Bioengineering 508: Physical Aspects of Medical Imaging

http://courses.washington.edu/bioen508/

For questions, remarks, discussions, errors in the book:
Class Discussion Board (link from class website)
Monitored by instructors frequently

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Today:

X-Ray Radiography

- Physics of X-rays
- Interactions of Radiation with Matter
- Projection Radiography

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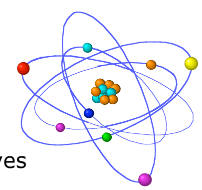
Some Elementary Particles

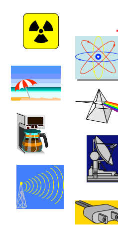
Electrons
large sparse outer cloud of atoms, ordered into shells
→ Chemistry, Table of the elements
Charge -1
Small mass



Photons
Light particles or electromagnetic waves
No Charge
Massless
Move at the speed of light

X-rays = Photons

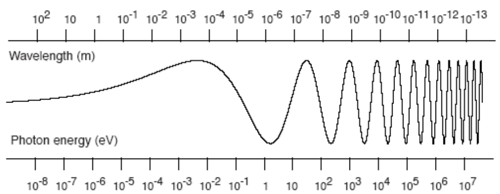
- Electromagnetic radiation of rather high energy



Type of EM radiation	Wavelength (cm)	Energy (eV)
gamma rays	10^{-14} - 10^{-8}	10^{4} - 10^{8}
x rays	10^{-9} - 10^{-7}	10 - 10^{5}
UV radiation	$5x10^{-7}$ - $4x10^{-5}$	3 - 25
visible light	$4x10^{-5}$ - $7x10^{-5}$	2 - 3
infra-red (heat)	10^{-4} - 0.1	0.001 - 2
microwaves	0.1 - 1	10^{-4} - 10^{-3}
radio waves	1 - 10^{5}	10^{-9} - 10^{-4}
AC (60 Hz) current	$5x10^{8}$	$4x10^{-14}$

X-ray energy relationships

- Energy E and frequency ν proportional: $E = h \cdot \nu$
- Energy E and wavelength λ related inversely: $E = h \cdot c / \lambda$
- frequency and wavelength related through speed of light: $\nu = c / \lambda$



Discovery of X-rays

- discovered in 1895 by Wilhelm Roentgen in cathode tubes (first Nobel Prize in Physics in 1901)
- *attenuated by various materials differently*

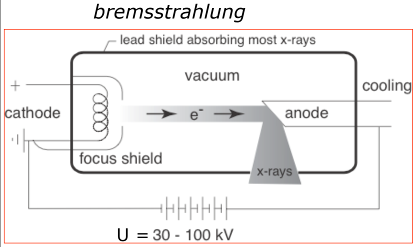
Revolutionized Medicine:

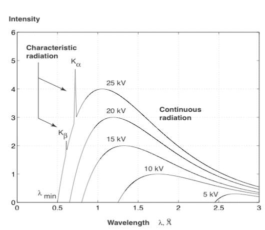
- first Medical Imaging
- and beginning of scientific medicine

Radiograph of Frau Roentgen's hand with wedding ring "floating" around bone - From Roentgen's announcement letter

X-ray Production

- In evacuated tube, heated cathode current releases electrons
- Electrons are accelerated to anode by voltage *U* (*Energy E = qU*)
- In field of anode atoms, electrons release their energy as *bremsstrahlung*



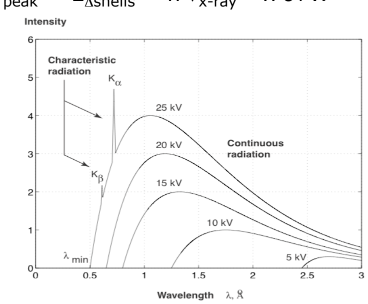


- Yields a continuous X-ray spectrum
- But what are the spikes on the highest energy spectrum?

Closer Look at X-ray Spectrum

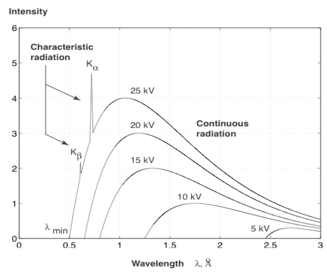
- *Characteristic radiation* from knock-outs in inner electron shell and subsequent filling of the low-energy empty position. Energy emitted is characteristic of the energy levels of the anode material.

$$E_{x\text{-ray peak}} = E_{\Delta shells} = h \cdot \nu_{x\text{-ray}} = h \cdot c / \lambda \qquad \text{with } c = \lambda \cdot \nu$$



X-ray Source Parameters

- Amount of x-ray photons = Cathode current · time [mAs]
- Energy of the emitted photons controlled by voltage between anode and cathode [kV] - but a spectrum of energies produced. Often peak photon energy quoted [kVp]



Interaction of Photons with Matter

The dominant photon interaction mechanisms for γ and x-rays:

- Photoelectric absorption
  - Interaction with (initially) bound atomic electron
  - Incident photon disappears
  - Photon energy absorbed by electron, momentum by atom
  - probability increases at: low incident photon energy and high electron density in medium (mass density x Z)
- Compton scatter
  - Interaction with "free" electron (photon energy >> Binding E.)
  - Scattered photon changes direction and loses energy
- Rayleigh (coherent) scatter
  - Interaction with with entire atom or molecule - elastic scatter
  - Photon changes direction (though usually by small angle)
- Pair production
  - γ ray must have sufficient energy to create e^+ - e^- pair
  - E_γ > 1.022 MeV (> 2 m_e)

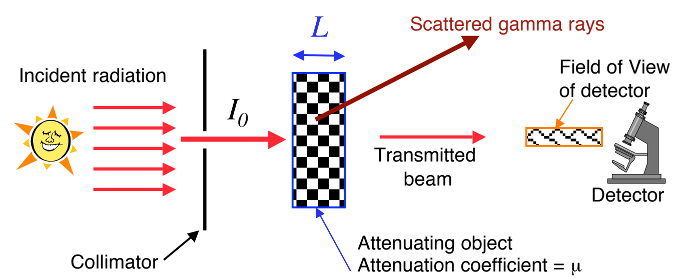
Secondary Ionization

- In Photoelectric Effect and Compton Scattering, atoms are ionized.
- In pair production, we have two charged particles produced
- These energetic charged particles moving in matter ionize more atoms producing many free electrons
- This *secondary ionization* is the basis for most detector systems.
- Ionization also leads to breaking molecular bonds - basis of most radiation biological effects.
- Dose monitoring necessary when working with radiation

Effect of interactions in matter: Attenuation

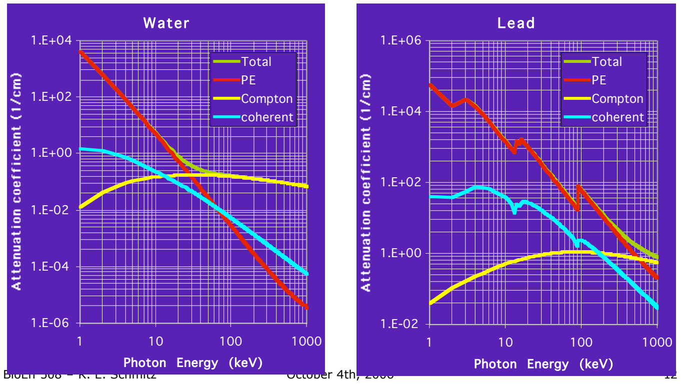
Narrow Beam Approximation

Single interaction statistical event, but overall effect governed by exponential law: $I = I_0 e^{-\mu L}$ Lambert's Law



Linear Attenuation Coefficients

- Function of photon energy and material: $\mu = \mu(E, \text{material})$
  Units: [1/cm]



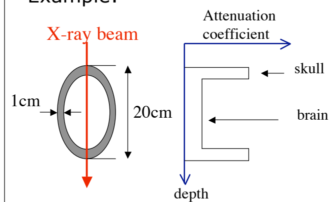
Attenuation - the fuller story

$I = I_0 e^{-\mu L}$ only valid for homogenous material (not body!) and one incoming photon energy.

For inhomogenous material: $\mu = \mu(x)$, need $\mu \cdot dx$ integrated over that material in the direction of the beam:

$$\mu \cdot L \Rightarrow \int_{x\_in}^{x\_out} \mu(x) \cdot dx \quad \Rightarrow I_{out} = I_0 \cdot \exp\left(-\int_{x\_in}^{x\_out} \mu(x) \cdot dx \right)$$

Example:



We can break this problem down into 3 homogenous regions: skull-brain-skull

$$\Rightarrow \mu \cdot dx = 2 \cdot \mu_{skull} \cdot \Delta x_{skull} + \mu_{brain} \cdot \Delta x_{brain}$$

$$I_{out} = I_0 \cdot \exp\left(-\left(2 \cdot \mu_{skull} \cdot \Delta x_{skull} + \mu_{brain} \cdot \Delta x_{brain}\right)\right)$$

Attenuation - what makes X-ray imaging possible

X-rays image radiodensity = amount of absorption in material

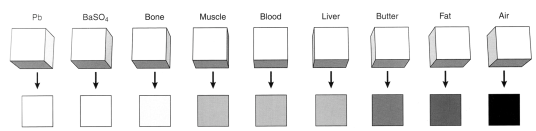
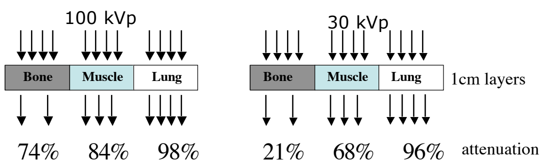


Figure 1.12. Radiodensity as a function of composition, with thickness kept constant.

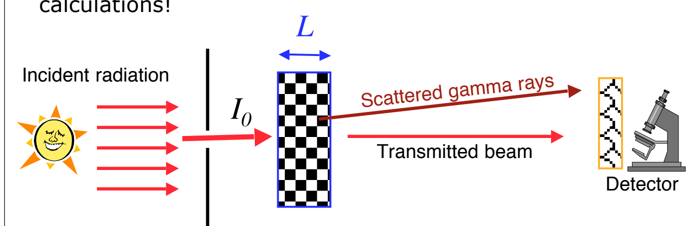
Attenuation is Energy dependent:



For thin layers, lower energies distinguish diff. material better

What happens in the real world?

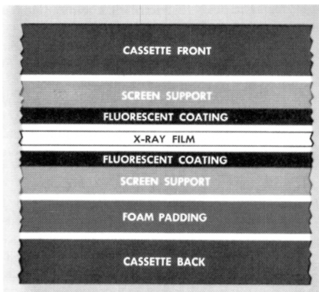
Narrow beam approximation does not apply when scatter can get measured - or absorbed in dosimetry calculations!



For calculating shielding, dosimetry, or flux to an imaging system, scattered gamma rays **must** be taken into account. Much more complicated!

X-ray detectors

1. Screen-Film detector



Film has silver halide crystals (grains) in emulsion. When exposed to enough photons, the grains turn metallic silver which darkens the film.
Very low quantum efficiency, QE ~2%

Fluorescent *screens* (phosphor) on both sides of the film absorb X-ray photons and covert them to visible light (amplification)
⇒ Boost QE of the film from 2% to 25% but add blur.

Film is indirect detector, because need the phosphor first.

Fluorescence - glowing in visible light immediately when hit by photons
Phosphorescence - after-glow after the radiation has stopped

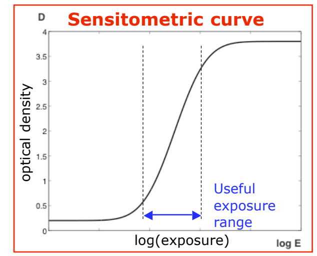
Characteristics of film

- *Graininess* (larger grains for faster film)

- *Contrast*: slope of sensitometric curve (D vs. log(E))
  with: D = optical density - darkness of film after exposure
  E = exposure, $E = I_{in\ source}$ * duration
  only useful in linear region.

- *Speed*: inverse of amount of light needed to darken film
  function of grain size and scatter

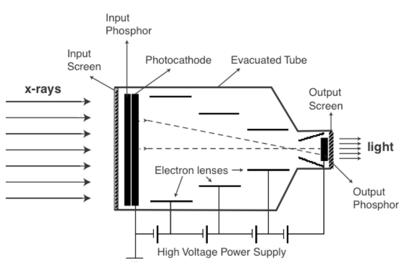
- *Resolution*
  function of grain size and scatter



X-ray detectors

2. Image intensifier, coupled to camera

X-rays converted into light at phosphor screen, then into electrons at photocathode,
Electrons accelerated and focused in tube with electromagnetic fields,
Converted back into light at output screen, coupled to camera.



Advantages:
- dynamic real-time imaging

Disadvantages:
- worse spatial resolution (camera)
- more noise (conversions)
- geometric pin cushion distortion, especially at edges

X-ray detectors for *Computed Radiography*

3. Storage phosphors

Special phosphor screen: no immediate absorption of X-ray energy in the phosphor. Stored until stimulated with laser light.

- Incident x-rays boost electrons into conduction band and trap them there (by impurities). Latent image of “stored energy” stable for long time periods.

- Extract stored information by pixelwise scanning with a laser beam which lets electrons fall back into valence band and release visible light.

- Light captured by optic array and passed to photomultiplier, converted to electrical signal.

- Signal is digitized and recorded.

- Phosphor ready for next use after strong light source irradiation

Storage Phosphors - Advantages

+ Much wider useful exposure range than film-screen (no grains must be blackened)

+ Linear exposure range, i.e. no contrast reduction in low- and high-density areas of the image.

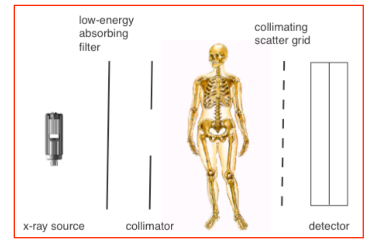
→ Very tolerant to over and underexposure.

+ Image can be post-processed (image enhancement, quantification)

+ Digital image easy to store, transport, distribute…
Immediate availability through digital image database

X-ray imaging chain

Complete radiographic imaging chain:
- X-ray tube
- Aluminum filter - absorbs low-energy photons (beam hardening)
- Collimator - limits irradiated area
- Patient - attenuates and scatters x-rays
- Collimating scatter grid
  - absorbs large-angle scatter photons
- Detector



Radiographic Image Quality

- Resolution - how many line pairs per mm can be distinguished (lp/mm)
  - quality of anode tip, good angle for good beam focus
  - thicker patients: more scatter, less resolution (use collimator grid)
  - light scattering properties of phosphor
  - film resolution, mainly determined by grain size
  - sampling size for image intensifiers / computed radiography
  - laser spot size for read-out in computed radiography

  Ideally high resolution and high speed, but interdependent
- Noise
  - Photon counting is poisson process
  - SNR ~ square root number of counts
  - faster detector or higher speed - less photons needed, lower SNR
  - minimum dose requirement
- Contrast
  - determined by film contrast or can be manipulated in digital methods
  - higher contrast - lower useful exposure range
- Artifacts
  - generally artifact-free except for pin-cushion effect and organ overlay

Finally: Images

X-rays produce transmission images: Shadowgrams
Structures visible due to different attenuation in diff. materials

See 4 primary densities: gas, fat, water(soft tissue), bone.

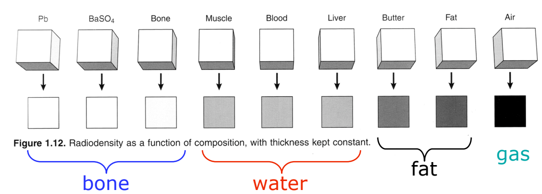
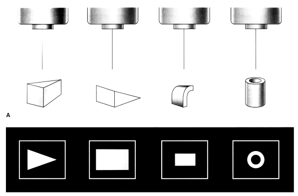


Figure 1.12. Radiodensity as a function of composition, with thickness kept constant.

(Aside: X-ray projection images should be called Radiographs)

The need for >1 Projection

2 dimensional projection of 3D object ⇒ always need at least 2 projections to identify correctly

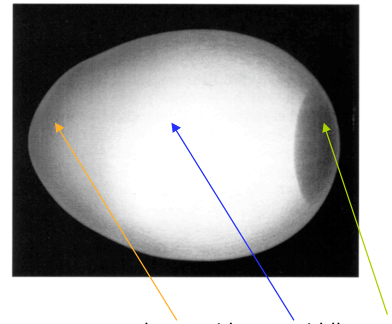


Radiographs of geometric objects.

In which ways can different objects make the same radiograph?

What is this?

What is this object and how does that explain this image?



What is the structure on the outside vs. middle, end?

Clinical Use - Advantages and Disadvantages

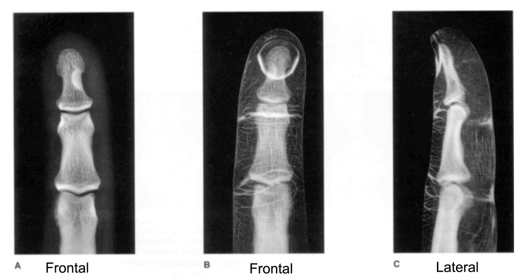
Looking at this image - what are disadvantages of X-ray imaging?

Advantages:
- Cheap
- Fast
- Available

Disadvantages:
- Overlap of structures
- Poor contrast resolution

Then what about this?

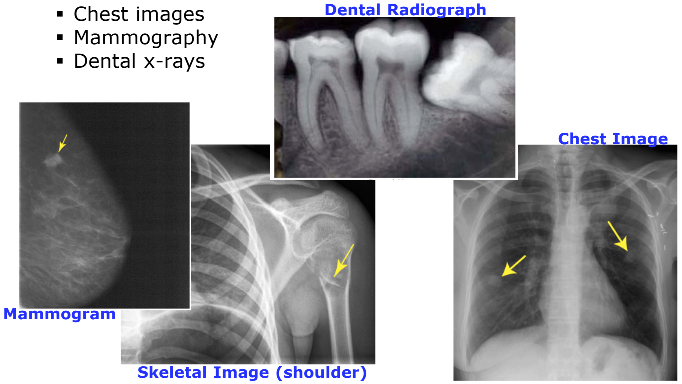
Looks like great contrast! You can see skin! Appears 3D!



Trick: cream containing a metallic salt was applied to finger!
Real radiograph of finger looks like image on left.

Clinical Use - Static images

•- film-screen combo or computed radiography
- Skeletal X-rays
- Chest images
- Mammography
- Dental x-rays



Dental Radiograph
Chest Image
Mammogram
Skeletal Image (shoulder)

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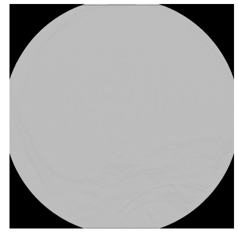
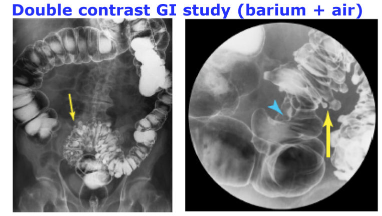
Clinical Use - Dynamic images

• *Fluoroscopy* (real time) with image intensifiers and TV screen for motion investigation or instant images:
- intraoperative fluoroscopy - image guided procedures: surgery, biopsy,
- angiography - imaging perfusion of iodinated blood in vessels
- barium fluoroscopy of the GI tract - barium as oral contrast
- urography - excretion of iodinated fluid through kidney



Cerebral angiogram



Double contrast GI study (barium + air)

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Biological Effects and Safety

X-rays passing through tissue deliver energy when attenuated

→ ionization in tissue
→ chemical changes to cells
→ biologic damage:
cell may be able to repair itself
cell can be destroyed, inable to divide,
or divide in uncontrolled ways (tumors)

Absorbed radiation dose measured in Gray (Gy) (energy/mass)
1 Gy = 1 Joule/kg
Also determined as organ-dose to a specific organ.

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Organ Effective Dose

Biological effect depends heavily on type of irradiation (dose doesn't)
→ Quality Factor for different radiations:

Equivalent Dose = dose*quality factor, biologically active dose measured in Sieverts (Sv)

Radiation	Xrays	Neutrons	α Particles
QF	1	5-20 depending on Energy	20

Risk for cancer or genetic disorders differs *for various organs*
→ Tissue weighting factors for different organs

Effective Dose = equivalent dose * weighting factor for specific organ
Also measured in Sieverts (Sv)

Tissue	Skin/Bones	Bladder	Gonads
WF	0.01	0.05	0.2

Total for all organs adds up to 1.

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Safety

Patients - Doctor's discretion of benefit vs risk
individual patient dependent (age etc)

Workers - Time
Distance
Shielding

Aim for ALARA As-Low-As-Reasonably-Achievable

Homework

1. Read chapter 5.

2. Find 2 medical images of abnormal anatomy or physiology (pathology) formed using next lecture's modality (X-ray CT).
   Place these images in a document.
   Write 1-2 brief sentences describing each image.
   Write 1-2 brief sentences describing differences between the images.