller SNR
  - patient size, antiscatter grid, intensifying screen, film

X-ray image characteristics

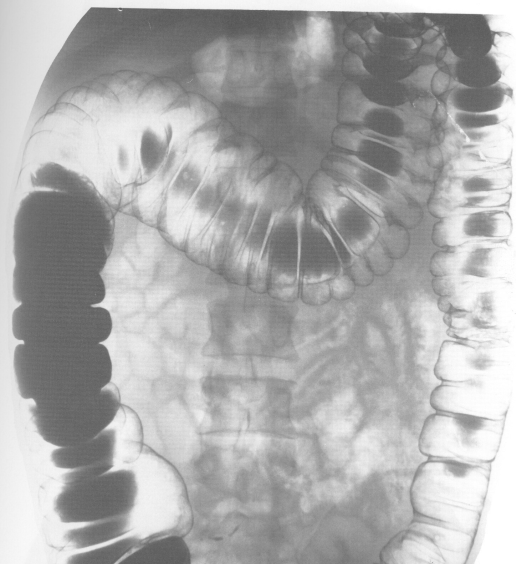
- **Signal-to-noise ratio (SNR)**
- **Spatial resolution**
  - point spread function (PSF), line spread function (LSF), edge spread function (ESF), modulation transfer function (MTF)
  - thickness of the intensifier screen
  - speed of the X-ray film
  - geometric unsharpness
  - magnification factor (patient $\longrightarrow$ film). Place patient as close as possible.

X-ray image characteristics

- **Signal-to-noise ratio (SNR)**
- **Spatial resolution**
- **Contrast-to-noise ratio**
  - $\mathrm{CNR} = \frac{|S_A - S_B|}{\sigma_N} = |\mathrm{SNR}_A - \mathrm{SNR}_B|$

X-ray contrast agents

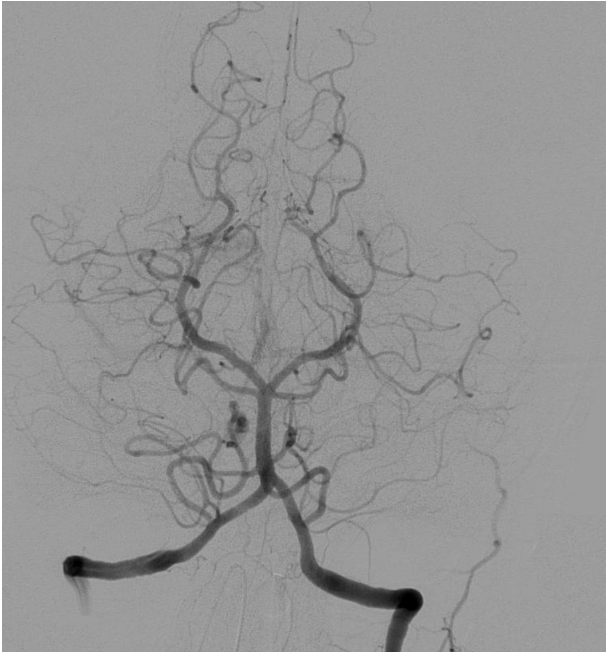
- barium sulfate, gastrointestinal tract



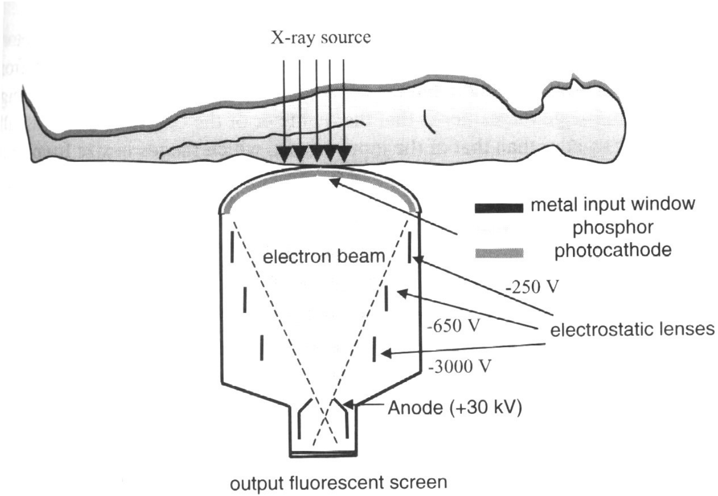
X-ray angiography (visualize the inside of blood vessels and organs of the body)

- Stenosis, clotting of arteries
- Iodine-based contrast agent (danger of kidney failure)
- Time series
- Excellent resolution (100 μm)
- Digital subtraction angiography (DSA)

Digital Subtraction Angiography (DSA) example

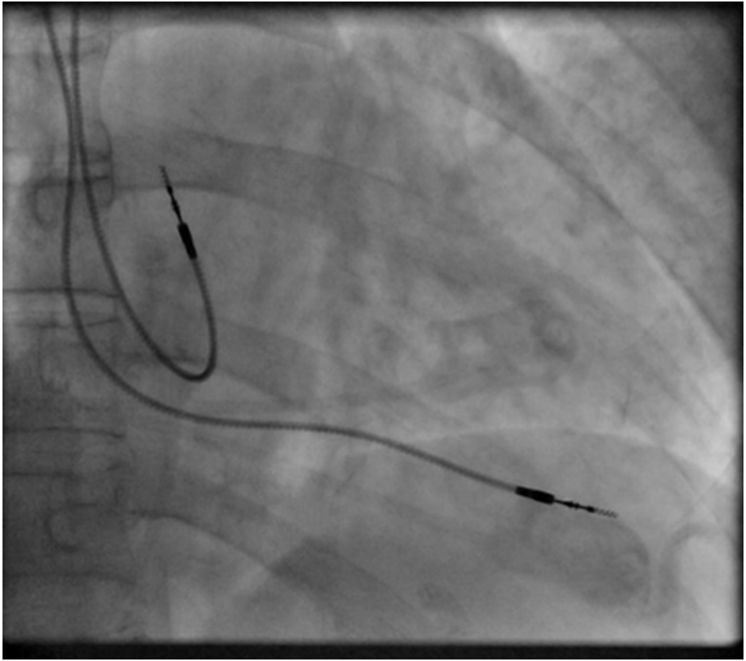


Fluoroscopy / Intra-operative imaging

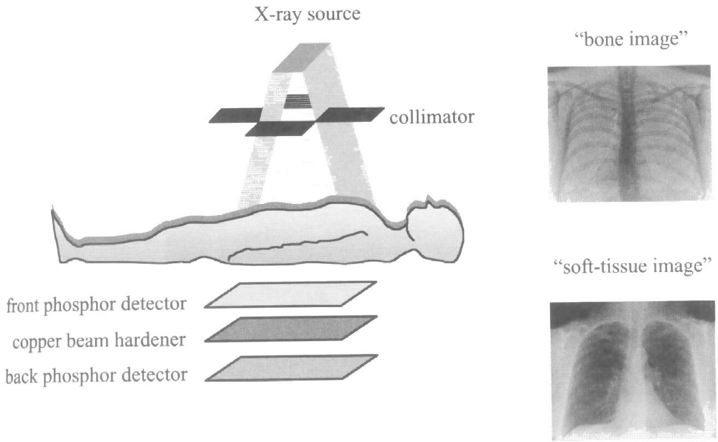


- Now a FPD/CCD instead of the fluorescent screen.

Fluoroscopy example

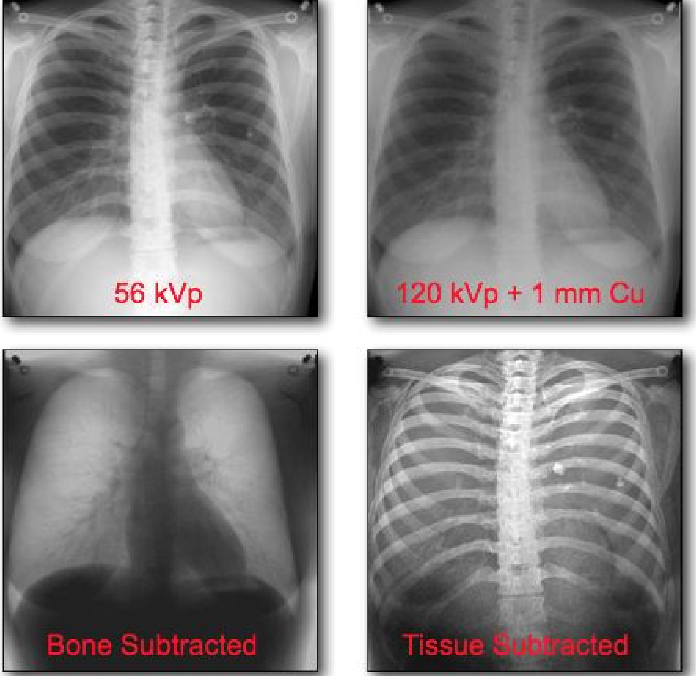


Dual-Energy Imaging

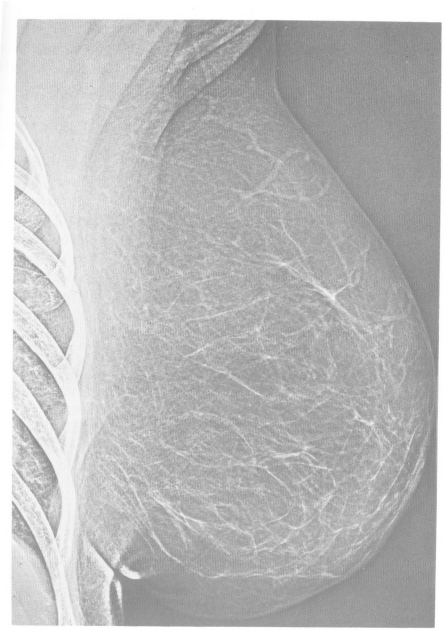


- Two exposures
- Two detectors
- Beam hardening

Dual-energy example



Mamography



X-ray Advantages / disadvantages

- Advantages
  - Widely used and available
  - Experts available
  - High-spatial resolution
  - Excellent imaging of hard tissues (bones)
- Disadvantages
  - Radiation exposure
  - Difficulty in imaging soft-tissues
  - 2D projection, hidden parts

New trends

- CCD/Medipix/Timepix sensors replace film
- higher sensitivity, faster exposure, lower dose
- dynamic imaging
- CT