X-Rays

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Overview

- Fundamentals of X-rays
- Generation of X-rays
- Detection of X-rays
- Imaging and diagnostic methods

Invention

1895, W. Röntgen

B. Röntgen hand

modern hand

Electromagnetic spectrum

Electromagnetic wave spectrum

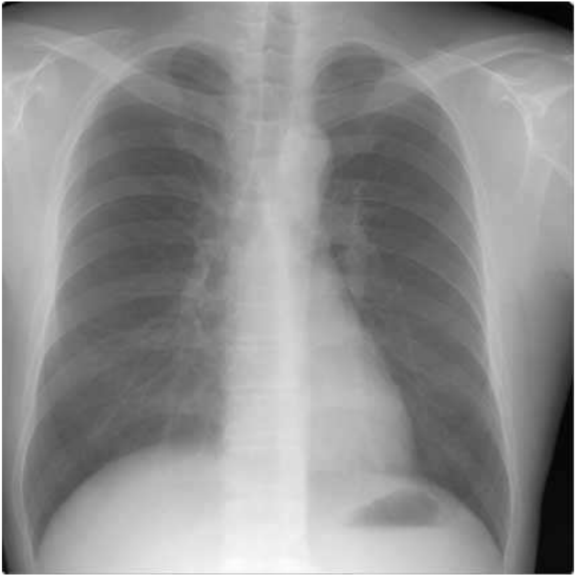
Energy (eV)	Frequency (Hz)		Wavelength (m)
4×10^{-11}	10^4		10^4
4×10^{-10}	10^5	AM radio waves	10^3
4×10^{-9}	10^6		10^2
4×10^{-8}	10^7	Short radio waves	10^1
		FM radio waves and TV	
4×10^{-7}	10^8		10^0
4×10^{-6}	10^9		10^{-1}
4×10^{-5}	10^{10}	Microwaves and radar	10^{-2}
4×10^{-4}	10^{11}		10^{-3}
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

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

Chest X-rays radiography machine

Chest X-ray



X-ray scanner

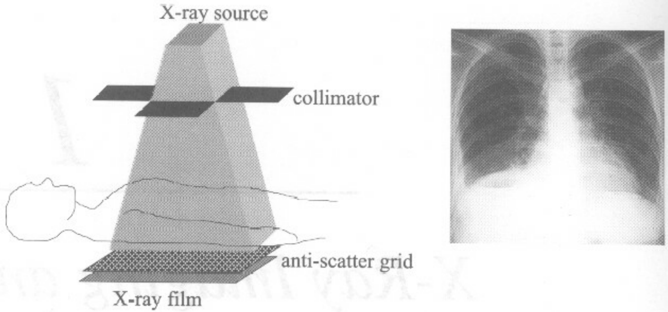


FIGURE 1.1. *(Left) The basic setup for X-ray imaging. The collimator restricts the beam of X-rays so as to irradiate only the region of interest. The antiscatter grid increases tissue contrast by reducing the number of detected X-rays that have been scattered by tissue. (Right) A typical planar X-ray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

X-ray source

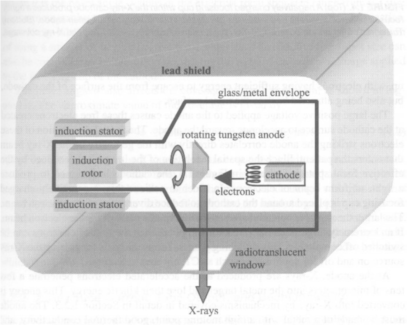
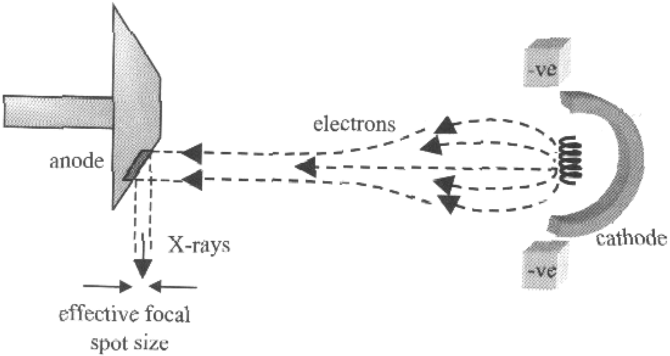


FIGURE 1.3. A schematic of an X-ray source used for clinical imaging.

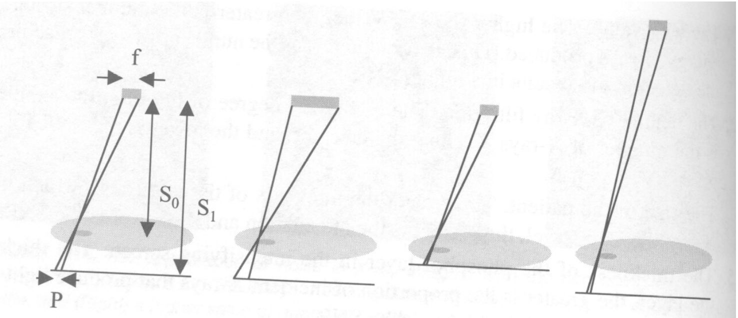
- $15 \sim 150\,\mathrm{kV}$, rectified AC
- $50 \sim 400\,\mathrm{mA}$ anode current
- tungsten wire ($200\,\mu\mathrm{m}$) cathode, heated to $\sim 2200^\circ\mathrm{C}$
- anode rotates at 3000 rpm
- molybdenum or thungsten-rhenium anode
- thermoionic emission

Beam focusing



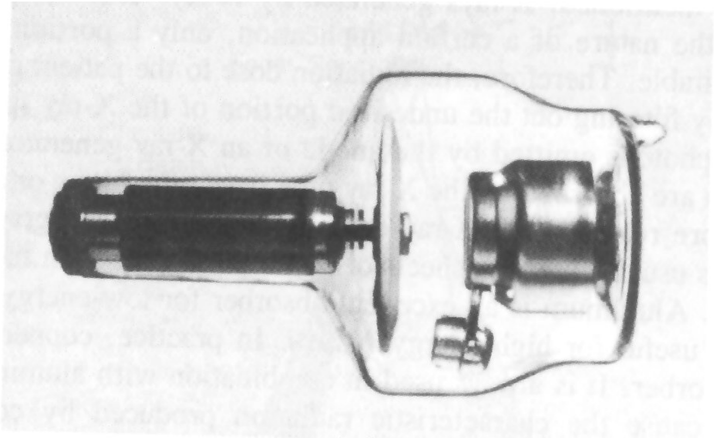
- Focal spot size $0.3\,\text{mm} \sim 1.2\,\text{mm}$

Penumbra



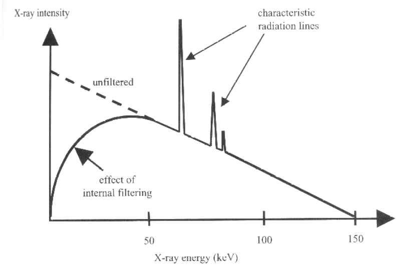
- geometric unsharpness
- small focal spot
- large distance

X-ray tube



X-ray parameters

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

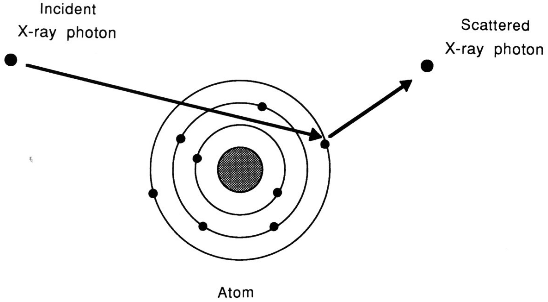


- Bremsstrahlung
- Characteristic radiation
- Filter low-energy rays that would not penetrate the patient — *Al* sheets. (skin dose reduced $80\times$)

Interaction between X-rays and matter

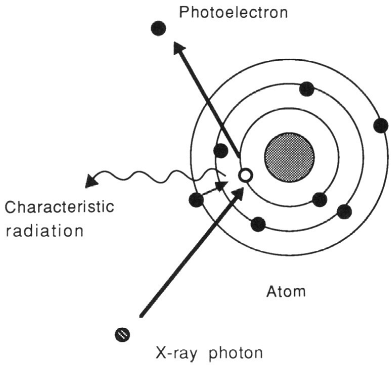
- Coherent scattering
- Photoelectric effect
- Compton scattering
- *(Pair production)*
- *(Photodisintegration)*

Coherent (Rayleigh) scattering



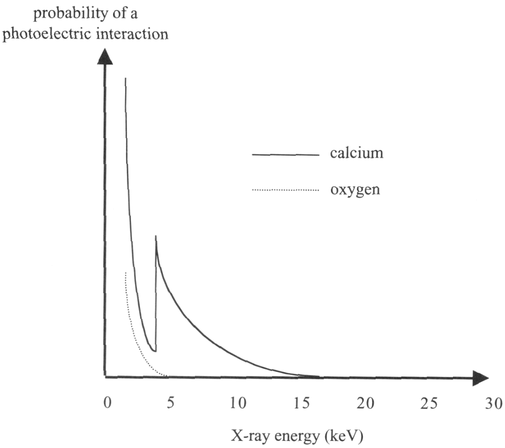
- Photon $\longrightarrow$ photon
- Low-energy radiation
- Probability $\propto Z_{\text{eff}}^{8/3}/E^2$.
  - Z_{eff} - effective atomic number
  - muscle $Z_{\text{eff}} \approx 7.4$, bone $Z_{\text{eff}} \approx 20$
- About $5 \sim 10\,\%$ of tissue interactions

Photoelectric effect



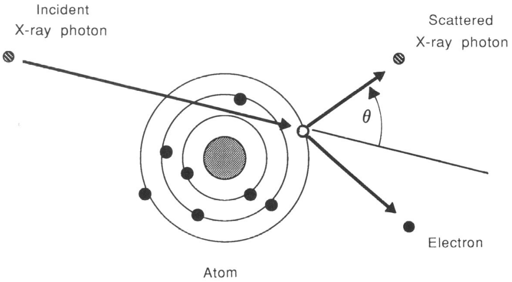
- High-energy radiation
- Photon $\longrightarrow$ characteristic radiation, photo-electron / Auger electron, positive ion
- $\longrightarrow$ ionization
- Desirable, X-ray photon completely absorbed

Photoelectric interaction wrt E



- K-edge
- Probability $\propto Z_{\mathrm{eff}}^3 / E^3$ (above K-edge)
- Excellent contrast bone/tissue at low E

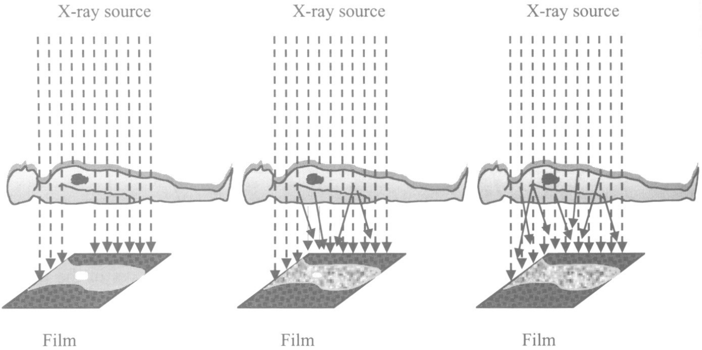
Compton scattering



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

- 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 $\log 2/\mu \approx 0.693/\mu$

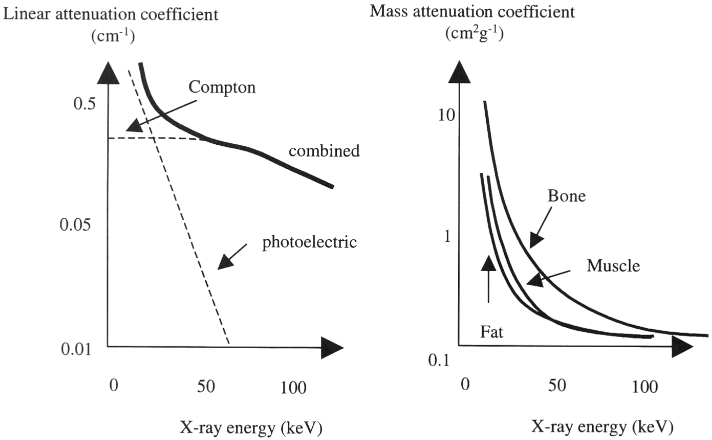
TABLE 1.2. The Half-Value Layer (HVL) for Muscle and Bone as a Function of the Energy of the Incident X-Rays

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

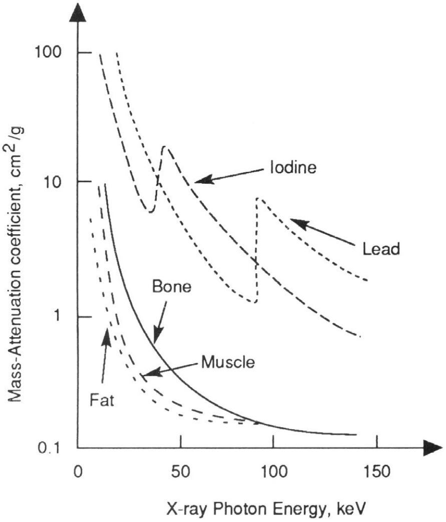
Mass attenuation coefficient μ/ρ

Attenuation factors wrt E

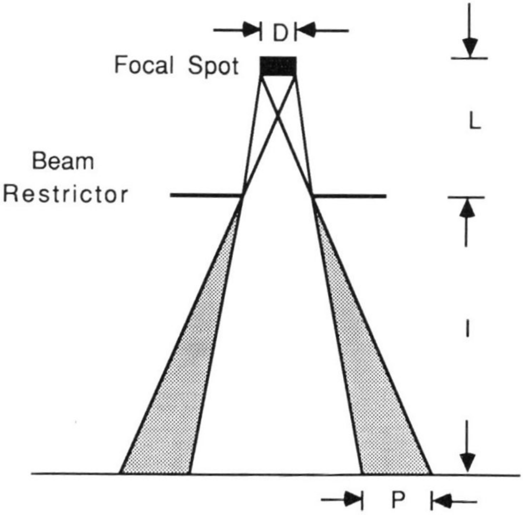
$$\mu = \mu_{\text{photoel}} + \mu_{\text{Compton}} + \mu_{\text{coherent}}$$



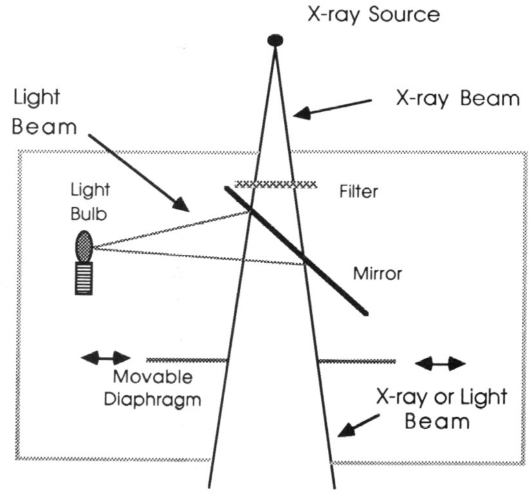
Attenuation wrt E (2)



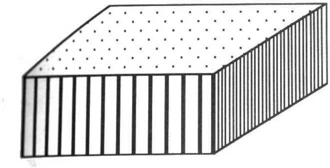
Beam restrictor / Collimator

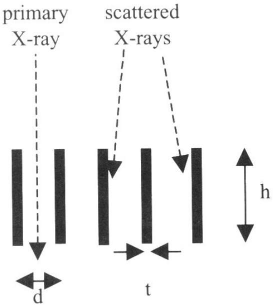


Beam restrictor / Collimator (2)



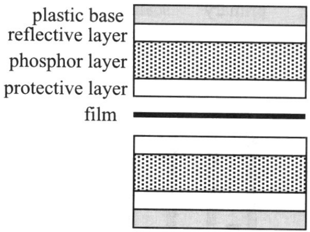
Antiscatter grid

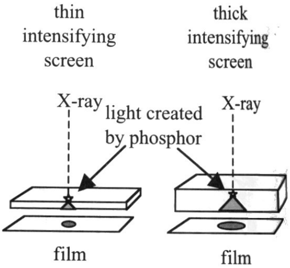




Bucky factor = efficiency

Intensifier screen

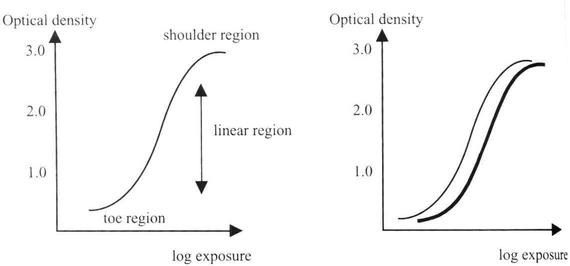




- 50× sensitivity increase
- thickness; trade-off resolution/sensitivity
- Gd — green, La – blue
- efficiency 20 %

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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  - thin-film transistor (TFT) array
  - *CsI* scintillator $\longrightarrow$ photo-diode/transistor
  - 41×41 cm, 2048×2048 pixels
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  - $41 \times 41\,\text{cm}$, $2048 \times 2048\,\text{pixels}$
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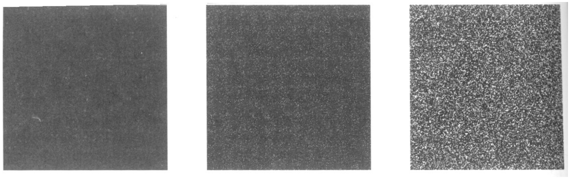
- Charge coupled device (CCD)
  - Phosphor screen, fiber-optic cables, CCD sensor
  - good sensitivity, low noise

X-ray image characteristics



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

X-ray image characteristics

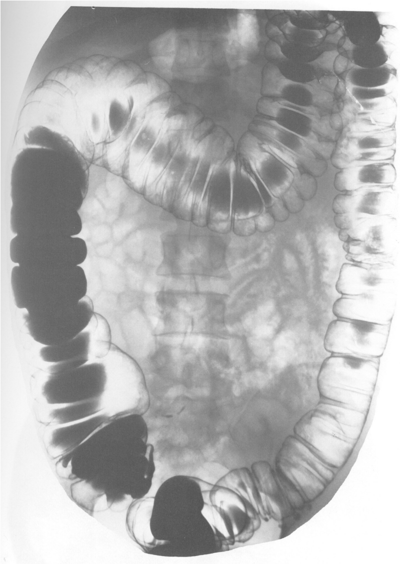
- **Signal-to-noise ratio (SNR)**
- **Spatial resolution**
  - point spread function (PSF), line spread function (LSF), edge spread function (ESF), modulation transfer function (MTF)
  - thickness of the intensifier screen
  - speed of the X-ray film
  - geometric unsharpness
  - magnification factor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

X-ray image characteristics

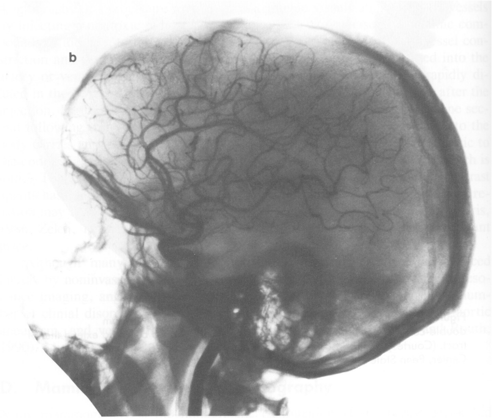
- **Signal-to-noise ratio (SNR)**
- **Spatial resolution**
- **Contrast-to-noise ratio**
  - $\text{CNR} = \frac{|S_A - S_B|}{\sigma_N} = |\text{SNR}_A - \text{SNR}_B|$

X-ray contrast agents

- barium sulfate, gastrointestinal tract



X-ray angiography

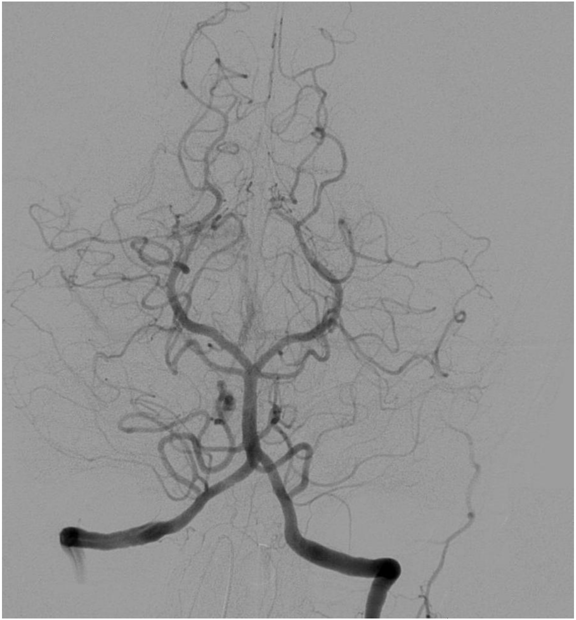


- Stenosis, clotting of arteries
- Iodine-based contrast agent (danger of kidney failure)
- Time series

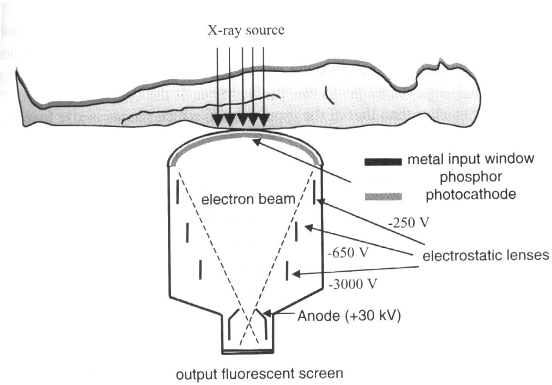
X-ray angiography

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

DSA example

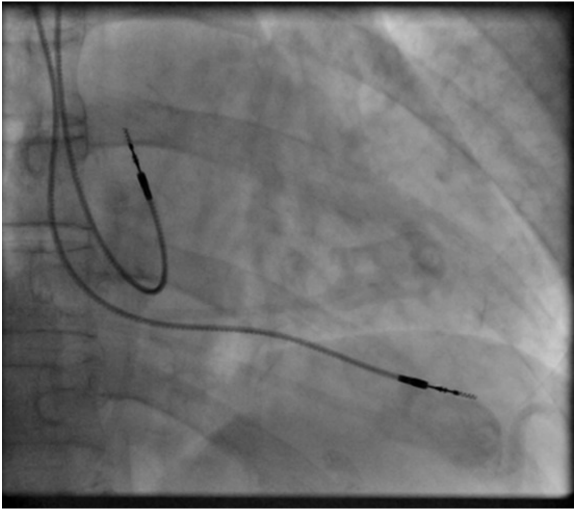


Fluoroscopy / Intra-operative imaging

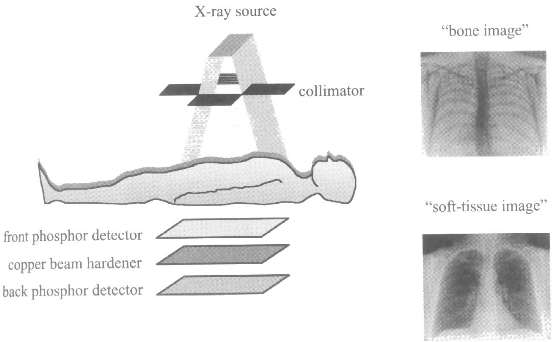


- Now a FPD/CCD instead of the fluorescent screen.

Fluoroscopy example

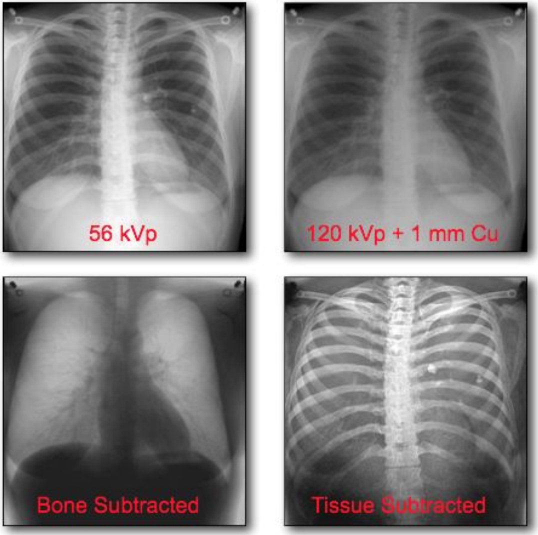


Dual-Energy Imaging



- Two exposures
- Two detectors
- Beam hardening

Dual-energy example



Mamography

- low U ($25 \sim 30\,\mathrm{kV}$), filter high-energy rays
- digital mamography, CCD sensor (1024×1024 pixels)

X-ray Advantages / disadvantages

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

New trends

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