

X-Rays

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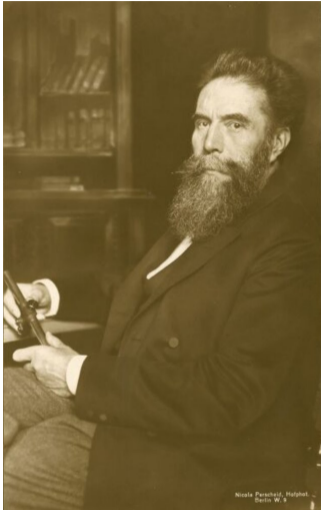
based on lectures 2005-2022 by Jan Kybic,
Department of Cybernetics, FEE CTU

2023

Overview

- ▶ 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 matter
 - ▶ 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



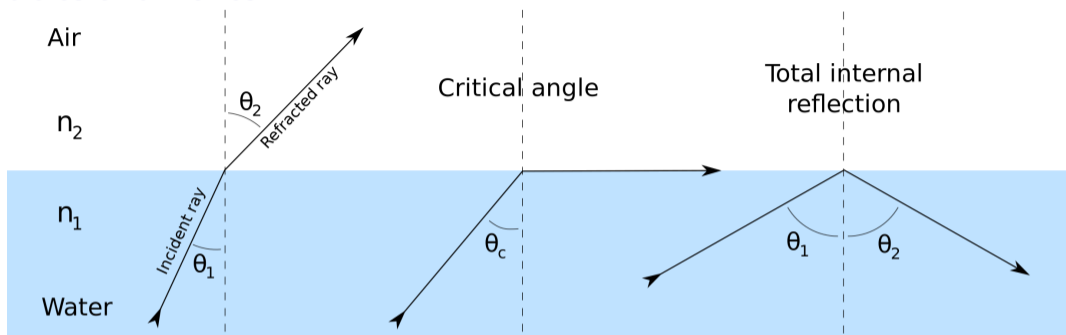
modern hand

Electromagnetic spectrum

Electromagnetic wave spectrum

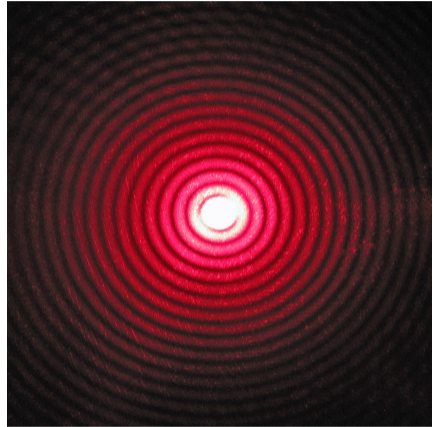
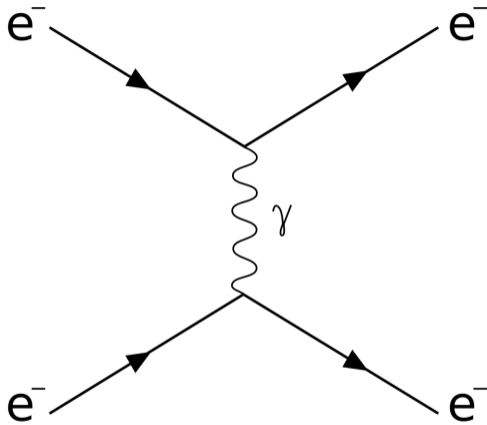
Energy (eV)	Frequency (Hz)		Wavelength (m)
4×10^{-11}	10^4	AM radio waves	10^4
4×10^{-10}	10^5		10^3
4×10^{-9}	10^6		10^2
4×10^{-8}	10^7	Short radio waves FM radio waves and TV	10^1
4×10^{-7}	10^8	Microwaves and radar	10^0
4×10^{-6}	10^9		10^{-1}
4×10^{-5}	10^{10}		10^{-2}
4×10^{-4}	10^{11}	Infrared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

Particles and waves



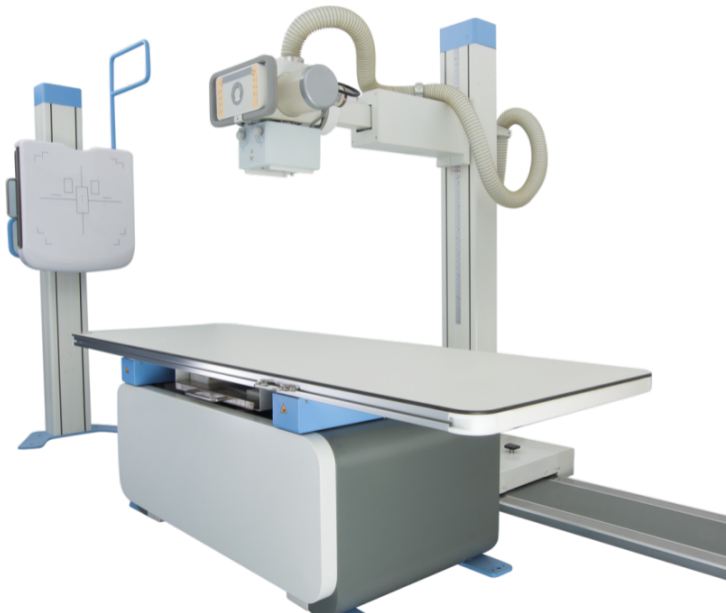
- ▶ refraction, reflection
- ▶ photons with energy $E = hf$, $h \approx 6.6 \cdot 10^{-34} \text{ J} \cdot \text{s} \approx 4.1 \cdot 10^{-15} \text{ eV} \cdot \text{s}$
 $1 \text{ eV} \approx 1.6 \cdot 10^{-19} \text{ J}$
 $c = f\lambda \approx 3 \cdot 10^8 \text{ m/s}$ $\lambda = 1 \text{ nm} \approx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

Particles and waves (2)

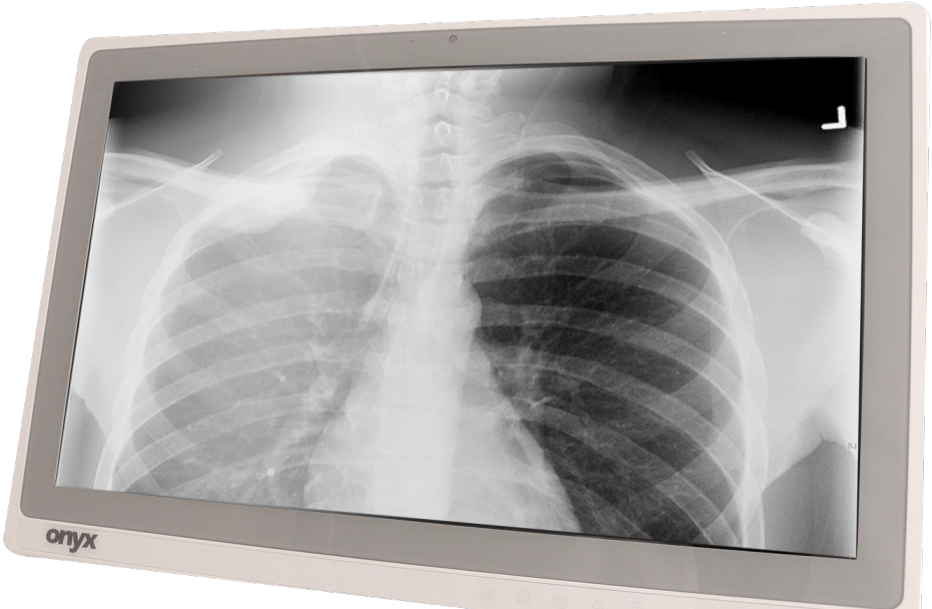


► scattering, diffraction

Chest X-rays radiography machine



Chest X-ray



X-ray scanner

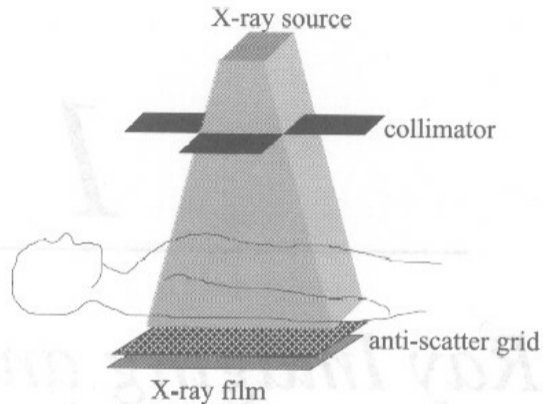


FIGURE 1.1. (Left) The basic setup for X-ray imaging. The collimator restricts the beam of X-rays so as to irradiate only the region of interest. The antiscatter grid increases tissue contrast by reducing the number of detected X-rays that have been scattered by tissue. (Right) A typical planar X-ray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

X-ray source

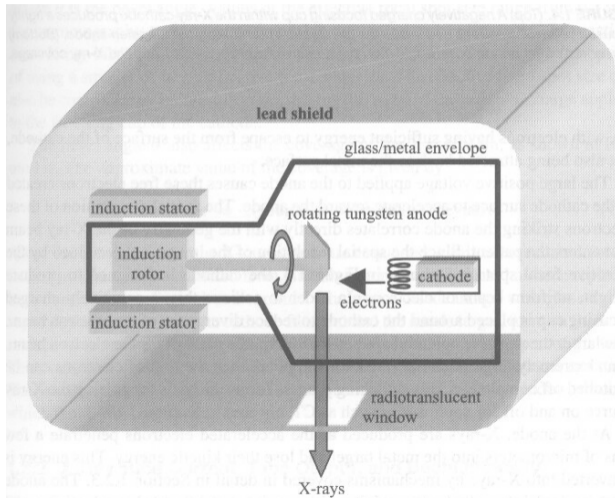
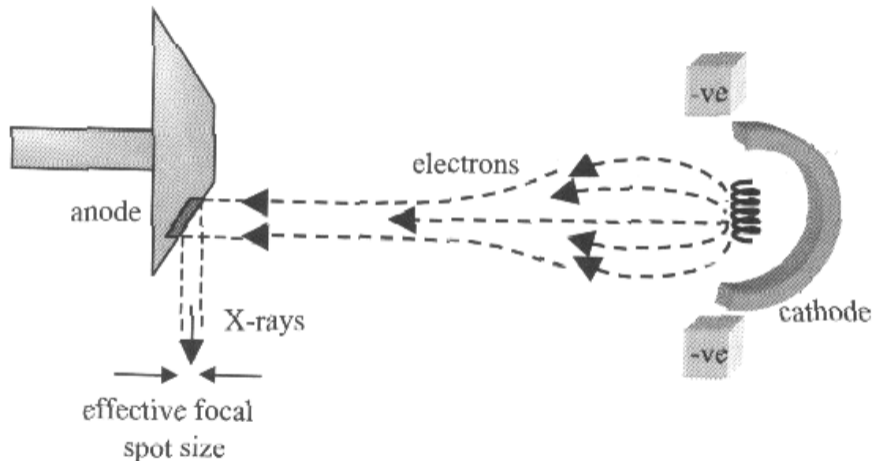


FIGURE 1.3. A schematic of an X-ray source used for clinical imaging.

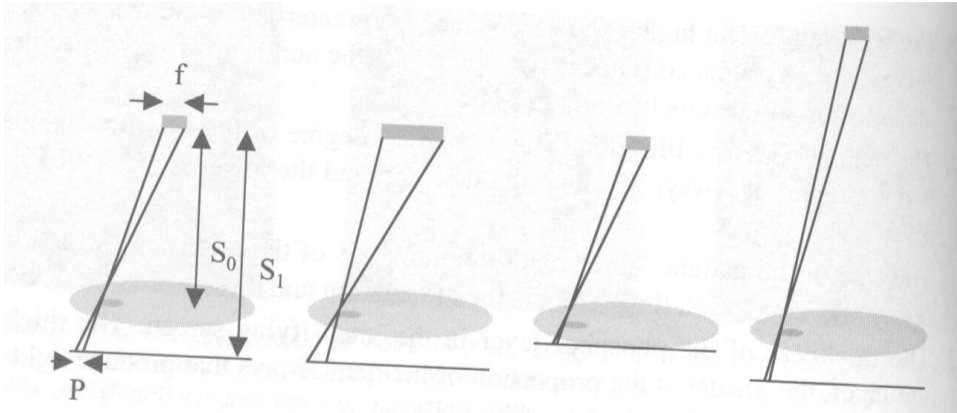
- ▶ 15 ~ 150 kV, rectified AC
- ▶ 50 ~ 400 mA anode current
- ▶ tungsten wire (200 μm)
cathode, heated to $\sim 2200^\circ\text{C}$
- ▶ anode rotates at 3000 rpm
- ▶ molybdenum or
tungsten-rhenium anode
- ▶ thermoionic emission

Beam focusing



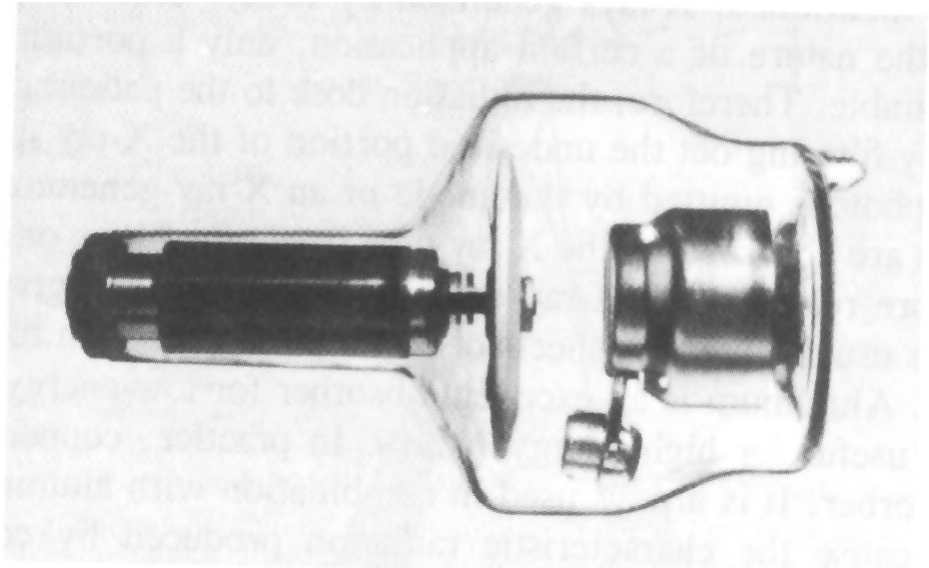
- ▶ Focal spot size 0.3 mm ~ 1.2 mm

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



- ▶ geometric unsharpness
- ▶ small focal spot
- ▶ large distance

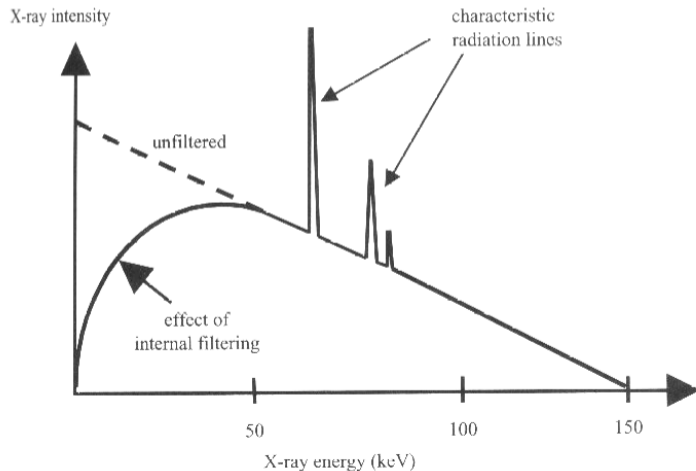
X-ray tube



X-ray parameters

Intensity: $[W/m^2]: \propto U^2 I$

Spectrum: (150 kV)

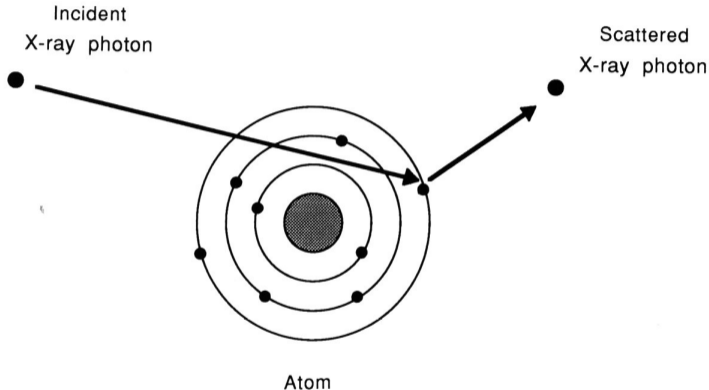


- ▶ Bremsstrahlung
- ▶ Characteristic radiation
- ▶ Filter low-energy rays that would not penetrate the patient — Al sheets. (skin dose reduced 80×)

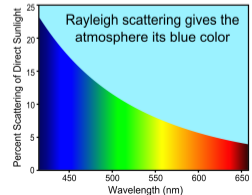
Interaction between X-rays and matter

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

Coherent (Rayleigh) scattering

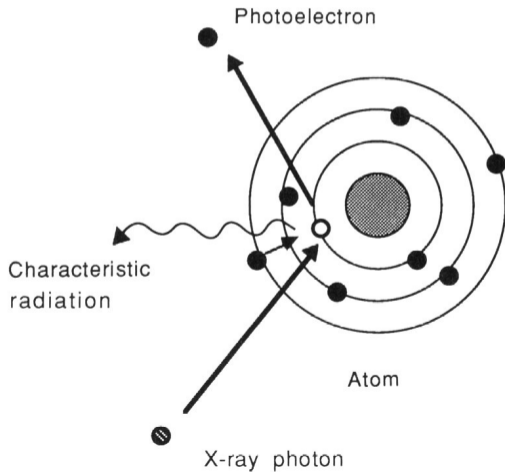


- ▶ Photon \rightarrow photon, almost same frequency
- ▶ Low-energy radiation
- ▶ Probability $\propto Z_{\text{eff}}^{8/3}$
 - ▶ Z_{eff} - effective atomic number
 - ▶ muscle $Z_{\text{eff}} \approx 7.4$, bone $Z_{\text{eff}} \approx 20$
- ▶ About 5 ~ 10 % of tissue interactions



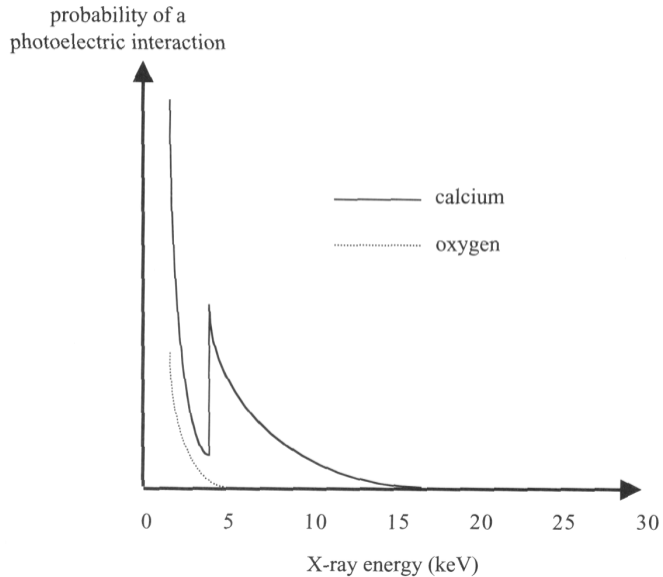
Photoelectric effect

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

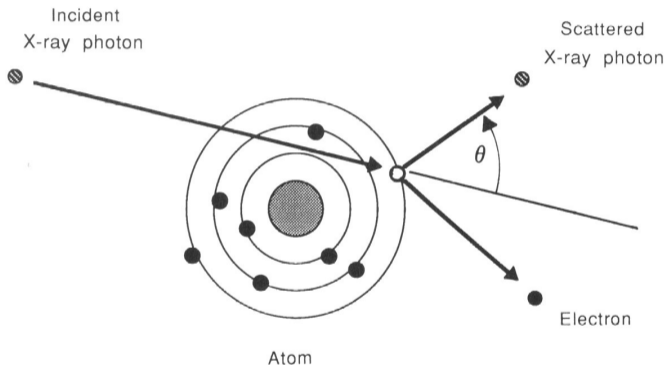


- ▶ High-energy radiation
- ▶ Photon \rightarrow characteristic radiation, photo-electron / Auger electron, positive ion
- ▶ \rightarrow ionization
- ▶ Desirable, X-ray photon completely absorbed

Photoelectric interaction wrt E



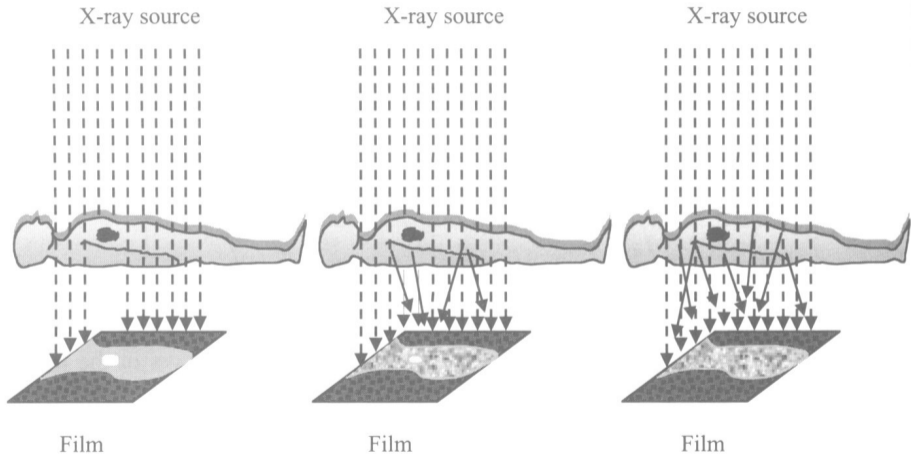
Compton scattering



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

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

Effects of Compton scattering



Attenuation

$$dI = -\mu I dx \quad \mu = n\sigma$$

$$I_x = I_0 e^{-\mu x}$$

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

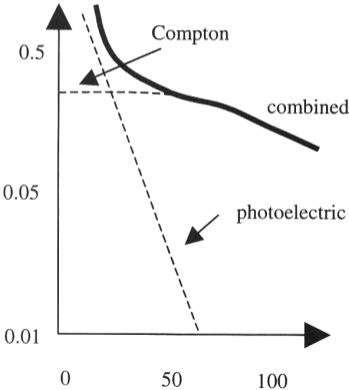
Mass attenuation coefficient μ/ρ

Attenuation decreases with energy, $\mu \propto E^{-3}$

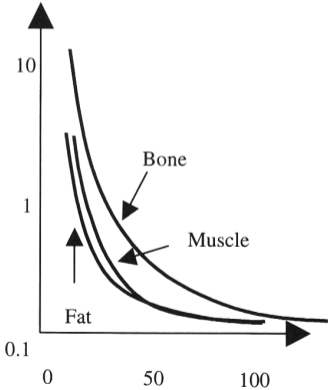
Attenuation factors wrt E

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

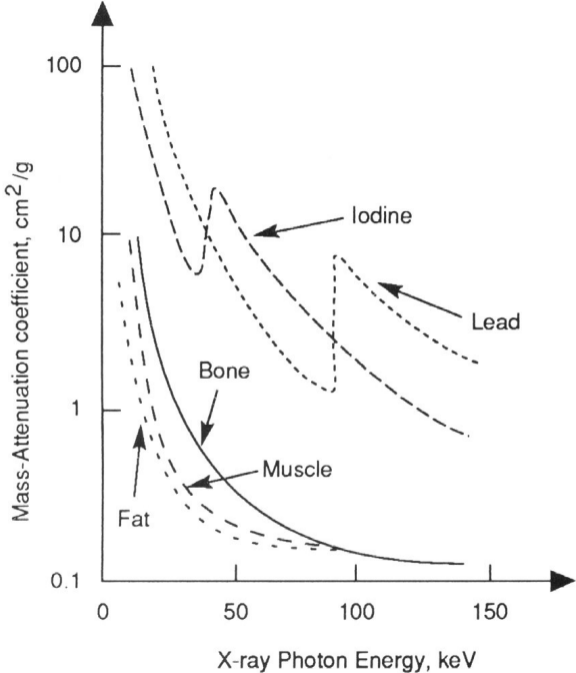
Linear attenuation coefficient
(cm^{-1})



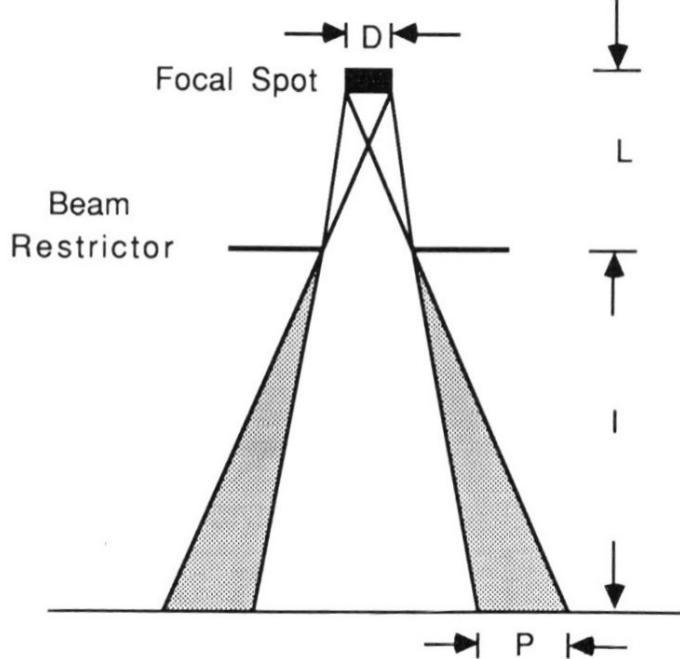
Mass attenuation coefficient
(cm^2g^{-1})



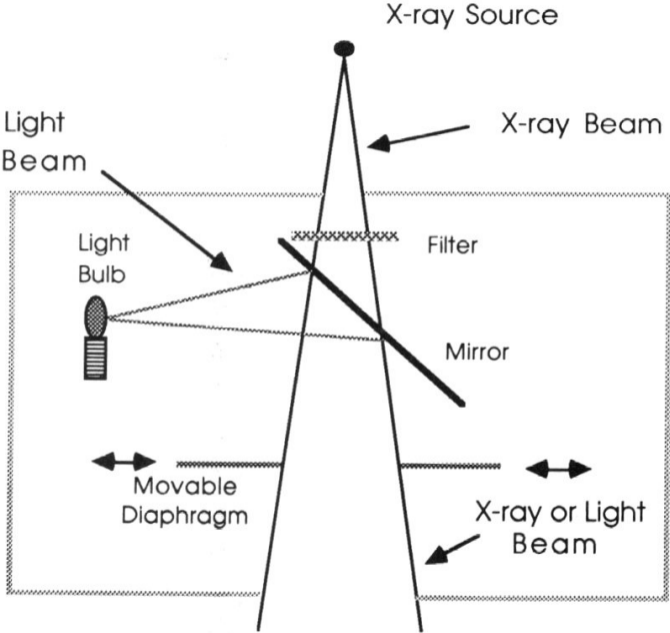
Attenuation wrt E (2)



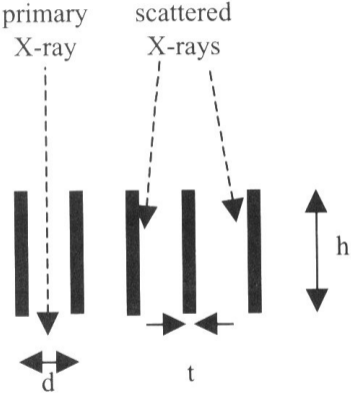
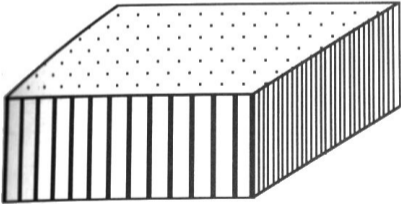
Beam restrictor /
Collimator



Beam restrictor / Collimator (2)

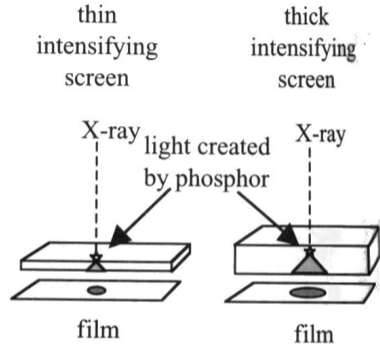
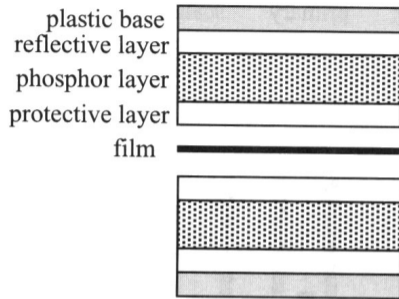


Antiscatter grid



Bucky factor = efficiency

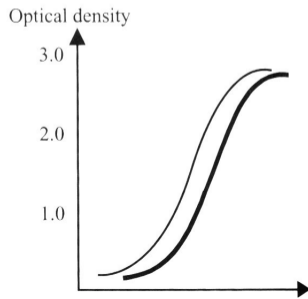
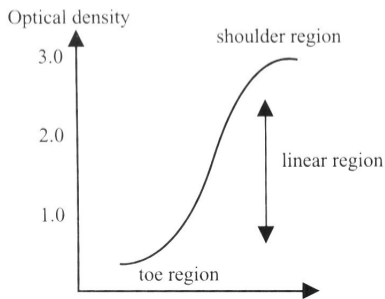
Intensifier screen



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

Film

- ▶ monochromatic (sensitive to blue), orthochromatic (sens. to green)
- ▶ double emulsion ($10\ \mu\text{m}$), 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 \rightarrow 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)
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 - ▶ thin-film transistor (TFT) array
 - ▶ CsI scintillator → photo-diode/transistor
 - ▶ 41×41 cm, 2048×2048 pixels
 - ▶ better dynamic range, quantum efficiency, and latitude wrt film

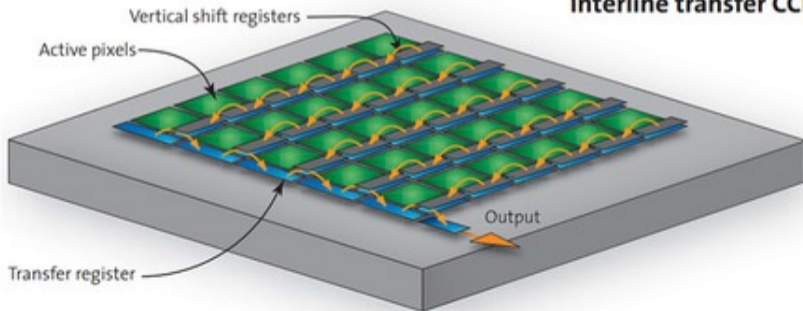
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- ▶ Charge Coupled Device (CCD), Willard S. Boyle and George E. Smith, Nobel Prize 2009 “for the invention of an imaging semiconductor circuit – the CCD sensor”
 - ▶ Phosphor screen, fiber-optic cables, CCD sensor
 - ▶ good sensitivity, low noise
 - ▶ 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

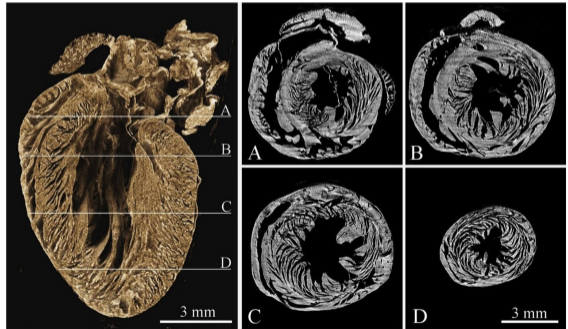
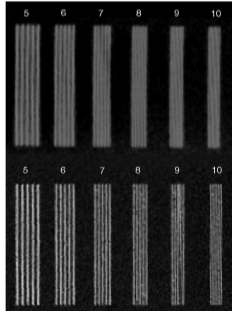


Interline transfer CCD

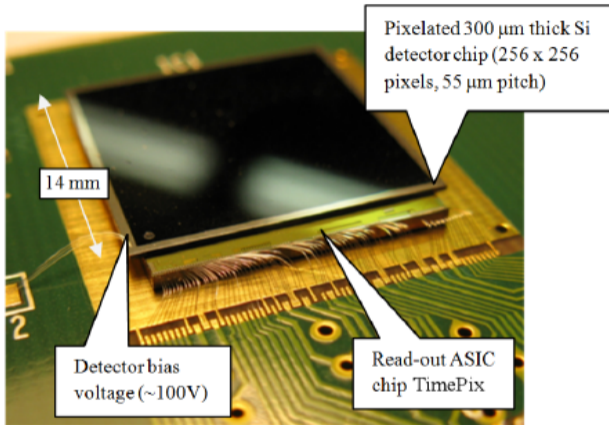
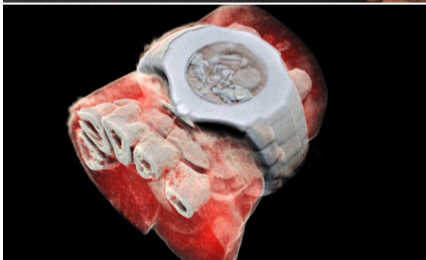


Medipix/Timepix detectors Radiation Measurements, <https://doi.org/10.1016/j.radmeas.2019.04.007>

- ▶ Medipix/Timepix detectors offer a very high spatial resolution in comparison to other detector types.
- ▶ Timepix/Timepix3 detector provide spectroscopic energy information.
- ▶ Medipix3RX has an implemented algorithm for charge sharing correction.
- ▶ Medipix and Timepix detectors allow for totally new methods in medical X-ray investigations.

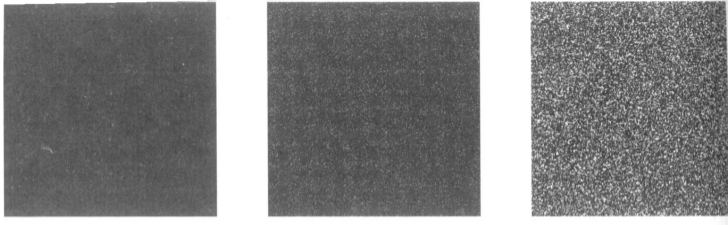


Medipix/Timepix detectors (2)



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
- ▶ $\mu = \lambda, \sigma^2 = \lambda$
- ▶ $\text{SNR} \propto \sqrt{\lambda}$, λ — intensity/photons per area/pixel
- ▶ exposure time and current, $\text{SNR} \propto \sqrt{TI}$
- ▶ higher U \rightarrow more high-energy rays \rightarrow more incident photons \rightarrow better SNR
- ▶ X-ray filtering \rightarrow smaller SNR
- ▶ patient size, antiscatter grid, intensifying screen, film

X-ray image characteristics

- ▶ **Signal-to-noise ratio (SNR)**

- ▶ **Spatial resolution**

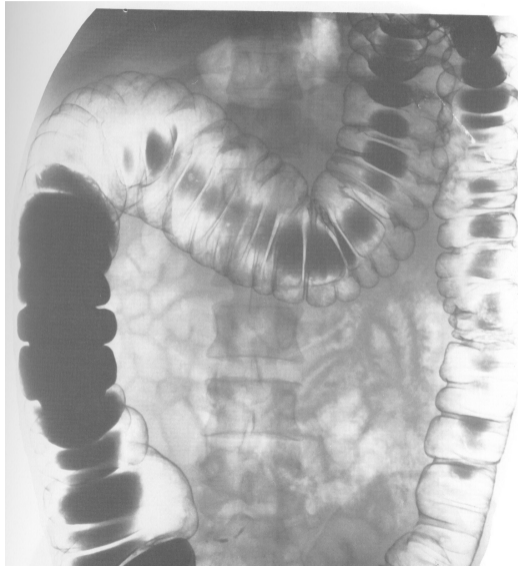
- ▶ point spread function (PSF), line spread function (LSF), edge spread function (ESF), modulation transfer function (MTF)
- ▶ thickness of the intensifier screen
- ▶ speed of the X-ray film
- ▶ geometric unsharpness
- ▶ magnification factor (patient → film). Place patient as close as possible.

X-ray image characteristics

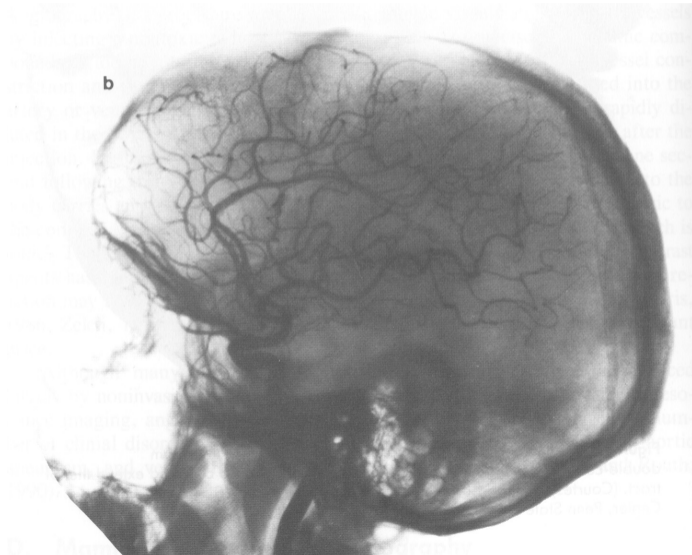
- ▶ **Signal-to-noise ratio (SNR)**
- ▶ **Spatial resolution**
- ▶ **Contrast-to-noise ratio**
 - ▶ $\text{CNR} = \frac{|S_A - S_B|}{\sigma_N} = |\text{SNR}_A - \text{SNR}_B|$

X-ray contrast agents

- ▶ barium sulfate, gastrointestinal tract

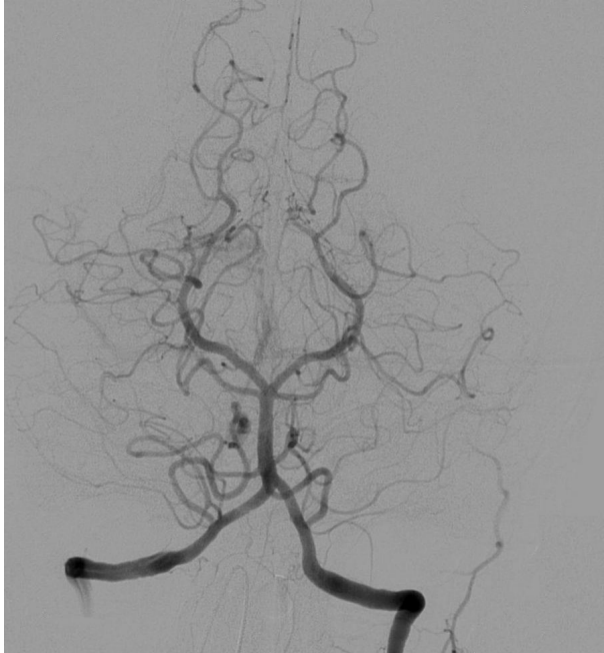


X-ray angiography (visualize the inside of blood vessels and organs of the body)

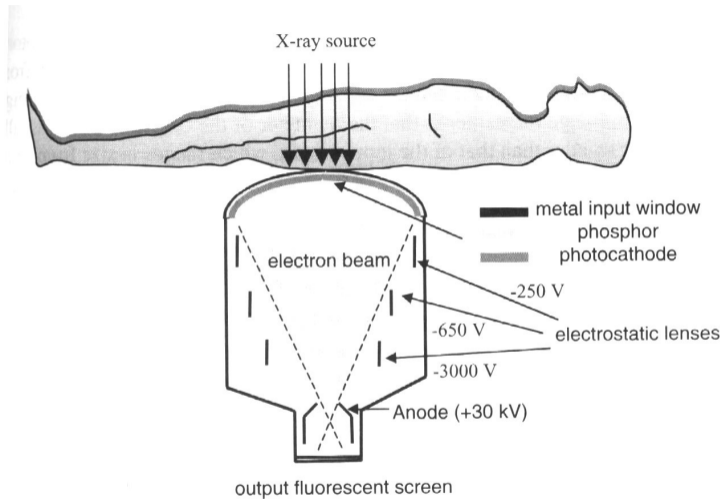


- ▶ Stenosis, clotting of arteries
- ▶ Iodine-based contrast agent (danger of kidney failure)
- ▶ Time series
- ▶ Excellent resolution ($100\ \mu\text{m}$)
- ▶ Digital subtraction angiography (DSA)

Digital
Subtraction
Angiography
(DSA)
example

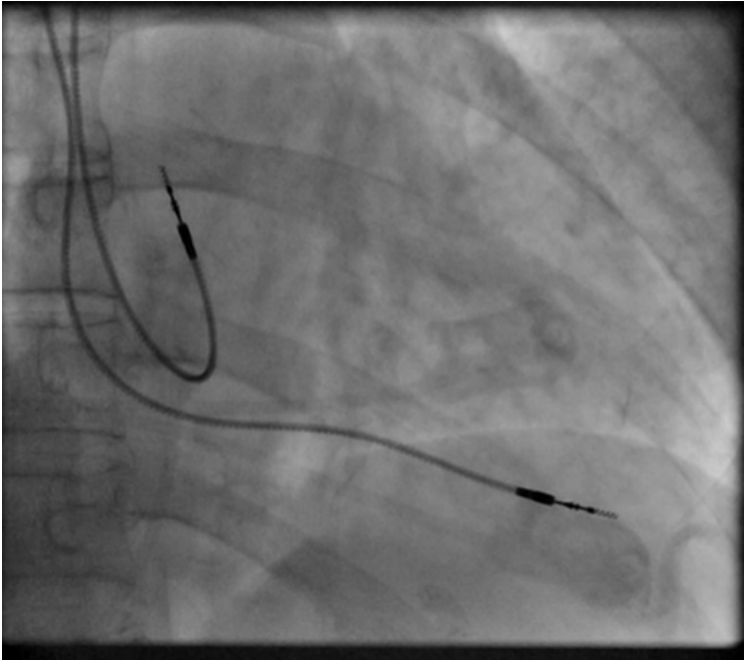


Fluoroscopy / Intra-operative imaging

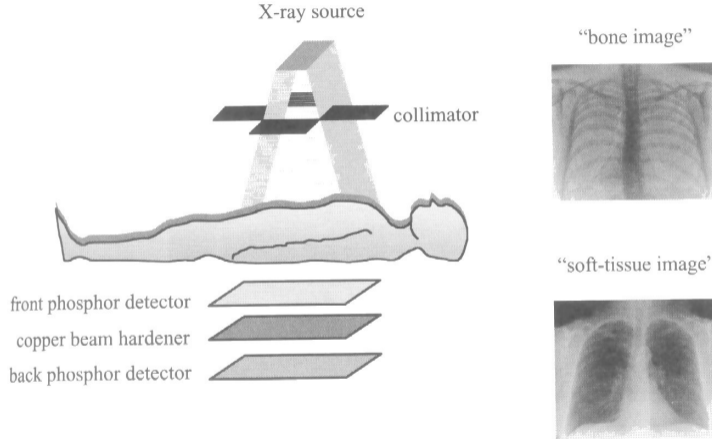


- ▶ Now a FPD/CCD instead of the fluorescent screen.

Fluoroscopy
example

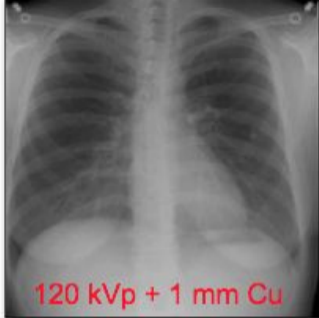


Dual-Energy Imaging

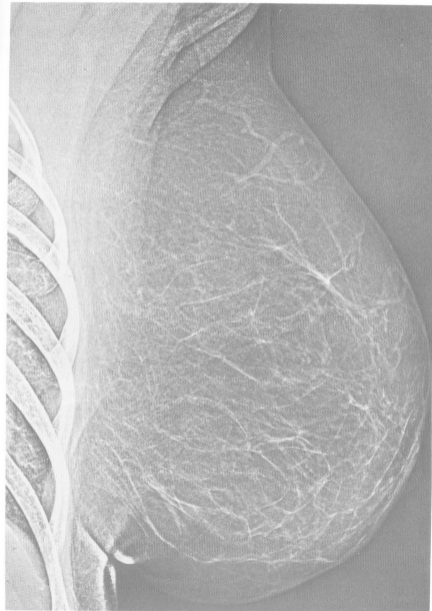


- ▶ Two exposures
- ▶ Two detectors
- ▶ Beam hardening

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