X-rays and x-ray imaging

BioE 301C

X-ray: OUTLINE

- Introduction
- Interaction of x-rays with matter
- X-ray production
- Hardware and applications
- Radiography and fluoroscopy

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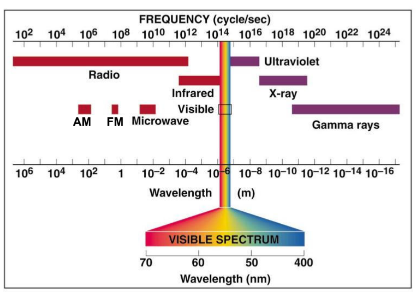
WHAT ARE X-RAYS?



Source: lepus.physics.ualr.edu/ ~tahall/EXAM2/emspec.jpg

$$E = h\nu = hc/\lambda$$

E = energy (Joules)

h = Plank's constant = 6.6×10^{-34} Joules-sec

ν = frequency (Hz = cycles/sec)

c = speed of light = 3.0×10^{8} m/s

λ = wavelength (m)

X-rays are a form of electromagnetic radiation (just like light)

- Can be considered a wave with λ = <0.05 to 10 nm
- Can be considered a particle with E = $\sim 10^{-15}$ to 10^{-14} J

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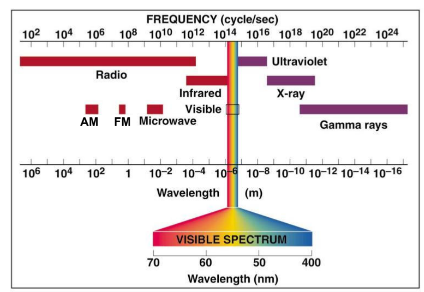
WHAT ARE X-RAYS?



Source: lepus.physics.ualr.edu/ ~tahall/EXAM2/emspec.jpg

$$E = h\nu = hc/\lambda$$

E is generally quoted in eV or keV (1 eV=energy of an electron accelerated by 1V)

Diagnostic imaging uses x-rays of 20-150 keV

E=12.4 keV corresponds to λ =1Å

At these energies, x-rays behave mostly like particles (photons)

X-rays are a form of electromagnetic radiation (just like light)

- Can be considered a wave with λ = <0.05 to 10 nm
- Can be considered a particle with E = $\sim 10^{-15}$ to 10^{-14} J

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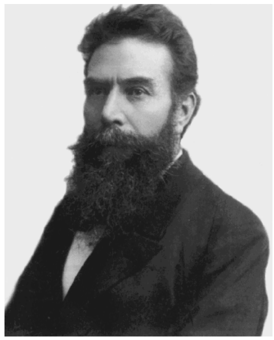
X-RAYS

discovered x-rays in 1895

1901 Nobel Prize in Physics



Wilhelm Conrad Röntgen
1845-1923

X-RAYS: key is differential transmission

Intensity is reduced as x-rays penetrate matter

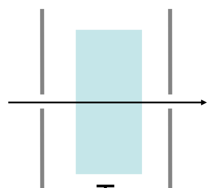
If all tissues transmitted the same fraction, x-ray images would not be interesting

Source: www.hughston.com/hha/a.cspine.htm

X-RAYS: exponential attenuation

assume all photons have the same energy (monoenergetic or monochromatic)

N_0



$N = N_0 e^{-\mu T}$

μ, linear attenuation coefficient, depends on:
- chemical composition (high Z attenuates more)
- physical density
- photon energy

X-RAYS: interaction mechanisms

$N = N_0 e^{-\mu T}$

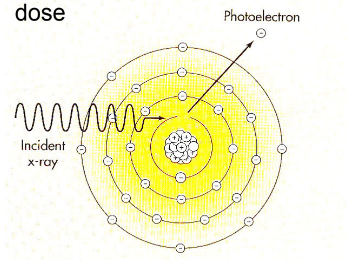
photons can:
- be absorbed (photon disappears)
- scatter (photon changes direction and possibly energy)

μ, linear attenuation coefficient, units: cm^{-1}
- probability per unit distance that photon interacts
- multiple, independent mechanisms
  - photoelectric absorption
  - compton scattering
  - coherent scattering
  - other reactions for higher energy x-rays (above 1000 keV)

$\mu = \mu_{PE} + \mu_C + \mu_{coh} + \ldots$

PHOTOELECTRIC EFFECT

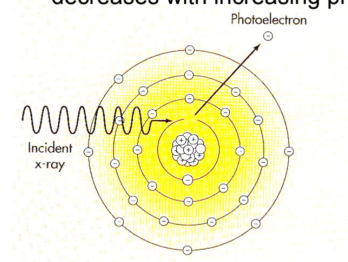
- X-ray is completely absorbed while ionizing an inner-shell electron
- X-ray energy must be greater than electron binding energy
- Entire energy of the photon contributes to radiation dose



Source: Figure 13-4, Bushong, S.C., Radiologic Science for Technologists: Physics, Biology, and Protection, 7th edition, Mosby, St. Louis, 2001

PHOTOELECTRIC EFFECT

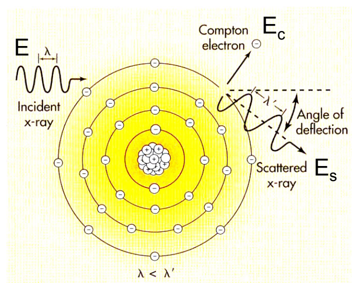
- μ_{PE}, (probability or likelihood of occurring)
  - increases rapidly with increasing atomic number Z (~ Z^3)
  - proportional to density (number of targets per unit distance)
  - decreases with increasing photon energy E (~ E^{-3})



Source: Figure 13-4, Bushong, S.C., Radiologic Science for Technologists: Physics, Biology, and Protection, 7th edition, Mosby, St. Louis, 2001

COMPTON SCATTERING

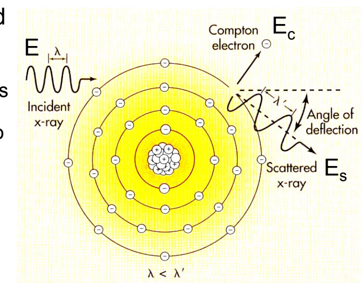
- X-ray interacts with an outer-shell electron
  - Electron ejected from atom
  - Atom is ionized
  - Scattered photon can go in any direction. $E_s < E$ depends on direction
  - E_c contributes to radiation dose
- Energy is conserved
  - $E = E_s + E_c$
  - in diagnostic imaging $E_s >> E_c$
  - scattered photon is quite penetrating
- Consequences
  - Reduces image contrast
  - Dose to personnel



Source: Figure 13-2, Bushong, S.C., Radiologic Science for Technologists: Physics, Biology, and Protection, 7th edition, Mosby, St. Louis, 2001

COMPTON SCATTERING

- μ_C, (probability or likelihood of occurring)
  - proportional to "electron density" (number of electrons per cm^3), which is approximately proportional to physical density
  - decreases slowly with increasing incident photon energy

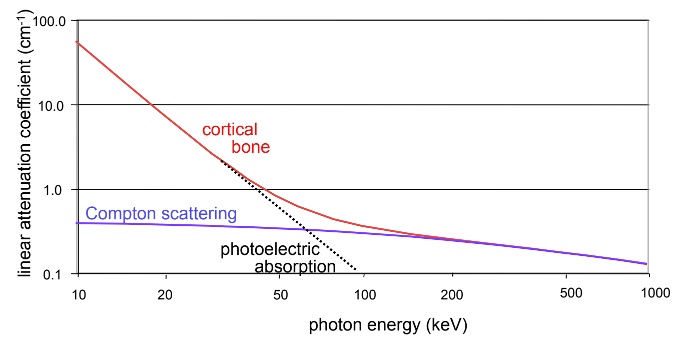


Source: Figure 13-2, Bushong, S.C., Radiologic Science for Technologists: Physics, Biology, and Protection, 7th edition, Mosby, St. Louis, 2001

COHERENT SCATTERING

- X-ray scatters but change in direction is very small
- X-ray does not lose energy
- Wave phenomenon, X-ray diffraction
- μ_{coh}, (probability or likelihood of occurring)
  - increases with increasing atomic number Z (~ Z^2)
  - proportional to density (number of targets per unit distance)
  - decreases with increasing photon energy E (~ E^{-2})
  - is never dominant in diagnostic imaging

RELATIVE PROBABILITIES



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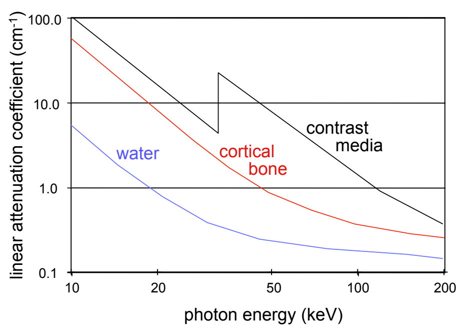
ATTENUATION COEFFICIENTS



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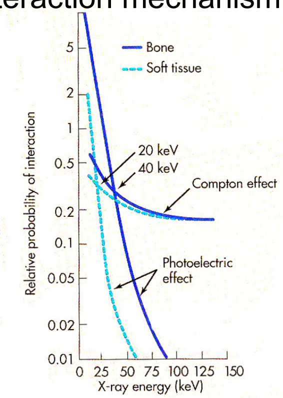
RELATIVE PROBABILITIES: most important interaction mechanism in diagnostic imaging



Source: Figure 13-13, Bushong, S.C., Radiologic Science for Technologists: Physics, Biology, and Protection, 7th edition, Mosby, St. Louis, 2001

Material	Effective Atomic Number	Mass Density (kg/m^3)
Lung	7.4	320
Fat	6.3	910
Muscle	7.4	1000
Bone	13.8	1850
Air	7.6	1.3
Barium	56	3500
Iodine	53	4930

Source: Tables 13-3 & 13-5, Bushong, S.C., Radiologic Science for Technologists: Physics, Biology, and Protection, 7th edition, Mosby, St. Louis, 2001

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RELATIVE PROBABILITIES: most important interaction mechanism in diagnostic imaging

depends on the "effective atomic number", Z_{eff}

- ~ 7.5 for soft tissues
- ~ 14 for bone
- ~ 53 for iodinated contrast media

soft tissues:

PE for E<20 keV, Compton for E>20 keV

bone:

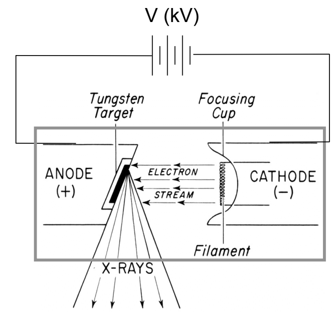
PE for E<60 keV, Compton for E>60 keV

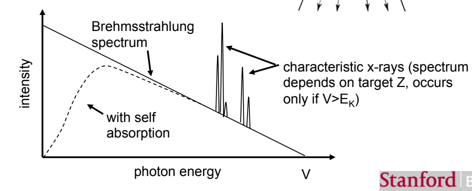
high Z materials (contrast media):

PE always

X-RAY PRODUCTION

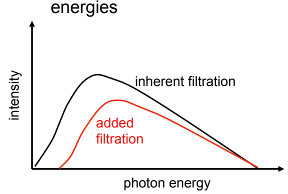
- current heats filament and emits electrons
- electrons accelerate and reach anode with kinetic energy V keV
- a small fraction of the electrons produce x-ray photons
- x-ray photon energy $\leq$ V keV

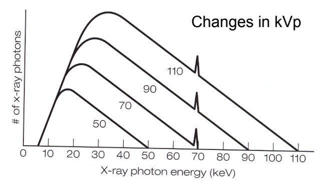


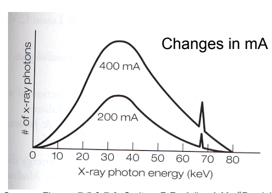


CONTROL OF X-RAY INTENSITY AND SPECTRUM

- kVp = kilovoltage peak
  - Maximum energy in the spectrum
- mA = tube current
  - Number of electrons per unit time striking the anode
- Exposure time
- Filtration
  - remove photons, primarily at low energies



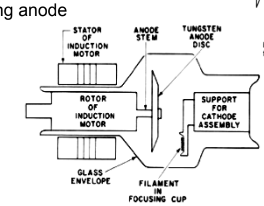


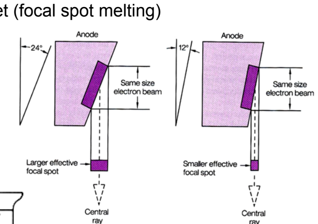


Source: Figures 7-5 & 7-6, Carlton, R.R., Adler, A.M., "Prnciples of Radiographic Imaging: an Art and a Science," 3rd edition, Delmar, 2001

X-RAY PRODUCTION

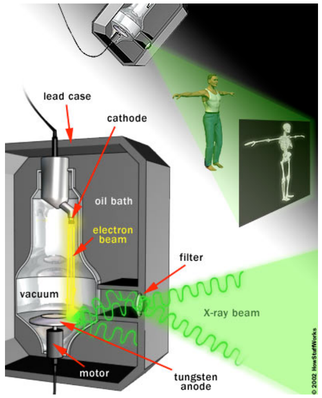
- **Ideal**
  - small focal spot to avoid blurring (typically 0.3 - 1.5 mm)
  - high output to shorten exposure time and reduce motion effects
- **Limitation**
  - low efficiency of x-ray production (~1%)
  - potential thermal damage to the target (focal spot melting)
- **Solution**
  - High melting point targets (W, Mo)
  - Efficient anode cooling
  - Tilted anode (line focus)
  - Rotating anode



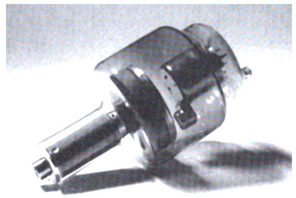


Source: Figure 6-14, Carlton, R.R., Adler, A.M., "Principles of Radiographic Imaging: an Art and a Science," 3rd edition, Delmar, 2001

X-RAY TUBE



Source: health.howstuffworks.com/x-ray.htm

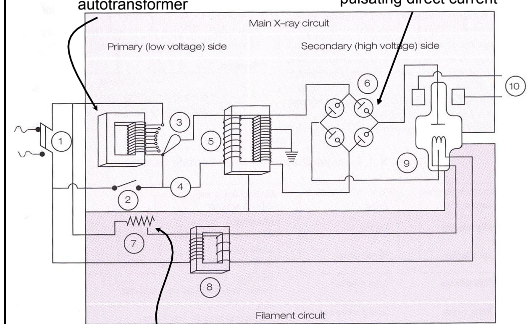


Source: Figure 6-20, Carlton, R.R., Adler, A.M., "Principles of Radiographic Imaging: an Art and a Science," 3rd edition, Delmar, 2001

X-RAY CONTROLS

kVp (peak x-ray energy produced) controlled by autotransformer

Rectification circuit converts alternating current to pulsating direct current



(1) Main breaker
(2) Exposure switch
(3) Autotransformer
(4) Timer circuit
(5) High-voltage step-up transformer
(6) Four-diode rectification circuit
(7) Filament circuit variable resistance
(8) Filament step-down transformer
(9) X-ray tube
(10) Rotor stator

Transformers convert one voltage level (V_p) to another (V_s): $V_s/V_p = N_s/N_p$

Number of turns in coil

mA (current) is controlled by the variable resistor

Source: Figures 5-16, Carlton, R.R., Adler, A.M., "Principles of Radiographic Imaging: an Art and a Science," 3rd edition, Delmar, 2001

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RADIOGRAPHY

- static projection imaging
- total attenuation along a line, but not it's distribution

Source: pain.health-info.org/pictures/Xray's/Xray.chest.JPG

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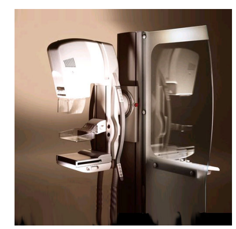
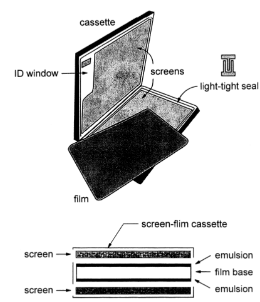
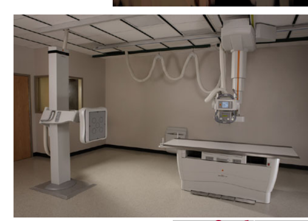
RADIOGRAPHY EQUIPMENT

- Analog (film/screen)
- Digital
- Automatic exposure control







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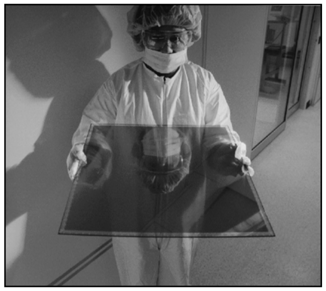
DIGITAL FLAT PANEL DETECTOR



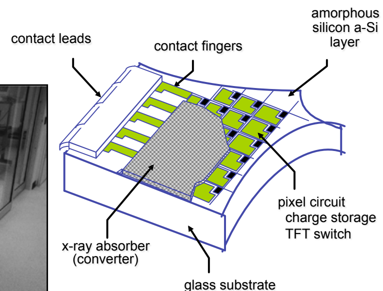
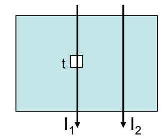


IMAGE CONTRAST

- lower energy photons: more contrast, higher radiation dose
- too much contrast can stress the detector dynamic range



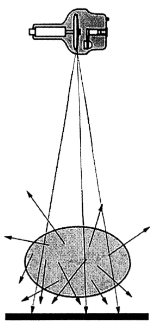
$C = (I_1 - I_2)/I_2 = 1 - e^{-\Delta\mu t} \sim \Delta\mu t$
with $\Delta\mu$ = difference in μ

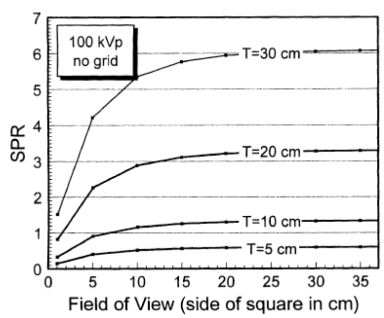
Source: www.e-radiography.net

kVp too low

SCATTER

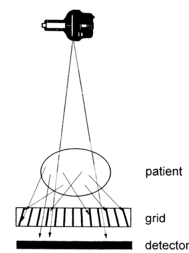
- Degrades image contrast. $C = C_{ideal}/(1+SPR)$
  (SPR= scatter to primary ratio)



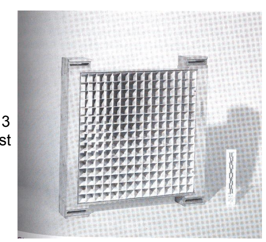


ANTISCATTER GRIDS

- radiopaque (lead) strips separated by radiolucent space
- Ideally
  - primary transmission = 1
  - scatter transmission = 0
- In practice
  - primary transmission ~ 80%
  - scatter transmission ~ 10%
- Improves image contrast



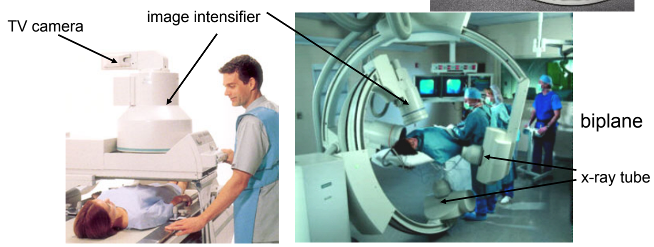
First grid made in 1913 by American radiologist Gustav Bucky



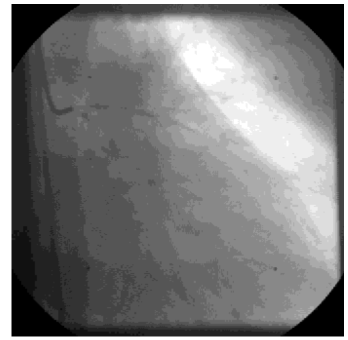
Source: Figure 18-2, Carlton, R.R., Adler, A.M., "Principles of Radiographic Imaging: an Art and a Science," 3rd edition, Delmar, 2001

FLUOROSCOPY and ANGIOGRAPHY

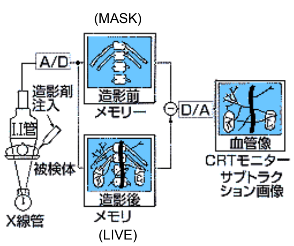
- Analog (image intensifier - TV)
- Digital
- Automatic brightness control



CORONARY ANGIOGRAPHY



DIGITAL SUBTRACTION ANGIOGRAPHY

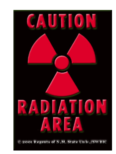


RADIATION DOSE: acute effects

Description	Dose
Maximum dose to general population per year	1 mSv or 0.1 rem
Maximum dose to people who work with radiation	20 mSv or 2.0 rem per year (5 year average)
Dose exposure which will cause nausea sickness and diarrhea in some people	0.5 Gy or 50 rad
Dose exposure which will kill many people in the few months after exposure	5 Gy or 500 rad

Source: Table 5.3, Brown, B.H., et al., Medical Physics and Biomedical Engineering, Institute of Physics, UK, 2001

- X-rays can be harmful, causing ulceration of the skin, infertility, and death
- Effect depends on exposure level and amount of exposure time



Sources: www.swbic.org/products/clipart/images/radiation.jpg, and www.fda.gov/cdrh/figure2a.jpeg

RADIATION DOSE: long term effects and risk comparisons

Description	Risk
background lifetime risk of fatal cancer	1 in 5
increased risk of fatal cancer from 10 mSv exposure (assuming linear no threshold hypothesis)	1 in 2000

Source: www.fda.gov/cdrh/ct/risks.html

Health Risk	Est. life expectancy lost
Smoking 20 cigs a day	6 years
Overweight (15%)	2 years
Alcohol (US Ave)	1 year
All Accidents	207 days
All Natural Hazards	7 days
Occupational dose (300 mrem/yr)	15 days
Occupational dose (1000 mrem/yr)	51 days

Source: http://www.physics.isu.edu/radinf/risk.htm

Diagnostic Procedure	Typical Effective Dose (mSv)	Number of chest X rays for Equivalent Effective Dose	Time Period for Equivalent Effective Dose from Natural Background
PA chest x ray	0.02	1	2.4 days
Skull x ray	0.07	4	8.5 days
Lumbar spine	1.3	65	158 days
I.V. urogram	2.5	125	304 days
Upper G.I. exam	3	150	1.0 year
Barium enema	7	350	2.3 years
CT head	2	100	243 days
CT abdomen	10	500	3.3 years

Source: www.fda.gov/cdrh/ct/risks.html

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X-RAY: SUMMARY

- Projection imaging with x-rays
- Contrast arises from density and atomic number
  - very good for bone-tissue-air differentiation, contrast media, and devices
  - very little soft tissue contrast
- Very high spatial resolution
- Very high temporal resolution (fluoro)
- After almost 120 years, it's still undergoing technical advances, and is still highly utilized

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WHERE TO LEARN MORE

- BioE 220/Radiology 220: Introduction to Imaging and Image-based Human Anatomy
- EE369A: Medical Imaging Systems I
- BioE 223/Radiology 223: Physics and Engineering of X-ray Computed Tomography

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