Basic Physics of Diagnostic X-ray Imaging

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Learning Objective

To understand the underlying physics principles of X-ray imaging including

- ✓ X-ray production
- ✓ X-ray interactions with matter
- ✓ Radiation units

Summary of Chapters 2, 3 and 6 in Bushberg et.al. The Essential Physics of Medical Imaging and ABR CORE Study Guide requirements 1a, 2, 4, 5 & 6

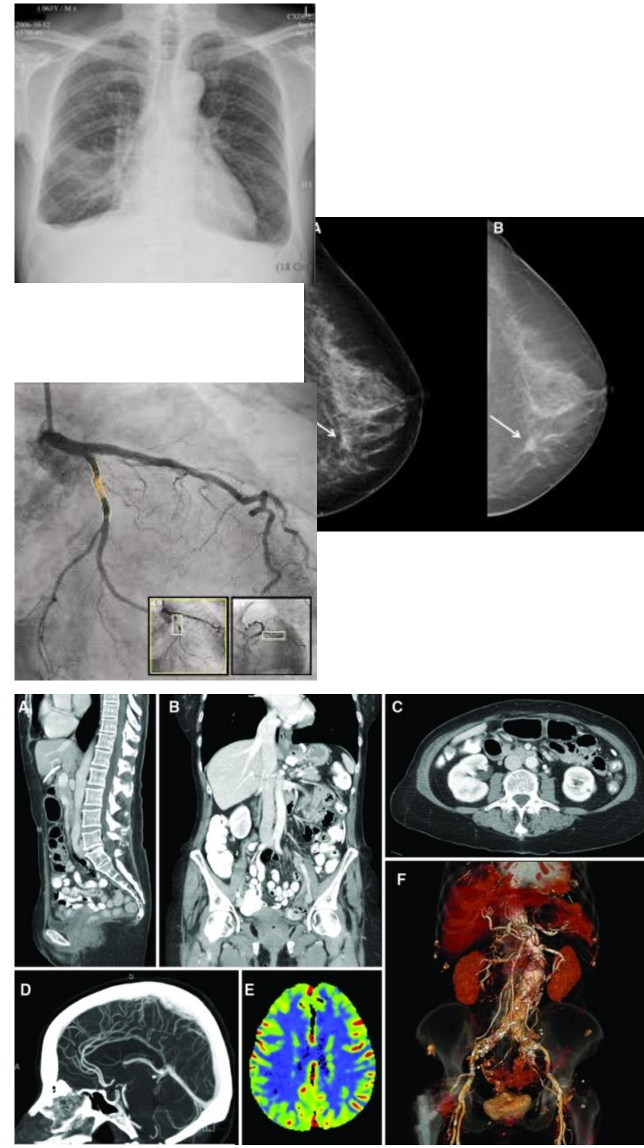
Diagnostic X-ray Imaging Modalities

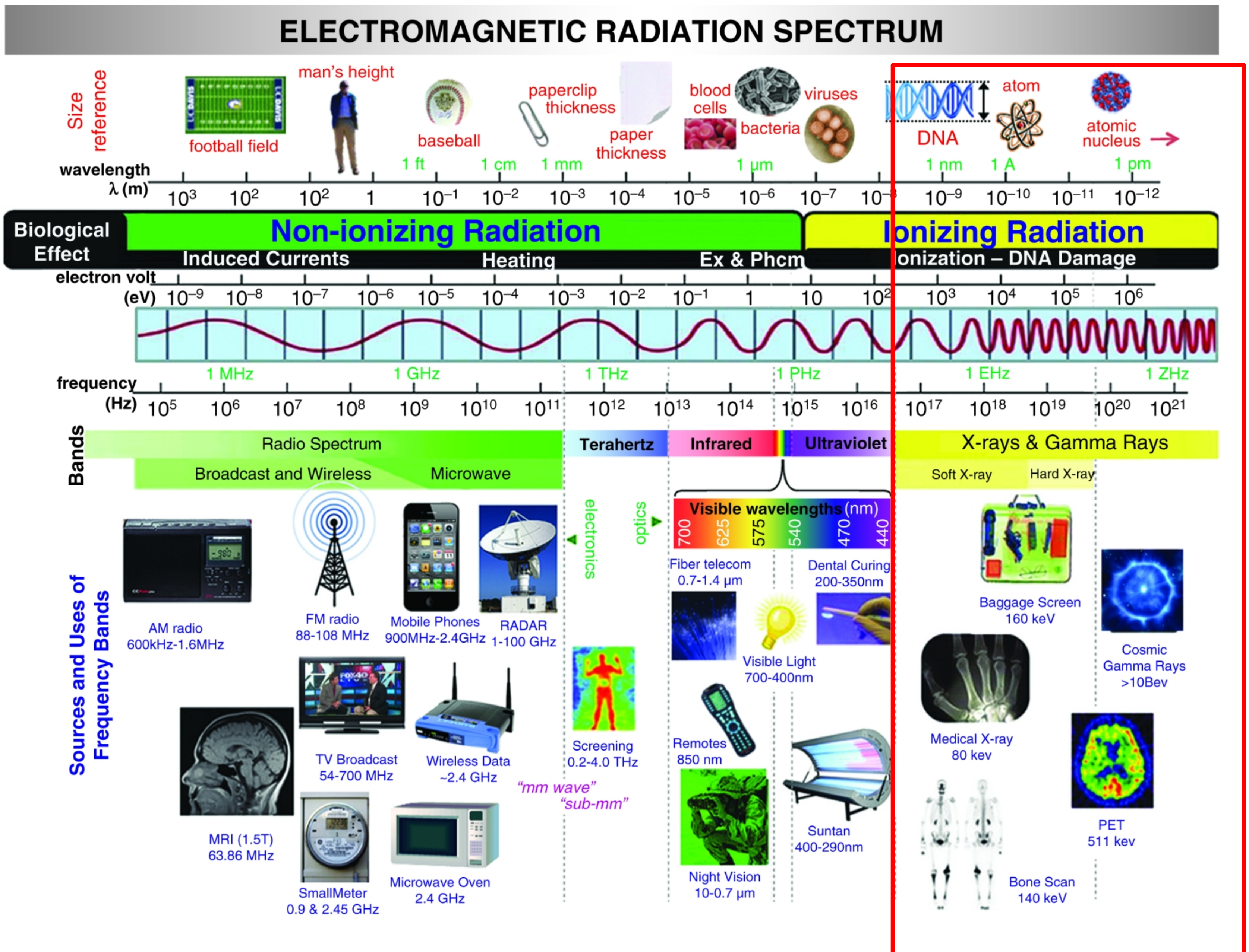
- Transmission Projection Modalities
  - Radiography
  - Mammography Fluoroscopy

- Breast Tomosynthesis (conventional tomography)

- Cross-sectional Imaging Modalities
  - Computed Tomography (CT)

All X-ray imaging modalities use radiation in the short wavelength, high frequency and high energy end of the electromagnetic radiation spectrum.





Bushberg et al. The Essential Physics of Medical Imaging, 3rd edition

Electromagnetic Spectrum

X-rays and gamma rays are part of the electromagnetic spectrum. They have short wavelength and high frequency together with high energy. As a result they are able to remove bound electrons from atomic shells resulting in ionization of atoms within the matter through which they travel. Radiation in the high energy end of the electromagnetic spectrum is called *ionizing radiation.*

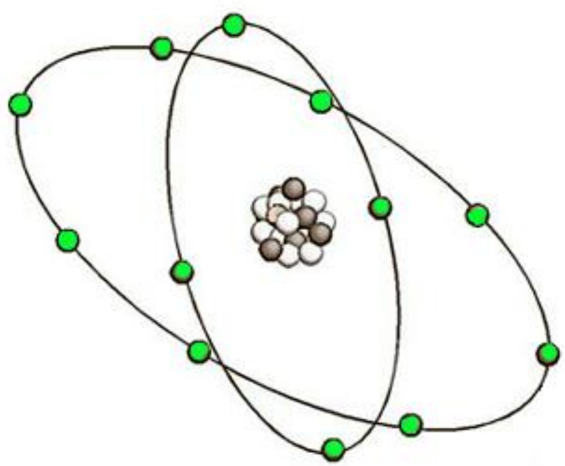
Even though gamma rays and x-rays are same kind of radiation we use different names for them to reflect their origins; gamma rays originate from nuclei of various radioactive materials while X-ray photons are produced in X-ray tubes by electron interactions with heavy metals. Radiography, fluoroscopy, mammography and computed tomography (CT) are all imaging modalities that use X-rays while gamma rays are used in nuclear medicine studies.

Non-ionizing radiation on the left, or low energy part of the EM-spectrum, has long wavelength and low frequency. Radio waves are an example of non-ionizing radiation. They are used in magnetic resonance imaging (MRI).

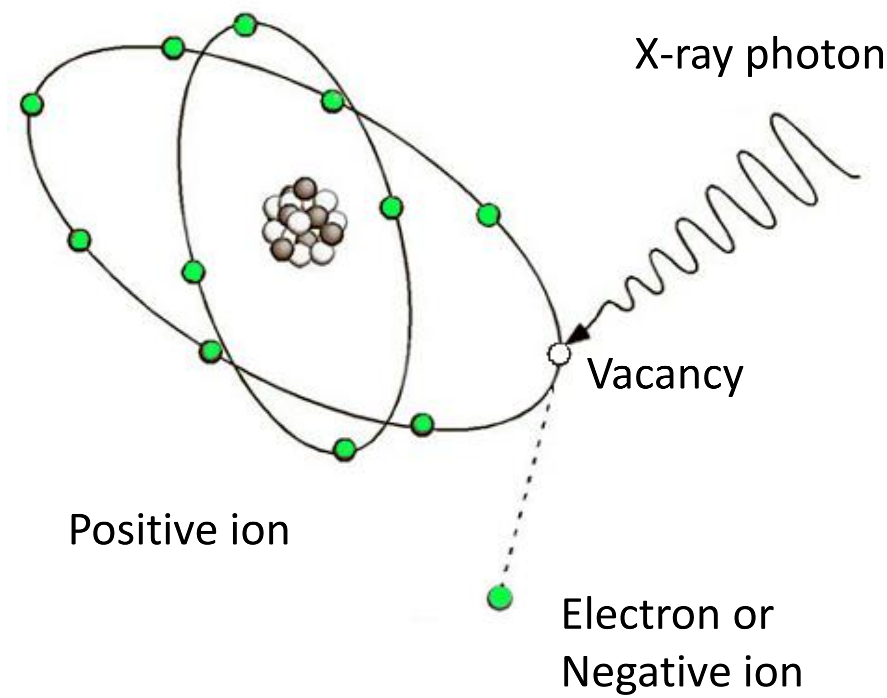
Note. Ultrasound imaging use high-frequency sound waves to generate images of patient anatomy. US is thus the only radiologic imaging modality that does not use electromagnetic energy.

Ionization - X-rays and γ-rays

X-rays and γ-rays are able to ionize the atoms in the matter through which they travel. In a neutral atom the number of protons in nucleus is the same as the number of electrons circulating the nucleus. When a photon removes an electron from it's shell an ion pair results: positively charged atom and negatively charged electron. In order ionization to take place the incoming photon energy must be at least as much as the electron binding energy.

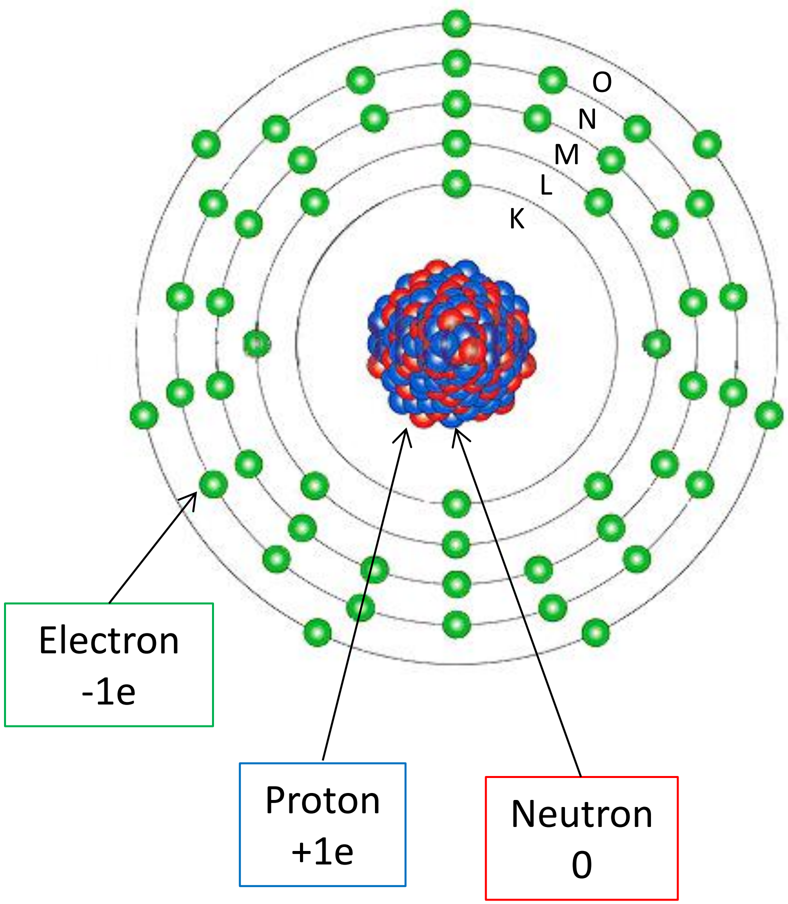


Neutral atom



Ion Pair

Atomic Structure



Elementary charge e=1.602 10^{-19} Coulombs

Iodine-127
Mass number, A = 127
Atomic Number or the number of protons, Z = 53
Number of neutrons, N = 74
Number of electrons, 53

Notation

127

53 74

Notes about atoms ...

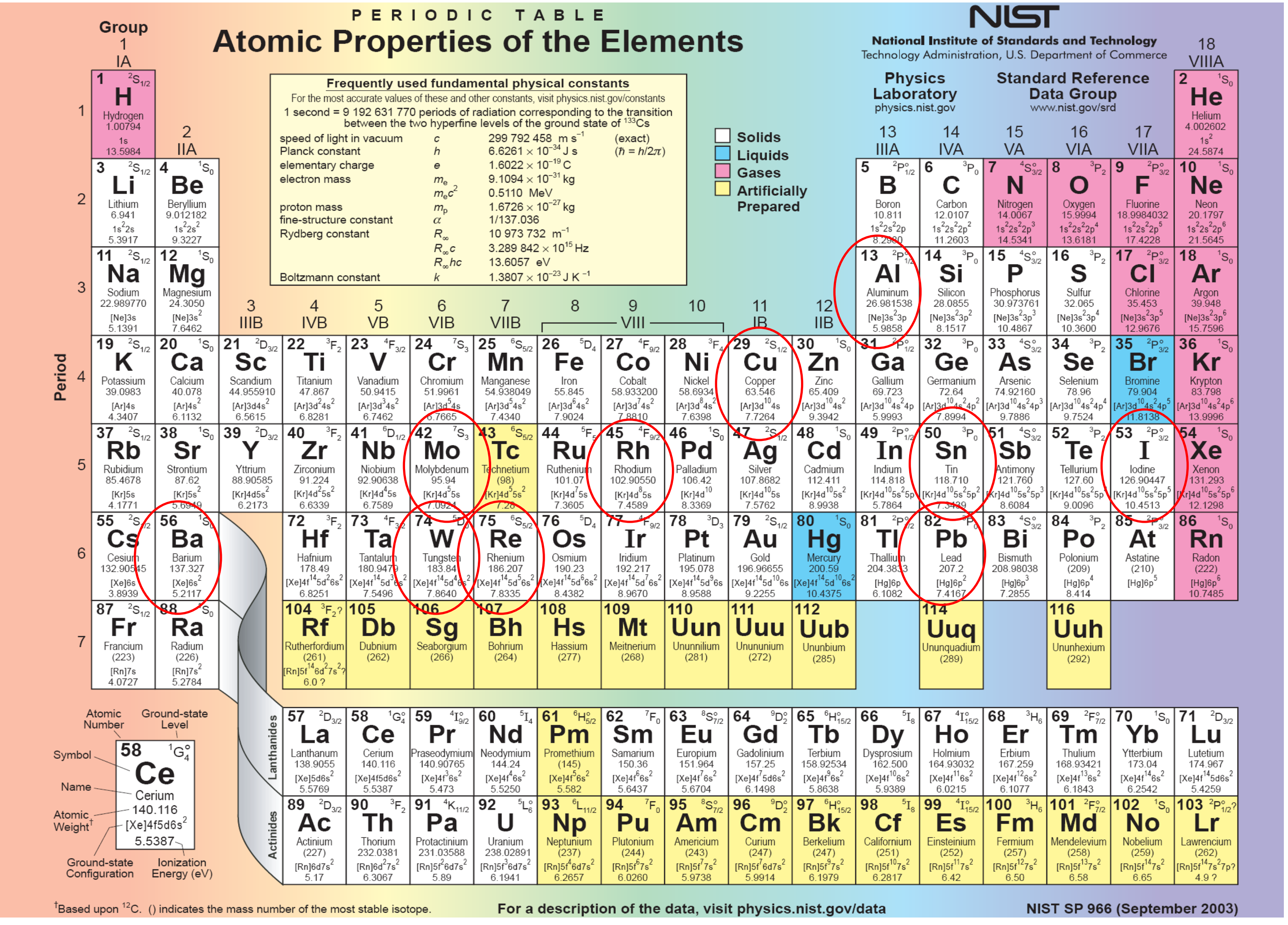
- Mostly empty space.
- Most of the atomic mass is in the nucleus.
- Atomic Number, Z
- Number of neutrons, N
- Mass number A = Z + N
- In neutral atom # protons = # electrons
- Electron shells are denoted by K, L, M, N ...
- Each shell is assigned a principal quantum number, n
- Each shell can have up to $2n^2$ electrons.
- Electron binding energy in a particular shell is the energy required to remove an electron from that shell and the atom.
- Binding energy is specific to a specific shell and for each particular element.
- Binding energy is largest for the electrons in the innermost shell.
- In order a photon to knock out an electron from its shell and the atom it needs to have energy that is equal or more than the electron's binding energy.

Important elements in radiology:

Contrast agents: Barium & Iodine

Anode target and filter materials: Tungsten, Rhenium, Rhodium, Molybdenum, Aluminum, Copper, Tin

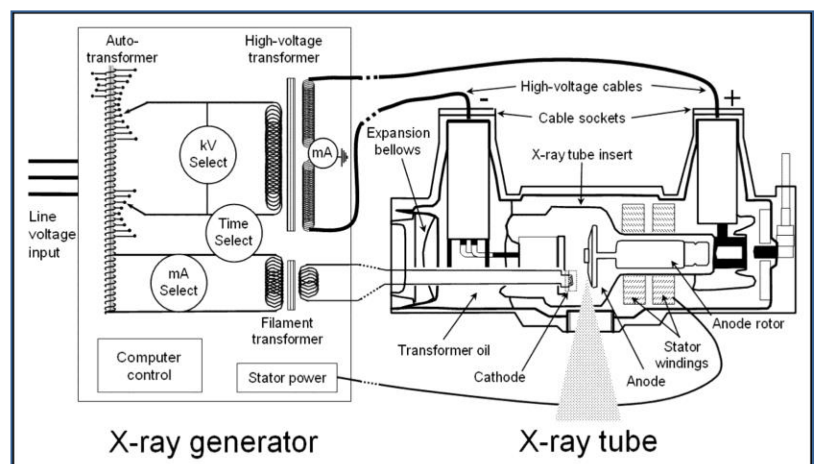
Materials used in radiation protection: Lead



X-ray Production

X-ray Production

- X-ray tube and X-ray generator are the necessary components for X-ray production and beam control.
- X-ray tube provides the means to produce X-rays.
- X-ray generator delivers electrical power to the X-ray tube, transforms the voltages to appropriate levels, rectifies alternate voltage waveforms into constant waveforms, and controls X-ray tube operation.
- At generator console the user selects appropriate values for technique factors (kV, mA, exposure time, AEC mode, AEC sensors, focal spot...).



X-ray Tube

Every X-ray tube has a glass or metal insert containing a vacuum. Major components within the insert are the cathode and anode assembly.

The tube insert is placed in a lead-lined shell, or tube housing. Lead lining controls “leakage” radiation to the environment. There is oil between the insert and tube housing that helps to dissipate the heat from the anode and to keep the tube from overheating.

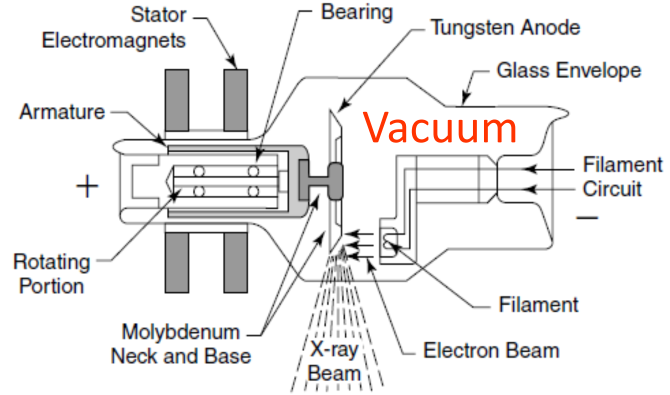
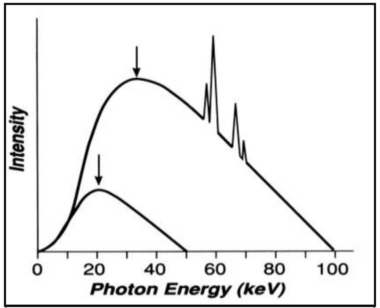


FIGURE 5-1
Simplified x-ray tube with a rotating anode and a heated filament.

X-rays are produced in an X-ray tube by boiling off electrons from a heated cathode (thermionic emission) and accelerating them towards the anode (stationary or rotating) by applying a high voltage between the cathode and the anode. When electron beam hits the anode surface X-rays are produced.



Distribution of X-ray energies within the beam represented as an X-ray spectrum.

X-ray Tube

To generator

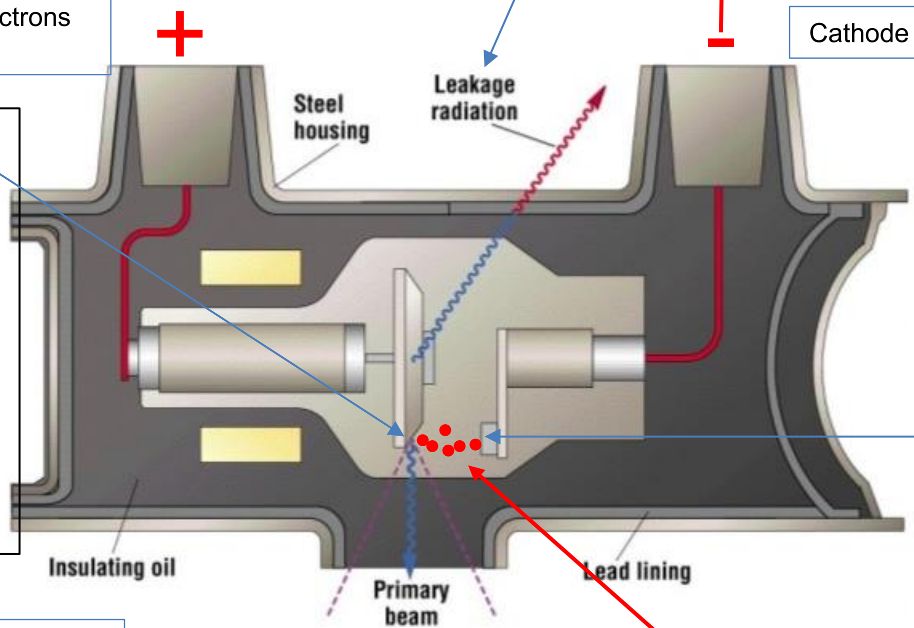
Voltage between anode and cathode
kV

X-rays are created into all directions. Lead lined tube housing keeps the radiation out of environment. The amount of radiation that is allowed to "leak" out is regulated.

Anode is positively charged attracting the negative electrons boiling off the filament.

Cathode is negatively charged.

ANODE: When electrons hit the focal spot they release more or less of their kinetic energy into the anode material. Most of this energy (99%) is converted into heat, the rest into X-rays.
Heat production limits the rate of X-ray production that can be achieved without damaging the anode.



CATHODE: When electric current flows within the filament it gets hot (like in the light bulbs) and electrons are released by thermionic emission. They are accelerated towards the anode by virtue of high electric voltage that is arranged between anode and cathode. Electromagnetic steering is used to focus the electron beam into a small focal area, or focal spot on the anode surface.

To remedy the tube heating, insulating oil around the tube insert is used together with a rotating anode. Only dental tubes and some low output portable X-ray machines and fluoroscopy systems have stationary anodes.

Tube port is the exit point for X-rays.

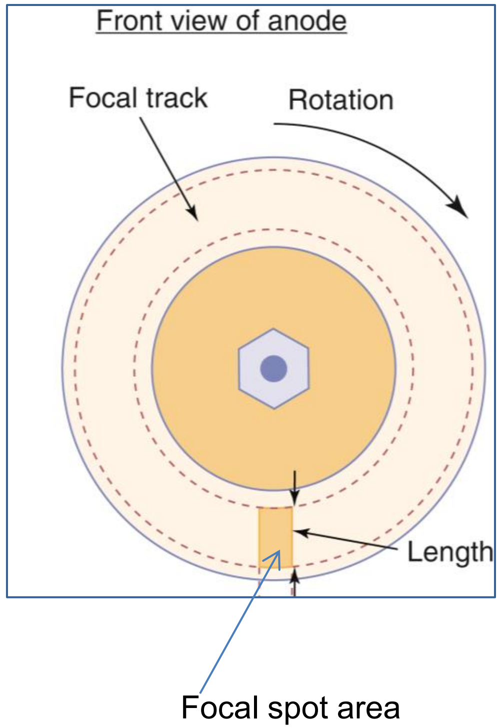
Current between cathode and anode
mA

Tungsten (Z=74) is the most widely used anode material due to its high melting point (6191 °F). Mammography tubes use Molybdenum (Z=42, 4753°F) and Rhodium (Z=45, 3565°F) as well as tungsten.

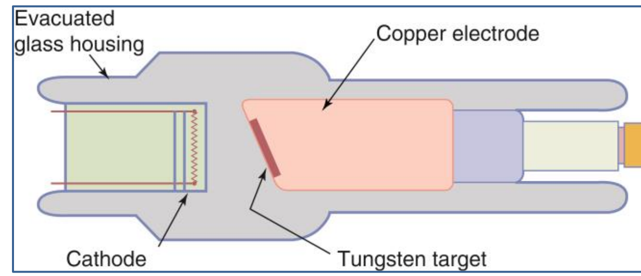
X-ray Tube

In order to distribute the heat into a larger surface area rotating anodes are used. This design converts a small focal spot area into a larger focal track area reducing local temperatures and permitting larger tube currents and longer exposure times.

X-ray systems are designed such that the x-ray tube won’t energize if the anode is not at full speed; this is the cause for the short delay when the X-ray tube exposure button is pushed.



Rotating anode spreads the heat from a small focal spot area into a focal track area.



Fixed anode X-ray tube is comprised of a tungsten insert placed in a copper block. Heat is removed from the target area by conduction into the copper block.

Most tubes have two focal spots (small and large) of different sizes. This is done by using two different size filaments.

X-ray Tube Failure

X-ray tubes have a finite lifetime and needs replacing. Most common causes of failure include filament failure, anode target failure, anode bearing failure in rotating anode tubes, arcing or short-circuit within the tube causing momentary loss of X-ray output, glass tube crack due to arcing, total or partial loss of vacuum, movement of glass envelop or tube insert within the tube housing, oil leak.

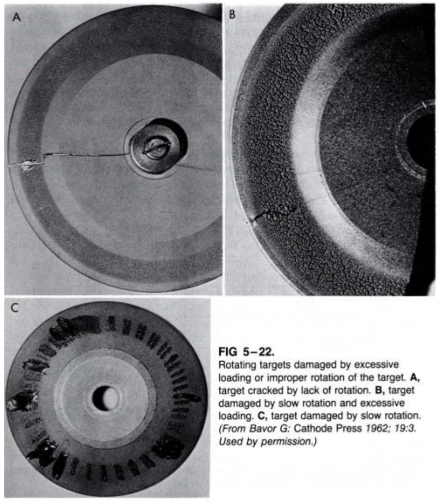
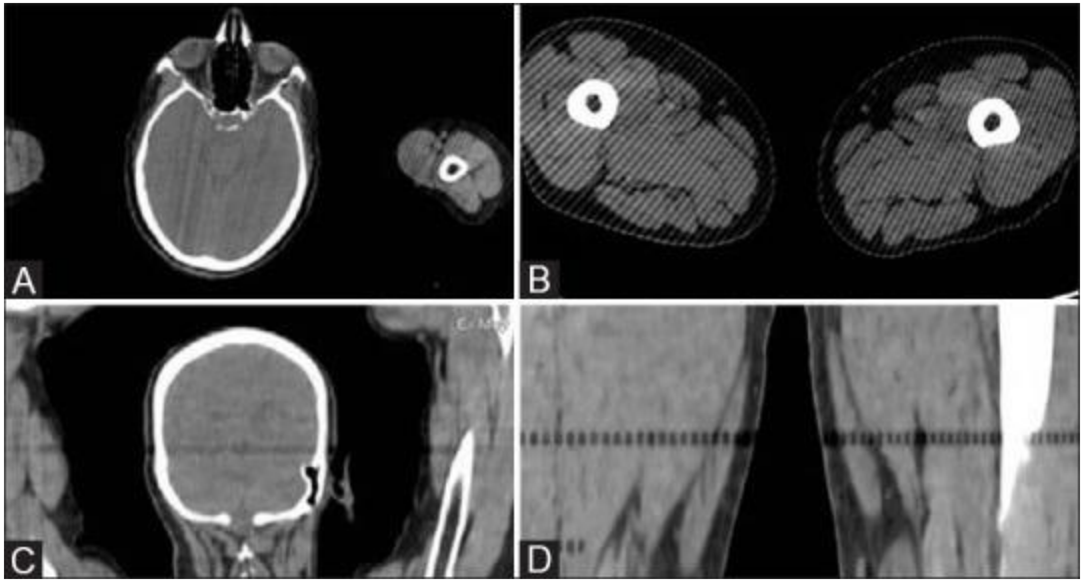


FIG 5–22.
Rotating targets damaged by excessive loading or improper rotation of the target. **A,** target cracked by lack of rotation. **B,** target damaged by slow rotation and excessive loading. **C,** target damaged by slow rotation. *(From Bavor G: Cathode Press 1962; 19:3. Used by permission.)*

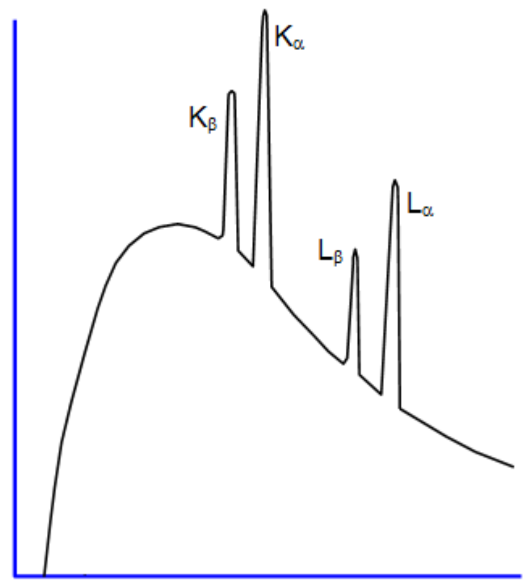
CT tube arcing artifact seen in the head region on the transaxial image (A) and corresponding coronal image (B); in the thigh region on the transaxial image (C) and corresponding coronal image (D).



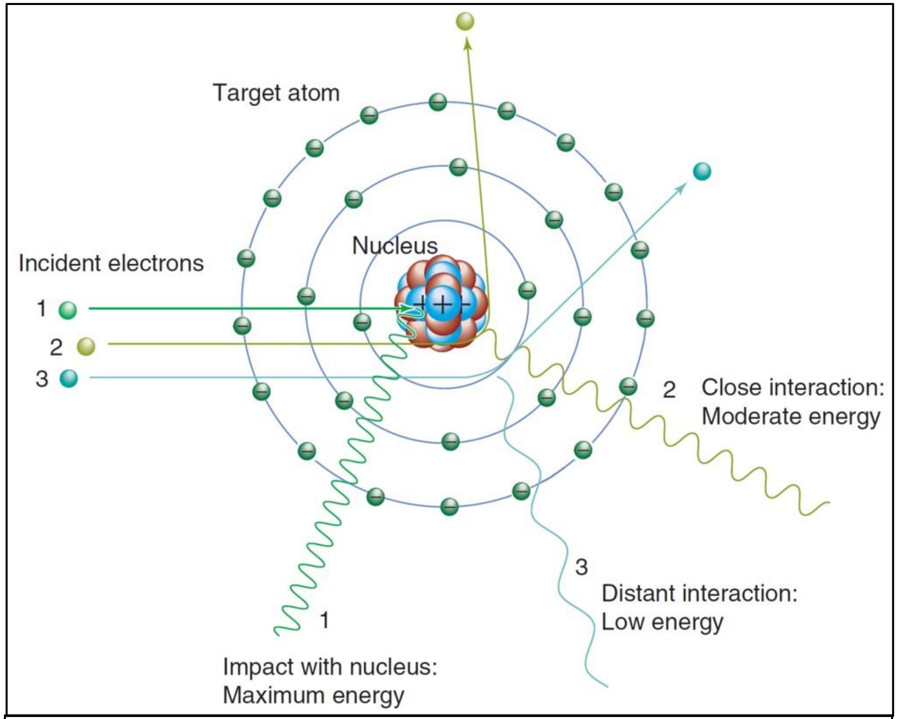
X-ray Tube

The vast majority of the diagnostic X-ray tubes today are equipped with rotating anodes, with the exception of dental X-ray tubes which still may use a stationary anode. X-ray tubes are designed for many different purposes ranging from very demanding applications in angiography and computed tomography CT with short, but heavy-duty and repeated series of exposures to the less demanding but still specific requirements in mammography and in dental imaging. Actual designs of the X-ray tubes therefore differs vastly.

Physics of X-ray Spectrum



Bremsstrahlung or Breaking Radiation



Creation of bremsstrahlung radiation. Electrons come within the proximity of an atomic nucleus and is influenced by its positive electric field. Electrical (Coulombic) forces attract and decelerate an electron and change its direction, causing loss of kinetic energy, which is emitted as an X-ray photon of equal energy (i.e. bremsstrahlung radiation). The amount of energy lost depends on how close to the nucleus the interaction is taking place.

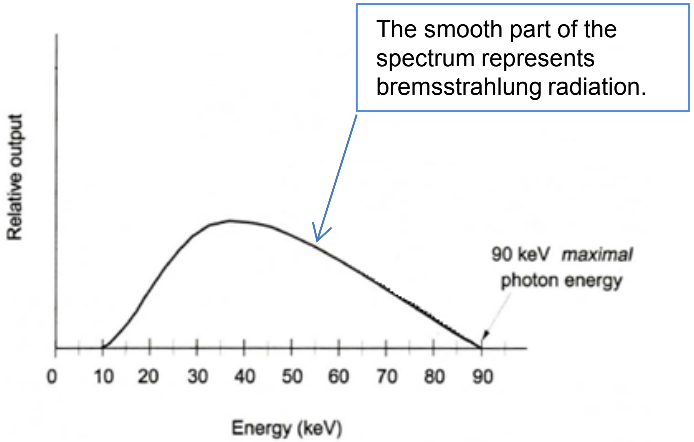
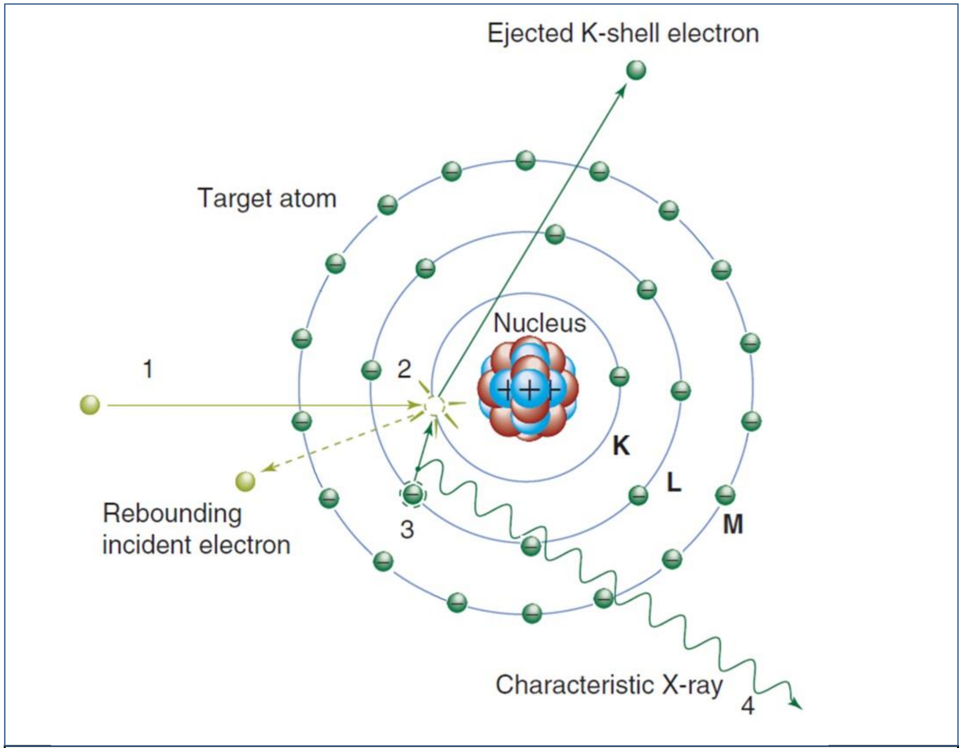


Figure 4.3. The distribution of energies in an x-ray spectrum produced by the inter action of 90 keV electrons with a target

Characteristic Radiation



Generation of characteristic X-rays in a target atom.
Electrons in an atom are distributed in shells each of which has an electron binding energy. The innermost shell is designated as K-shell and has the highest electron binding energy. Electron binding energies are "characteristic" of the elements. When the energy of an incident electron, determined by the X-ray tube voltage, exceeds the binding energy of an electron shell in a target atom, a collisional interaction can eject an electron from its shell, creating a vacancy, which is filled by an outer shell electron. Transition of an electron from an outer shell to an inner shell result in an emission of an characteristic X-ray. The energy of the characteristic X-ray is equal to the difference of the electron binding energies between the two shells involved.

The spikes on top of the bremsstrahlung spectrum represent characteristic radiation from electron transitions between two electron shells.

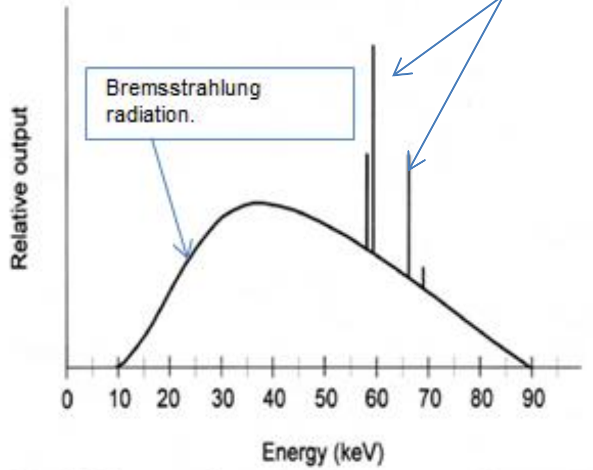


Figure 4.5. Total spectrum of x-ray tube with tungsten target: At a potential difference of 90 kVp bremsstrahlung plus characteristic radiation.

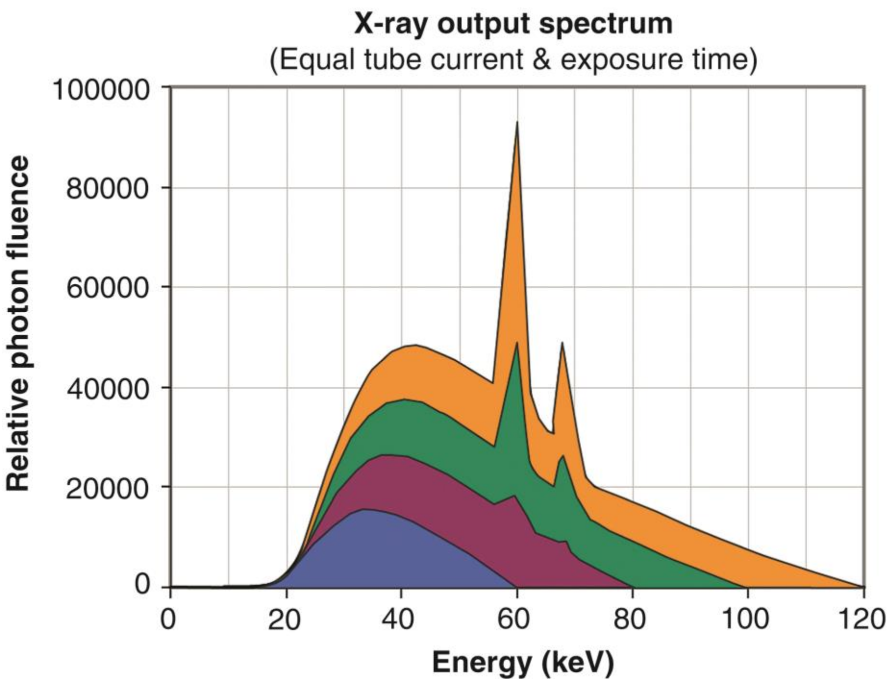
Characteristic peaks in an X-ray spectrum are specific to an element as the electron shell binding energies are element specific.

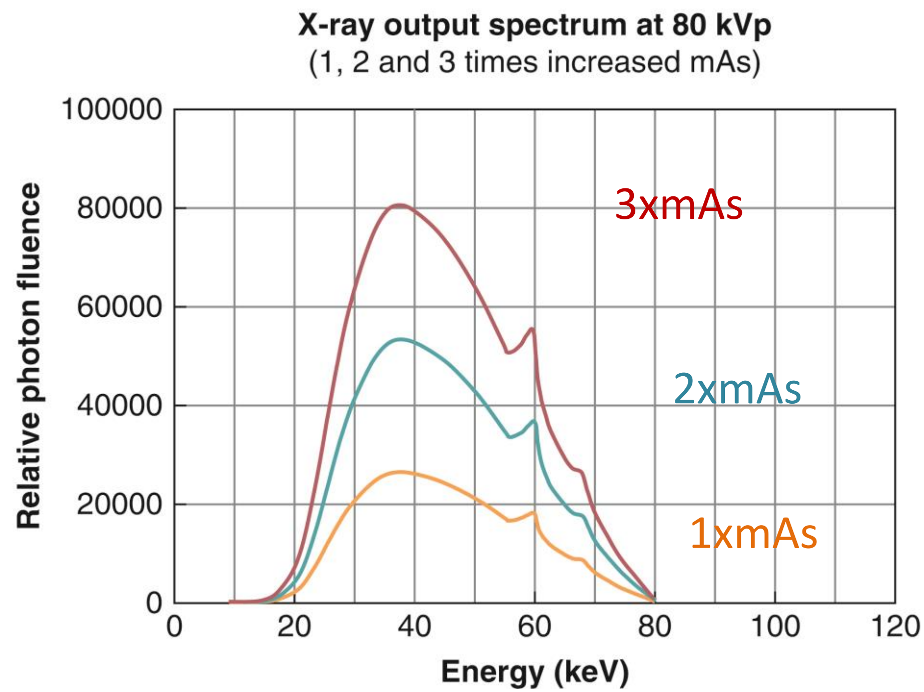
X-ray Spectrum

Major factors that determine how many photons per unit time is coming out from an X-ray tube and what the energy distribution (spectrum) is like:

- Anode target material
  - Defines the energies of the characteristic peaks.
  - Affects the efficiency of bremsstrahlung radiation production; the higher the atomic number, Z, of the target material, the higher is the efficiency of X-ray production.
- Tube voltage or kV
  - Determines the maximum energy of X-rays in the bremsstrahlung spectrum.
  - Affects the efficiency of X-ray production.
  - Penetrability (also called as beam quality) refers to the range of X-rays in tissue. The higher the tube voltage, the higher the overall energy of the X-ray beam and the more penetrating is the X-ray beam.
  - Power law dependence between kV and tube output.
- Tube current or mA
  - Affects the number of X-rays in the X-ray beam.
  - The higher the tube current the more X-rays there are in the X-ray beam.
  - Linear relationship between mA (and mAs) and the tube output.
- Exposure Time
  - How long the beam is on determines the total amount of radiation, or the total number of photons used for any particular exposure event.

Radiation quantity is the number of X-rays in the useful beam. Radiation quality refers to the penetrating power of the X-ray beam. Penetrability can be quantified by using half-value layer (HVL) parameter, which is that thickness of any particular material that reduces X-ray intensity to half of its original value.





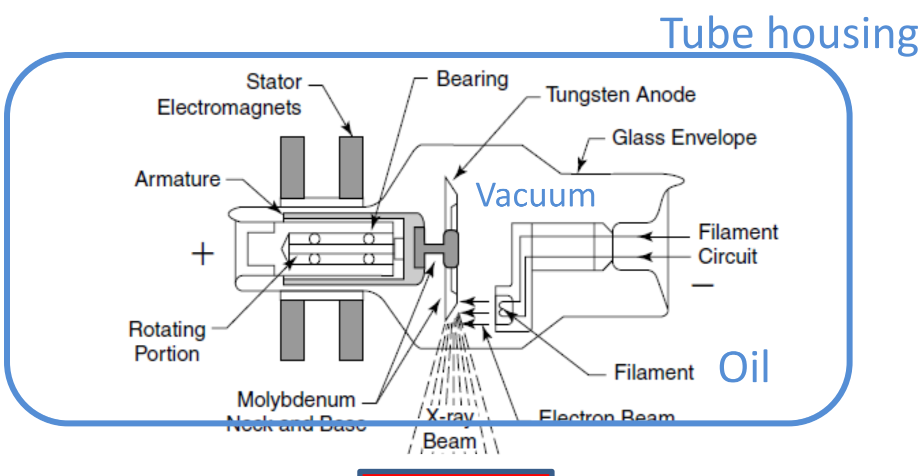
Demonstration of the effect of kV change on the spectrum when current (mA) and exposure time stay the same. It can be seen that spectrum shifts to the right towards higher energies when kV is increased. Also the number of X-rays in the beam increases with increasing kV. Characteristic peaks remain at the same energy as the anode material stays the same.

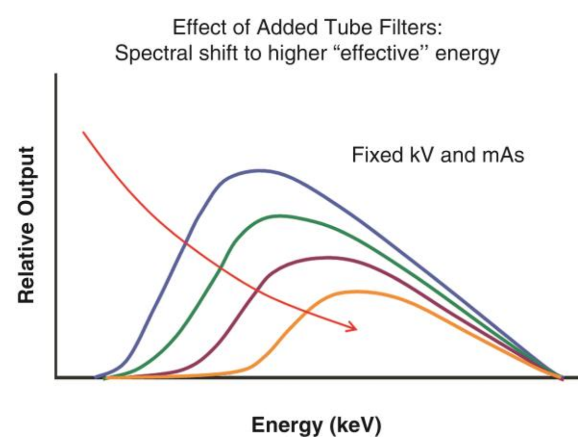
Demonstration of mAs change when voltage (kV) stays the same. Spectrum becomes higher as mAs increase. The number of X-rays created increase linearly with mA and mAs.

X-ray Beam Filtration

X-ray beam filtration refers to removal of X-rays from the beam when it passes through a layer of material. Filtration removes more low-energy X-rays than high energy X-rays shifting the spectrum towards higher energies which results in an X-ray beam that has greater penetrability.

Filtration in the diagnostic X-ray beams is divided into **inherent filtration** and **added filtration**. Inherent filtration refers to the permanent structures in the beam path; anode material itself, insulating oil, tube exit window etc. Additional filtration is added between the tube exit window and the X-ray beam collimator.



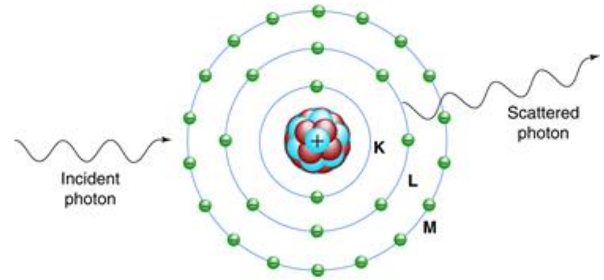


Added filtration – how much and what kind depends on modality/application.

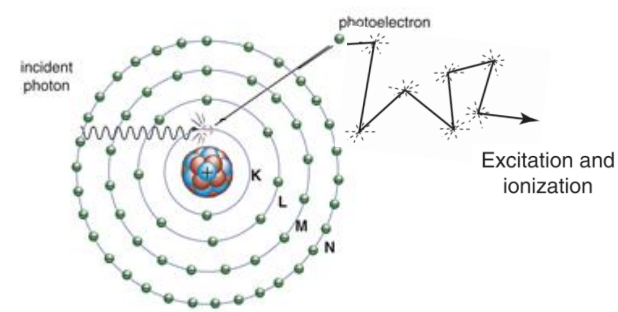
X-ray Interaction with Matter

X-ray Interactions with Matter relevant to Diagnostic Radiology

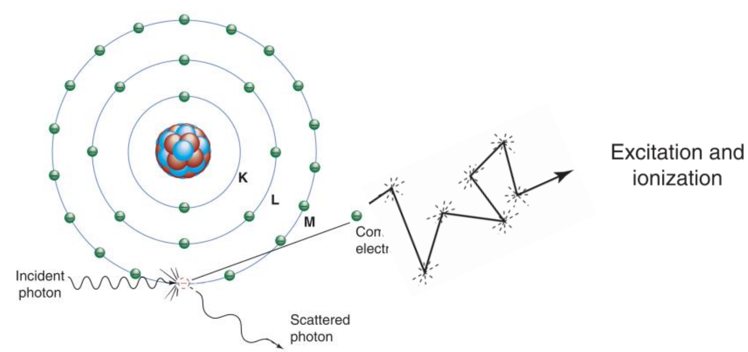
- Coherent scattering



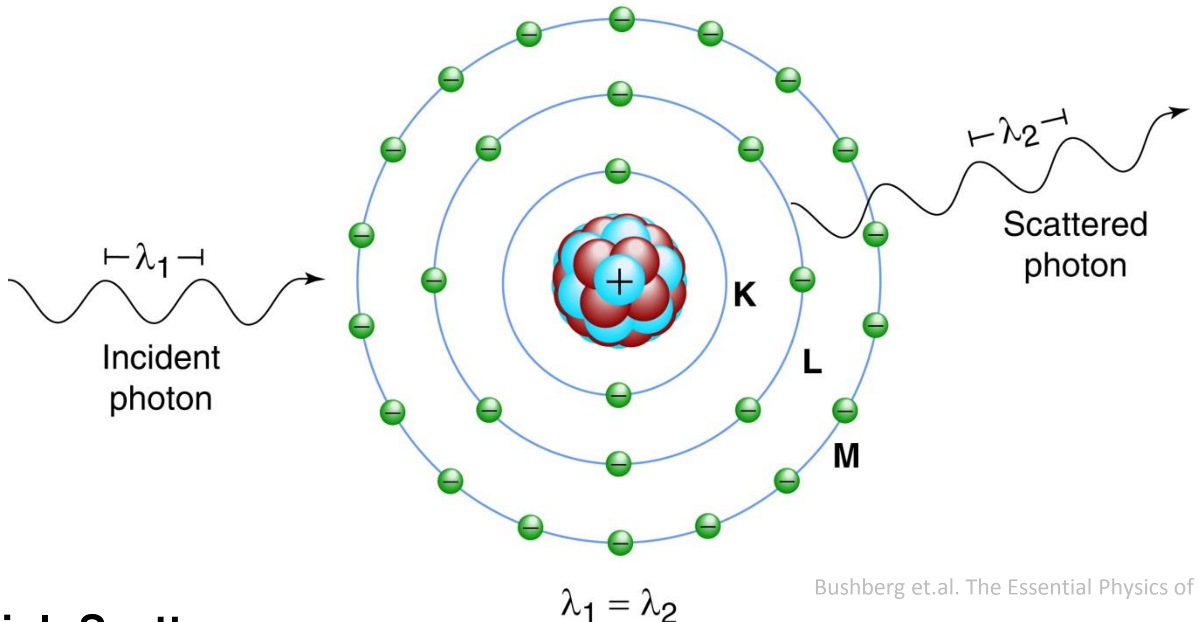
- Photoelectric absorption



- Compton scattering



Rayleigh (Coherent) Scatter



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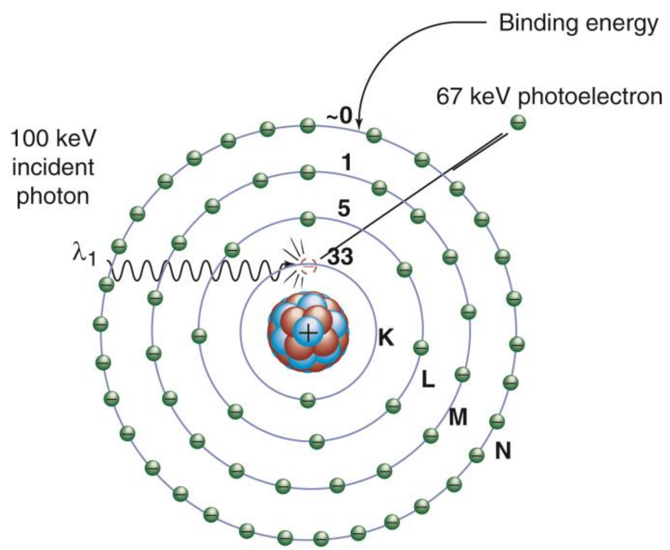
Rayleigh Scatter

- Takes place between a photon and an atom.
- No ionization.
- No energy deposition.
- Low probability in diagnostic energy range.
- In soft tissue
  - ✓ above 70keV less than 5% of interactions are coherent scatter.
  - ✓ at 30keV ≈10% are coherent scatter interactions.
- Not very important in diagnostic imaging.

Photoelectric Effect



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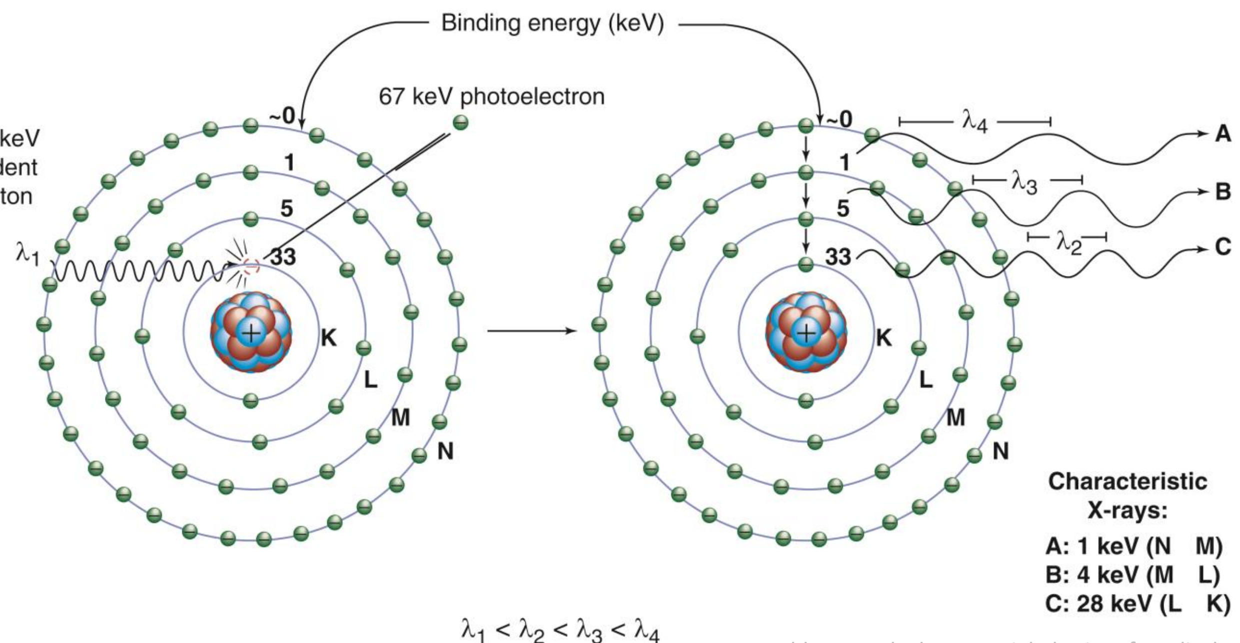
Photoelectric effect

- Takes place between a photon and an inner shell electron.
- Ionization takes place.
- Energy deposition in tissue.
- Incident photon energy must be equal to or higher than the binding energy of the photoelectron.
- Probability increases with electron density of the material.
- Probability proportional to $(Z/E)^3$

Photoelectric Effect



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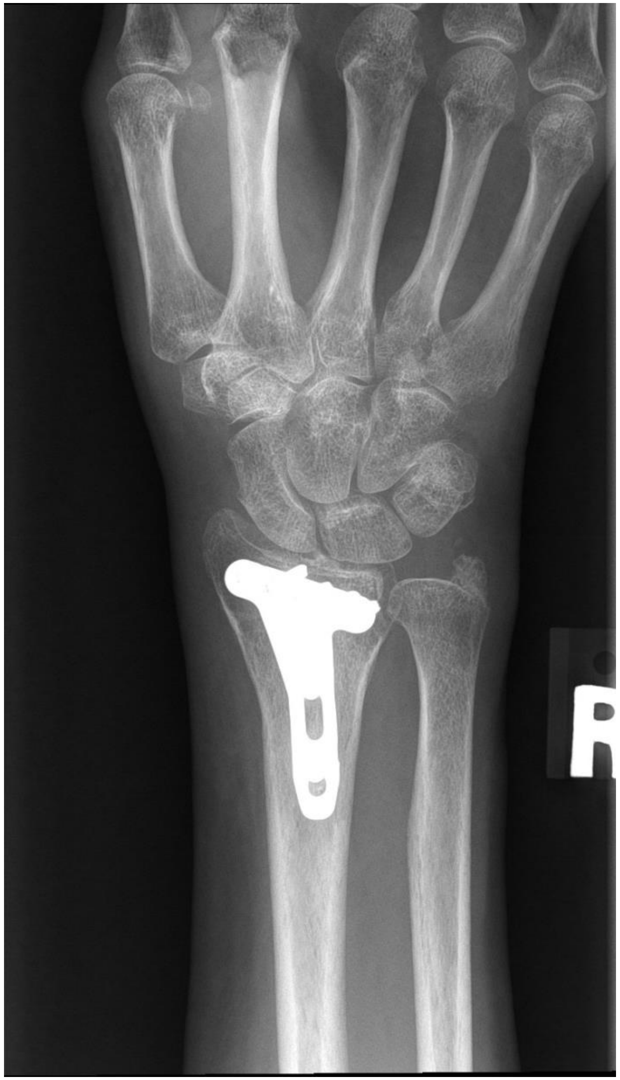
Photoelectric effect

- Photoelectric effect is followed by characteristic x-ray and/or Auger electron emissions.
- Probability of characteristic emission is low for low atomic number absorbers => does not occur frequently in diagnostic energy range.

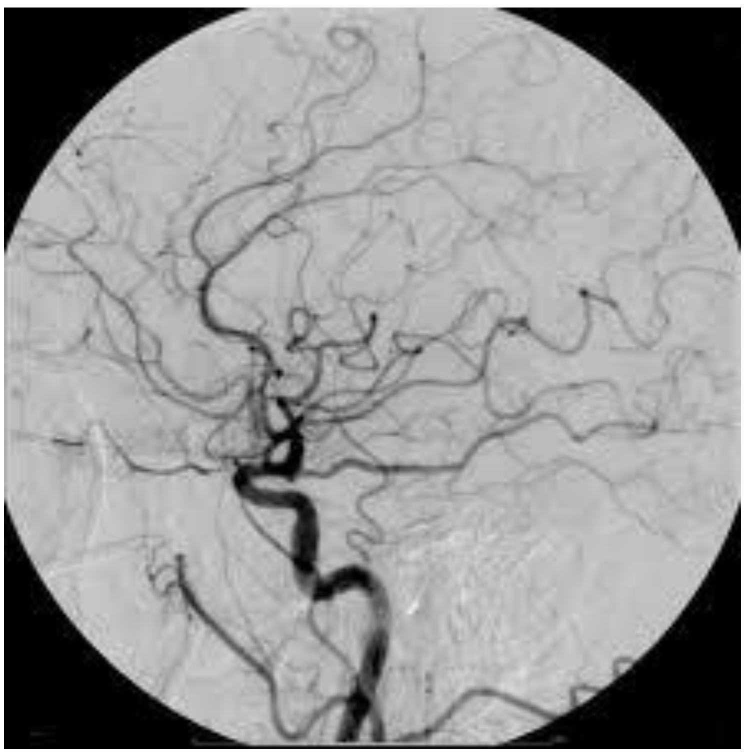
Photoelectric Effect

- Primary method by which x-ray based image contrast is developed in radiographs.
- Probability of PE is proportional to Z^3 => absorption of x-rays is higher in bone than in soft tissue.
- High Z materials appear “light” and low Z materials “dark”.



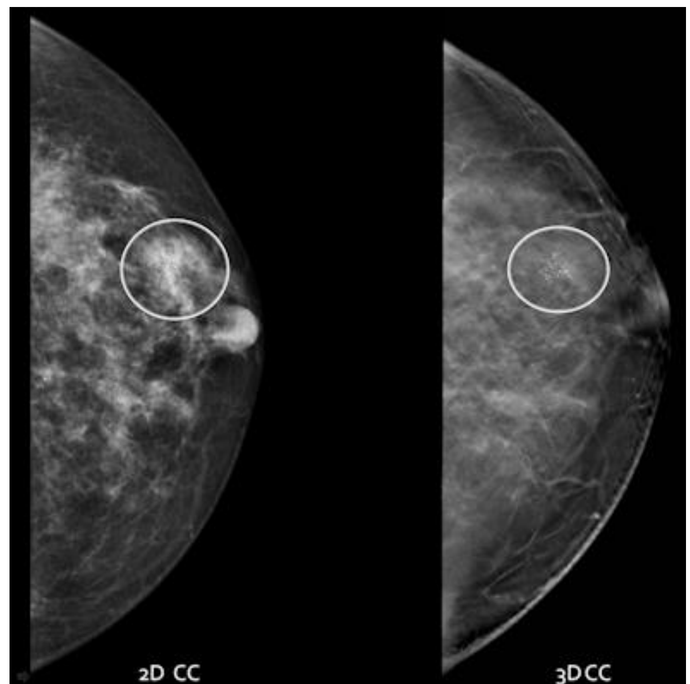
Contrast Agents

- Contrast materials that are used to enhance the absorption differences between adjacent tissues have high Z.
- Iodine Z= 53; Barium Z= 56



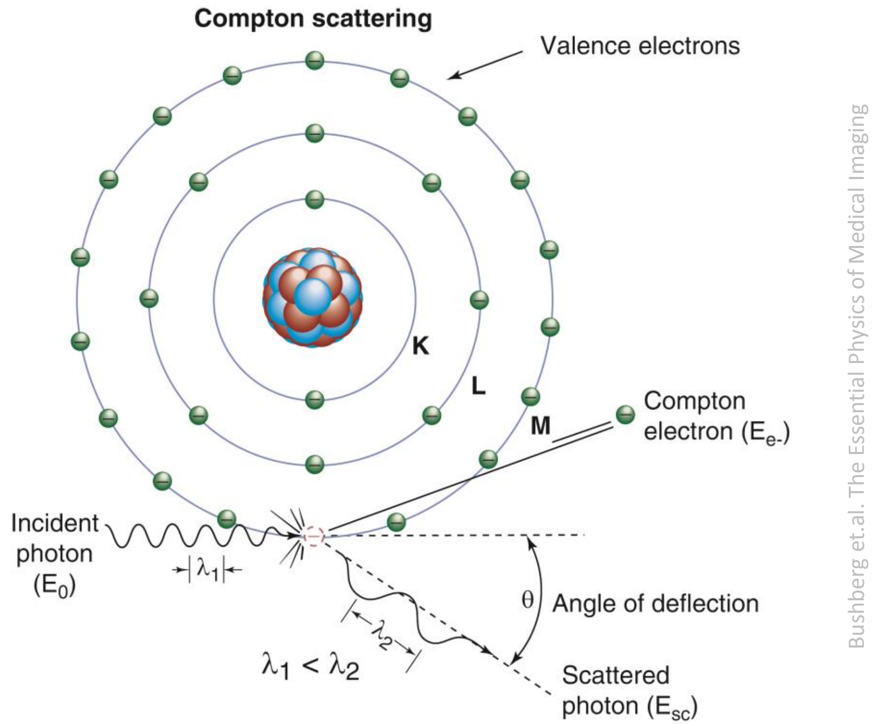
Photoelectric Effect

- Probability of PE is proportional to $1/E^3$ => absorption of x-rays is higher with lower energies.
- In order to improve image contrast in mammography, we use of low energy x-ray beams in order to maximize photoelectric effect and minimize scatter.



Micro calcifications - high Z

Compton (Incoherent) Scatter

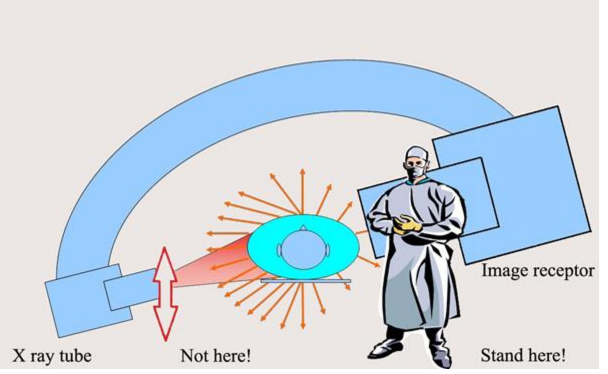


Compton Scatter

- Takes place between a photon and an outer shell electron.
- Ionization takes place.
- Energy is deposited in tissue.
- Probability increases with increased photon energy and electron density.
- Electron density is approximately the same for all elements and Compton effect is independent of Z.
- Predominant interaction in soft tissue above 26 keV, and in bone above 45 keV.

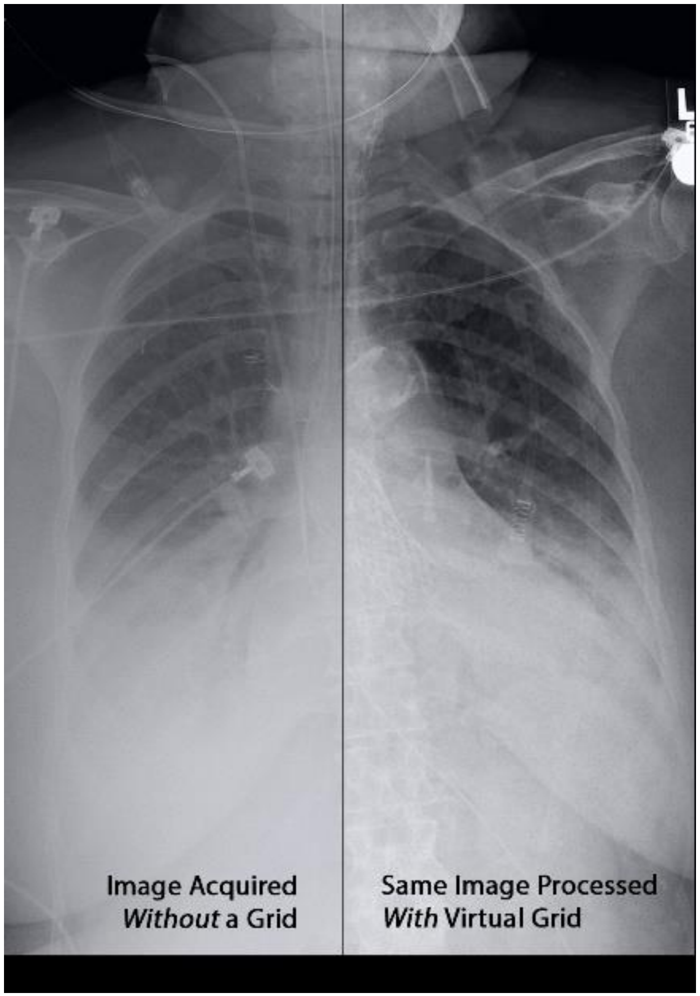
Compton Scatter

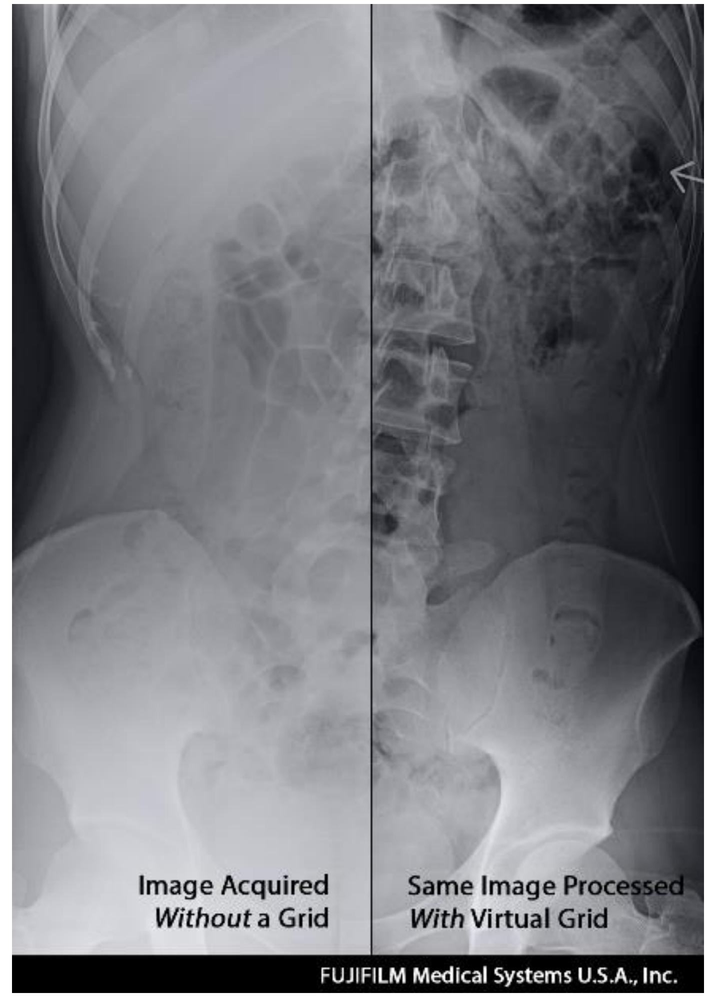
- Compton effect gives rise to radiation being scattered to all directions.
- When x-rays strike the patient, patient becomes a source of scatter radiation.



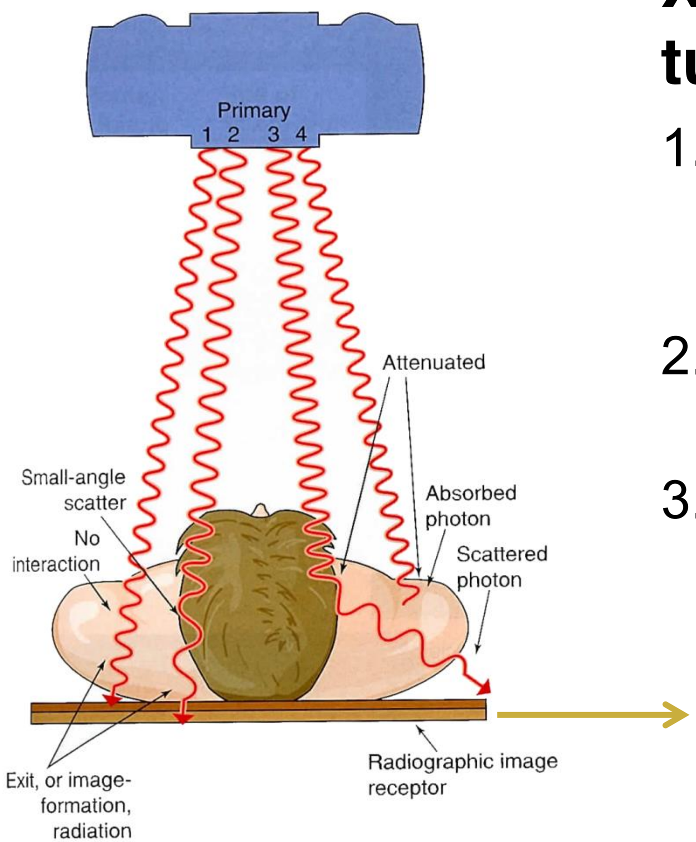
- Scattered x-rays that reach image receptor cause a background haze to images. This obscures small absorption differences between tissues resulting in loss of image sharpness.

Effect of scatter on a radiograph.





X-ray Attenuation



Shere et.al. Radiation Protection in Medical Radiography

Only a fraction of the X-rays entering to a patient exits from the patient's far side as they get either absorbed or scattered by atomic electrons and thereby removed from the beam. It is said that the beam gets attenuated.

X-rays emanating from an X-ray tube can either

1. Get transmitted, or pass through the patient without interacting with the matter.
2. Get completely absorbed by the patient.
3. Get scattered.

Enough transmitted x-rays are needed on the image receptor in order to get a diagnostic quality image.

In X-ray based imaging modalities we need to optimize imaging conditions to keep the patient dose as small as possible while still receiving enough photons in the image receptor to produce a diagnostic quality image.

X-ray Attenuation

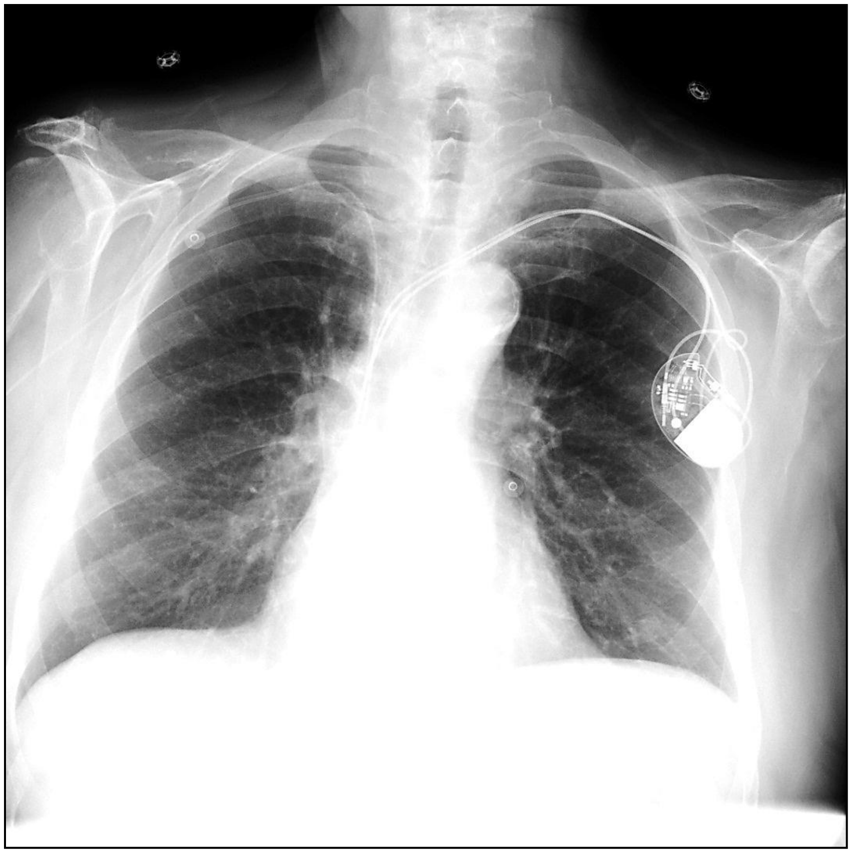
- X-rays that have no interactions with the tissue are transmitted through the patient and strike the image detector. These X-rays only contribute to the image production, but not to the patient dose as they leave no energy behind.
- X-rays that gets completely absorbed in a patient deposit all of their energy in a tissue thus contributing to the patient radiation dose. Having been completely stopped within the patient they never reach the image detector. They do contribute to the image production by virtue of differential absorption between transmitted beam and completely absorbed beam.
- During a scatter event, an X-ray changes its direction and deposits part of its energy in a tissue thus increasing the patient radiation dose. Some scattered X-rays reach the image detector resulting in diminished image quality (decreased image contrast). Thus scatter contributes to the patient radiation dose as well as image formation even in a negative manner.
    - ✓ Scatter is also the major source of personnel dose in those occasions when there is a need for a staff to stay in an examination room during exposure.
- It is the differential X-ray attenuation between various anatomical regions that is seen as different shades of gray in an X-ray image.

Differential Attenuation

- Radiographic image formation depends on a differential X-ray attenuation between various tissues.

- Some tissues attenuates more X-rays than others and the size of the differential determines the amount of contrast in the X-ray image.

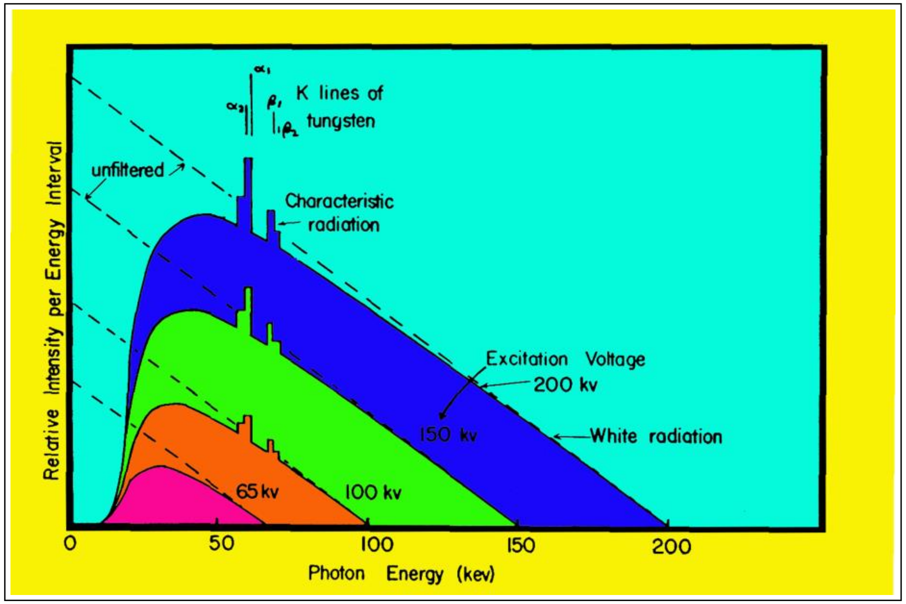
Attenuation of Various Structures



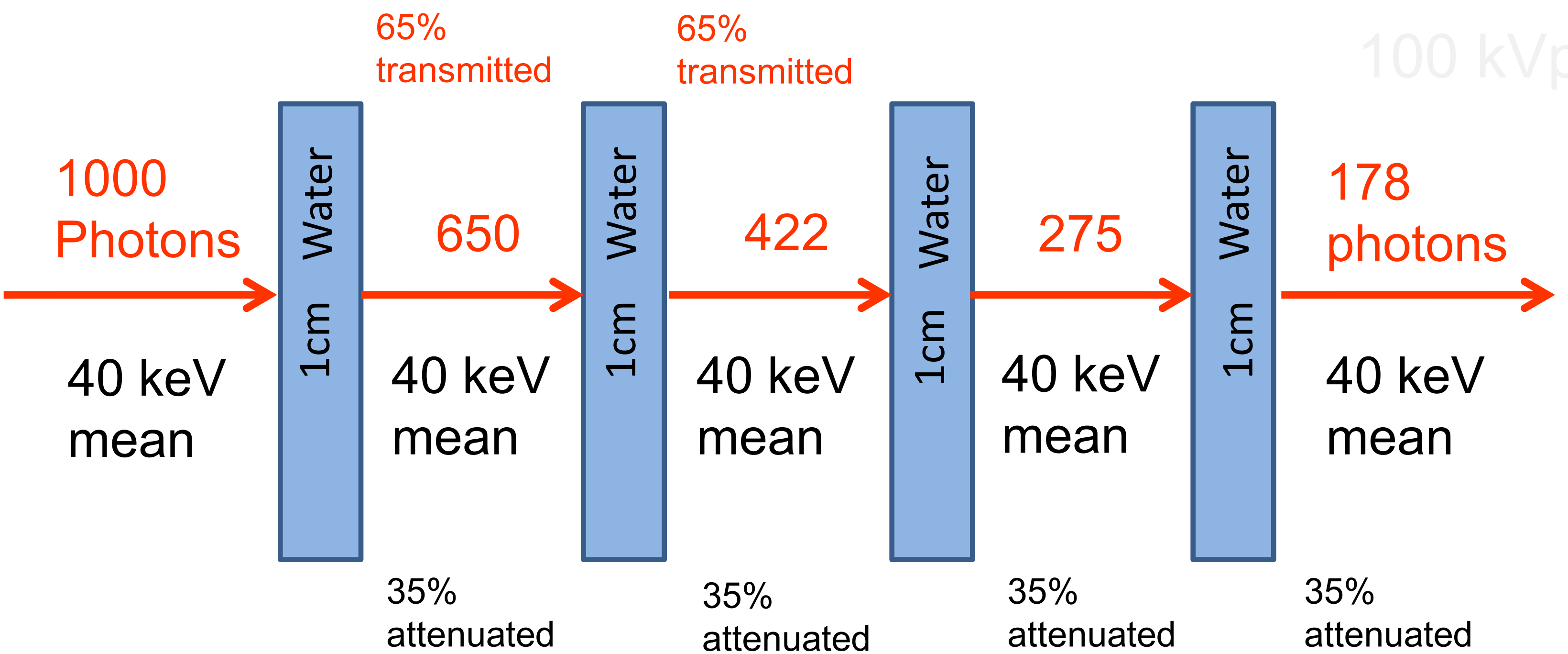
- Radiographic image formation depends on differential X-ray attenuation between various tissues.
- Some tissues attenuates more X-rays than others and the size of the differential determines the amount of contrast in the X-ray image.
- The less a given structure attenuates radiation the darker it will be on the radiograph, and vice versa.
- Bone is an effective attenuator and appears “white” on a diagnostic radiograph, whereas soft tissue appears gray while air-containing structures are “black”.

Monoenergetic vs Polyenergetic X-ray Beam

- All photons in a monoenergetic X-ray beam have the same energy.
- Polyenergetic X-ray beam contains a whole spectrum of photons with various energies representing bremsstrahlung and characteristic radiation photons.



Monoenergetic Beam Attenuation

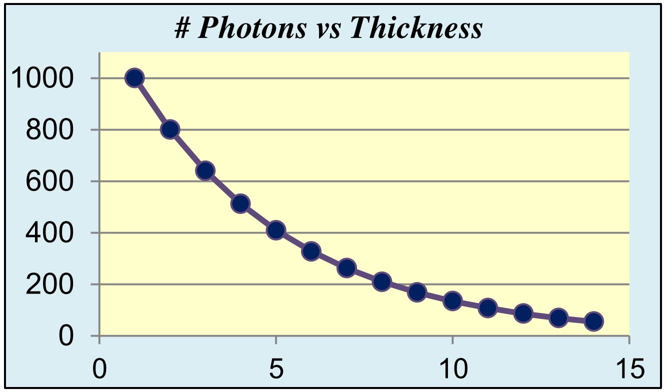


- Mean energy, and effective energy of an X-ray beam does not change when the beam propagates through matter.

Transmitted Photons vs. Thickness

- For monoenergetic photons an exponential relationship exists between the incident and transmitted photon numbers :

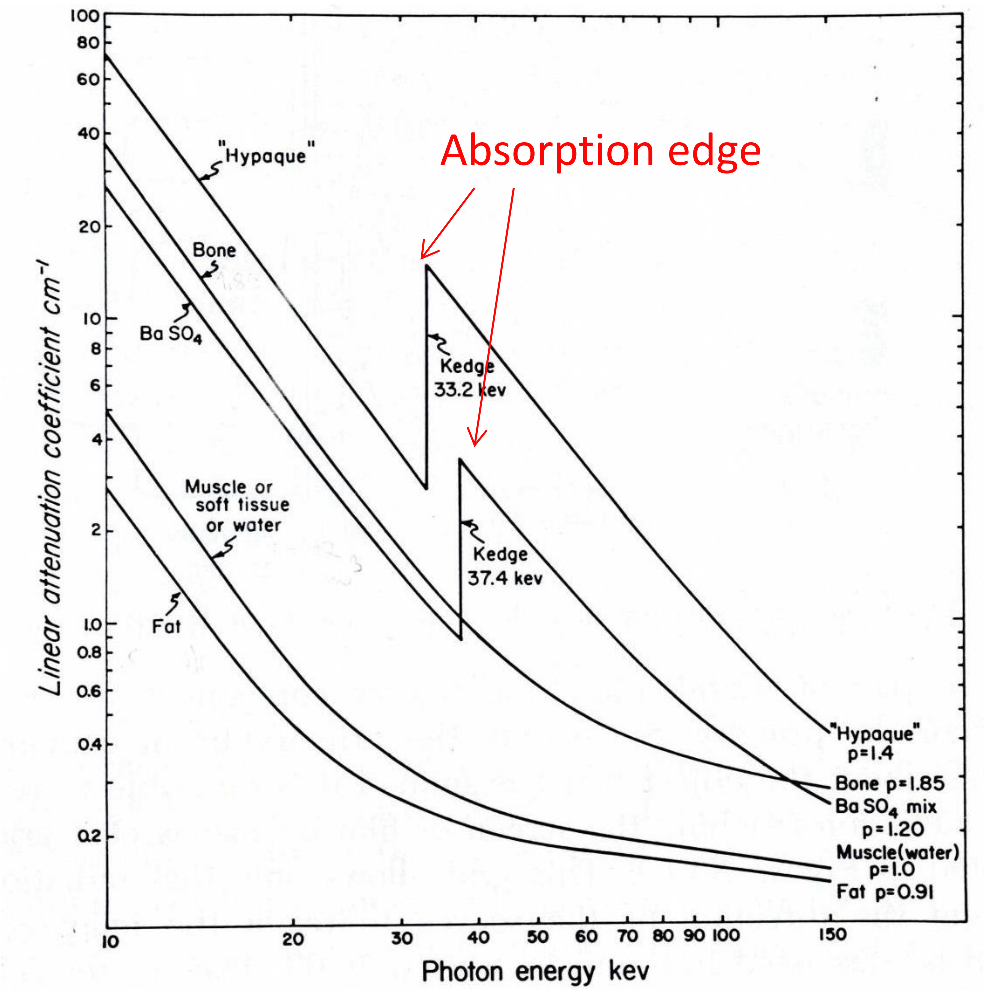
$$N = N_0 \exp(-\mu x)$$



- μ is the linear attenuation coefficient representing the fraction of photons removed per unit thickness of material.
  - ✓ Unit of μ is [cm^{-1}]

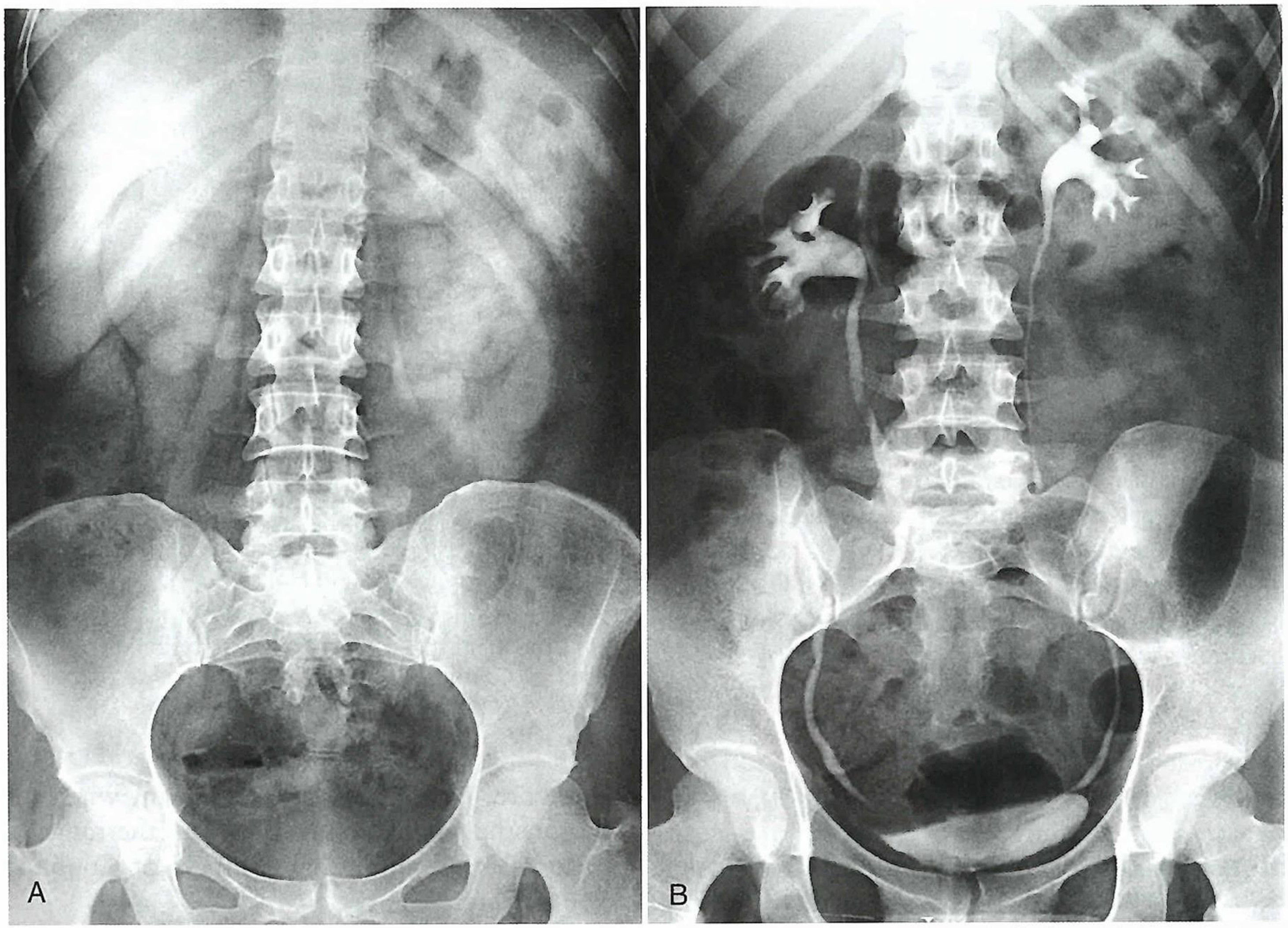
Attenuation Coefficients are material and energy specific.

Linear Attenuation Coefficient - μ_{total}

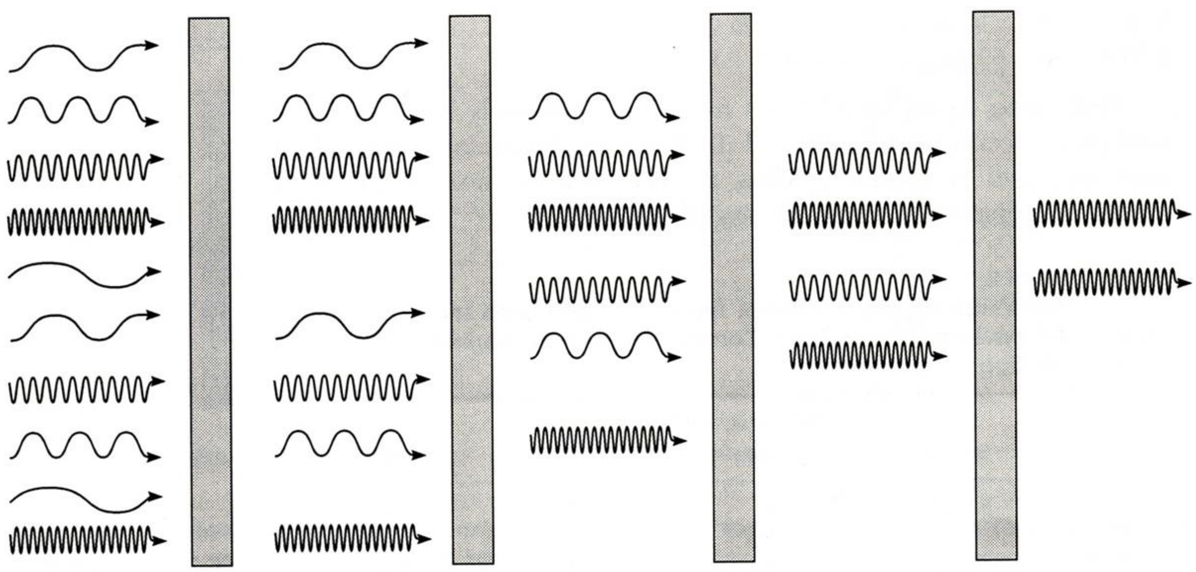


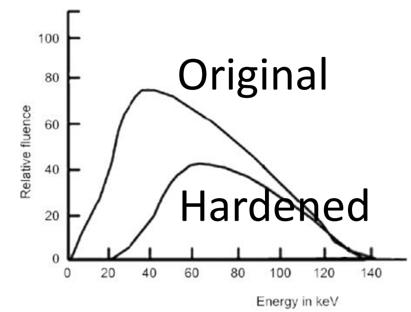
- Attenuation coefficients are material and photon energy specific.
- The binding energies of various electron shells correspond to "sudden" increases in attenuation (absorption edges). At this energy the probability for photoelectric effect increases.
- K-edge corresponds to K-shell binding energy and is the highest of these energies.

Changing attenuation between adjacent tissues with contrast material



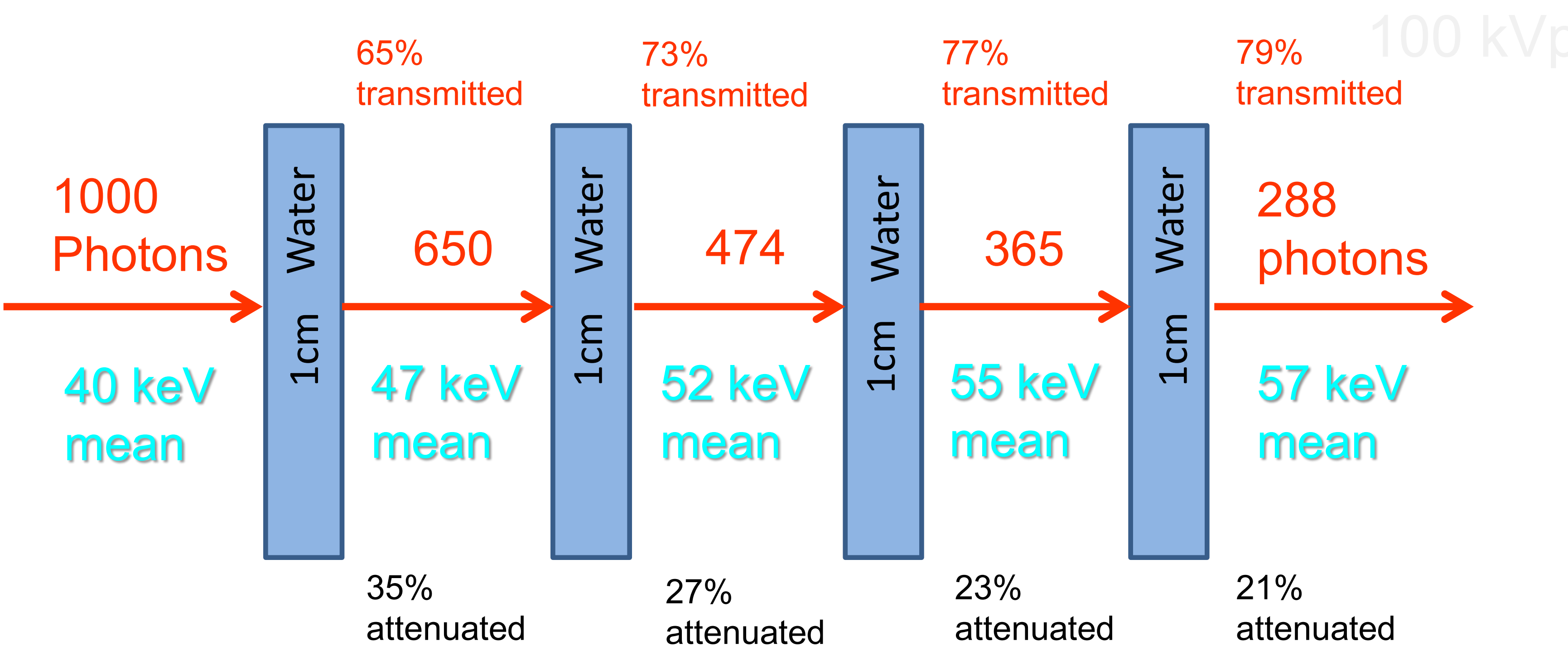
Polyenergetic Beam and Beam Hardening





- Polyenergetic X-ray beam quality changes as it travels through an absorber.
- Lower energy photons get more easily removed from the beam and the beam hardens as a function of depth traveled.
- Effective and mean energy of the beam increases.

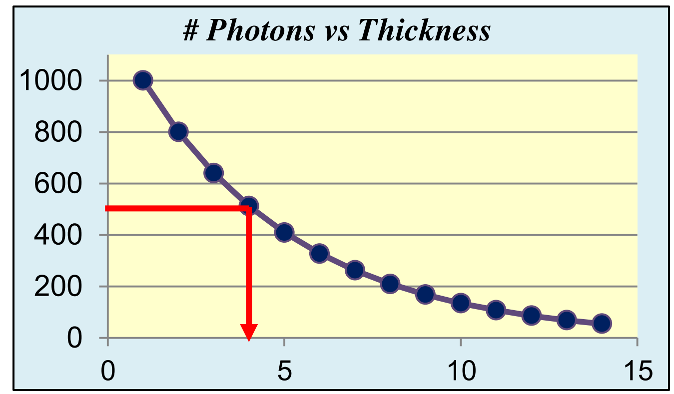
Polyenergetic Beam Attenuation



- Mean energy, and effective energy of an X-ray beam increases as a function of depth.
- This is called beam hardening.

Half Value Layer - HVL

- Half value layer (HVL) is defined as the thickness of material required to reduce the intensity of an X-ray beam to one-half of its initial value.



- Characteristic for each material and energy
- HVL quantifies the ability of an X-ray beam to penetrate tissue.

Half Value Layer - HVL

Energy [keV]	*HVL [mm] Soft Tissue*	*HVL [mm] Bone*	*HVL [mm] Lead*
	Z = 7.6	Z = 12.3	Z = 82
30	18	4	0.02
50	30	12	0.08
100	39	23	0.11
150	45	28	0.31

Radiation Parameters & Units

Exposure - X

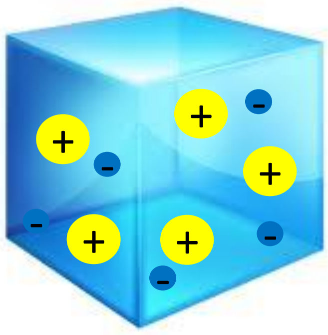
- Exposure is a measure of the radiation ability to produce ionization in air.
- The effect in tissue will be in general proportional to this effect in air.
- Exposure is the total electrical charge of one sign per unit mass of air

$$X = Q / m, \quad [\, C / kg \,]$$

✓ SI unit: Coulomb per kilogram [C/kg]

✓ Historical unit: Roentgen, R

$$1R = 2.58\ 10^{-4}\ C/kg$$



NOTE. Exposure pertains only for air, no other material.

Kerma - K

- Kerma (K) is the kinetic energy released in matter by x-rays.

- Air Kerma is the kinetic energy released by x-rays in air.

✓ SI unit: Gray

1 Gy = 1 J/kg

✓ Traditional unit: Rad

1 rad = 10 mGy

NOTE. Kerma pertains any material.

Two Different Unit Systems still in Use…

- SI Unit system :
  - Gray and Sievert
  - 1 Gy = 1 J/kg
  - 1 Sievert = 1 J/kg corrected by radiation type and/or tissue type

- Old System
  - 1 rad (radiation absorbed dose) = 0.01 J/kg = 10mGy
  - 1 rem = 10mSv

Absorbed Dose - D

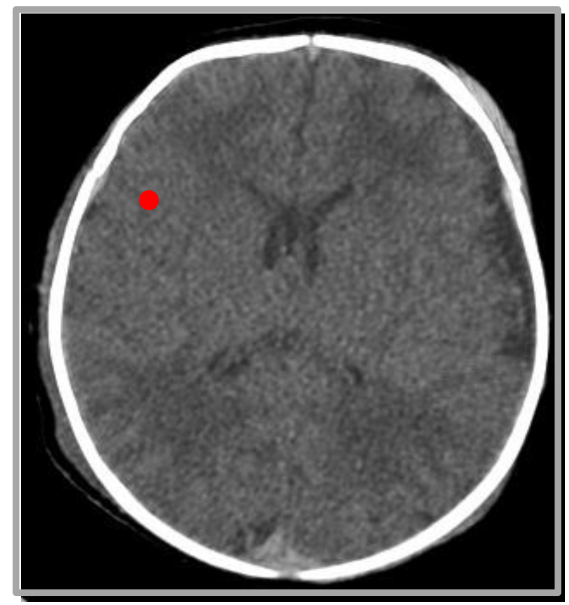
- Absorbed dose is the energy deposited by ionizing radiation per unit mass of material.

✓ SI unit: Gray

1 Gy = 1 J/kg

✓ Old unit: Rad

1 rad = 10 mGy



Organ Dose - D

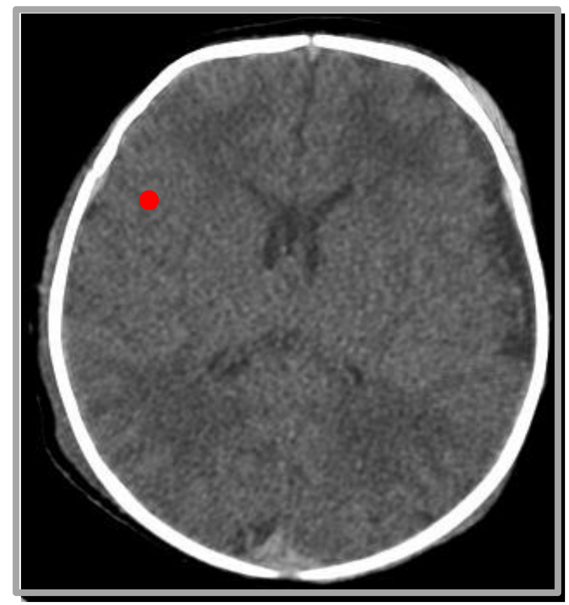
- Organ dose is the total energy deposited in an organ divided by the organ mass.

✓ SI unit: Gray

$1 \text{ Gy} = 1 \text{ J/kg}$

✓ Old unit: Rad

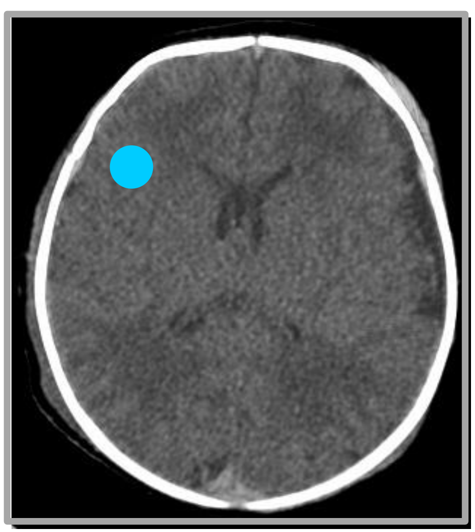
$1 \text{ rad} = 10 \text{ mGy}$



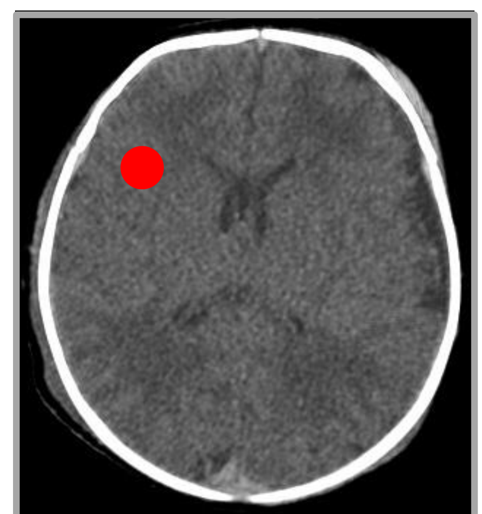
Radiation Type

- The same absorbed dose delivered by *different types of radiation* may result *in different degrees of biological damage* in tissue.
- This is taken into account by multiplying the absorbed organ dose with a radiation quality weighting factor, ω_R which expresses the biological effectiveness of a given type of radiation.

10 mGy
Neutrons



10 mGy
X-rays

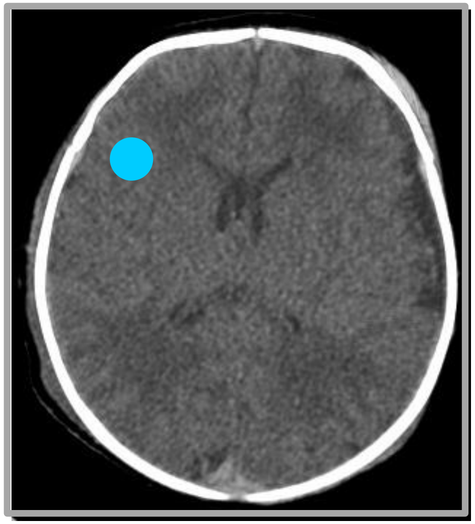


Equivalent Dose, H_T

- $H_T = \sum_R D_{T,R} \bullet \omega_R$

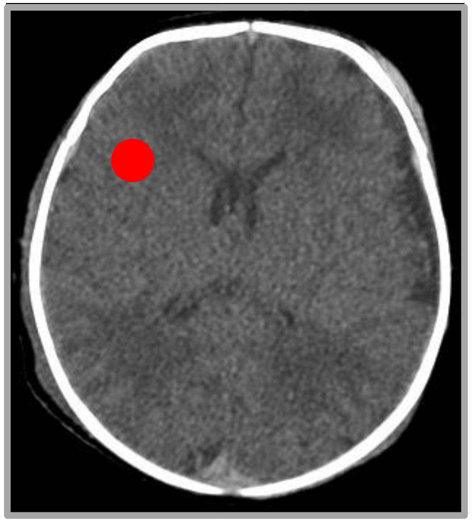
For X-rays $\omega_R = 1$

10 mGy
Neutrons



H_T = 200 mSv
Neutron ω_R = 20

10 mGy
X-rays



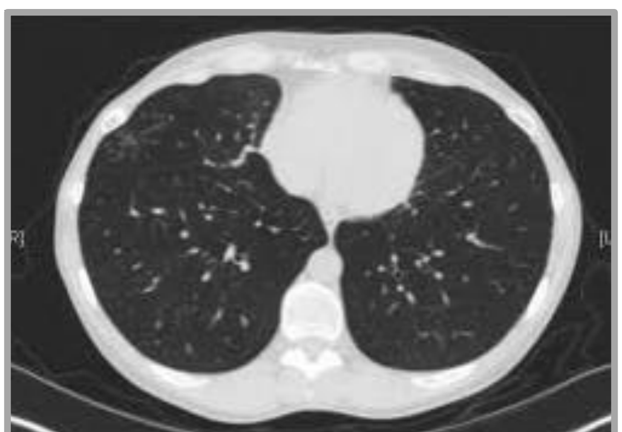
H_T = 10 mSv
X-rays ω_R = 1

Unit is Sievert [Sv]

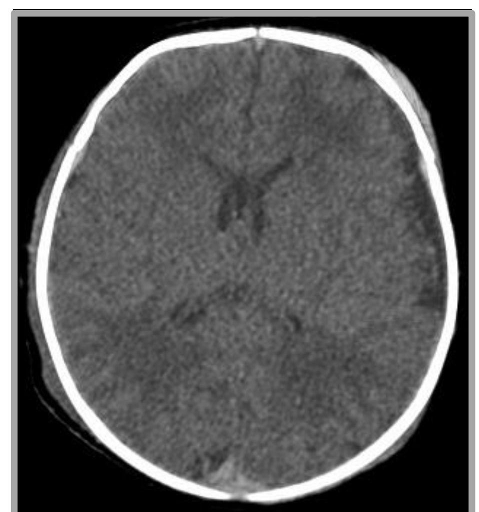
Radiosensitivity of Organs

- The same equivalent dose delivered by the same type of radiation may result *in different degrees of biological damage in different tissue types.*
- This is taken into account by multiplying the equivalent organ dose by the tissue weighting factor.

10 mGy
10 mSv
In lung



Lung
$\omega_T = 0.12$

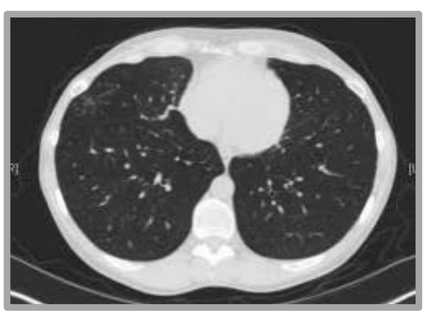


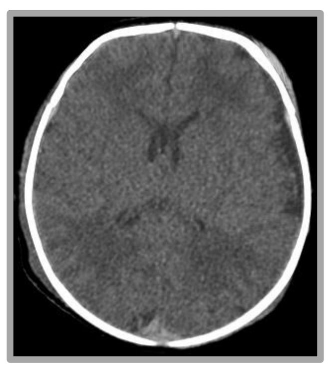
10 mGy
10 mSv
In brain

Brain
$\omega_T = 0.01$

Effective dose, E

- To reflect the combined detriment from stochastic effects due to the equivalent doses in all the organs and tissues of the body the equivalent dose in each organ and tissue is multiplied by ω_T and the results are summed over the whole body to give the effective dose.
- $E = \sum_T H_T \bullet \omega_T$





E = 1.2 mSv + 0.1 mSv

NOTE. Tissue weighting factors are “generic” rather than patient-specific; age and gender are not taken into account.

Tissue Weighting Factors – ICRP 103

Tissue	ω_T
Bone surfaces, brain, salivary glands, skin	0.01
Bladder, Liver, Oesophagus, Thyroid	0.04
Gonads	0.08
Breast, Colon, Lung, Red bone marrow, Stomach, Remainder*	0.12

Specified remainder tissues (14 total, 13 in each sex) are: Adrenals, extra-thoracic tissue, gall bladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, uterus/cervix

Summary

Exposure	X	Charge/Unit Mass	C/kg
Kerma	K	Kinetic Energy Released in Matter	[J/kg]
Absorbed Dose	D	Energy/Unit Mass	[J/kg]
Organ Dose	D	Energy / Organ Mass	[J/kg]
Equivalent Dose	H	Radiation type corrected dose	[Sv]
Effective Dose	E	Tissue type corrected whole body equivalent dose	[Sv]