# Limited Scope X-Ray Technician Course

## Module 1: Radiation Physics & X-Ray Physics

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OLYMPIC HEALTH PHYSICS

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## Outline

- Electromagnetic Spectrum/Radiation
- Wave properties and Energy
- Bohr Model – Electron Shell Structure
- Excitation and Ionization
- Radiometric Quantities (how we measure radiation)
- X-Ray Interactions
- X-Ray Production
- Use of kVp / mAs
- Heat Load / Heat Units
- Parts of the X-ray Tube / X-ray System
- X-Ray Equipment Operation & Control

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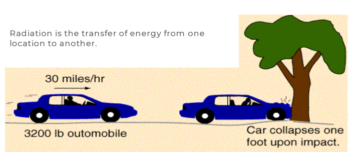
## What is Radiation

- **Radiation** is defined as energy in transit as either an electromagnetic wave or energetic particles.
- On the most basic level radiation is simply the transfer of energy from one location to another.
    - For example, a car hitting a tree.

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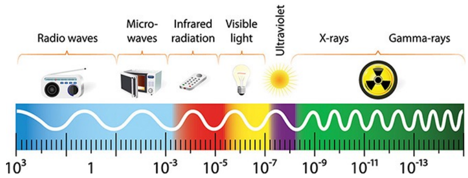
# THE ELECTROMAGNETIC SPECTRUM




All electromagnetic phenomena is radiation (i.e. energy in transit)

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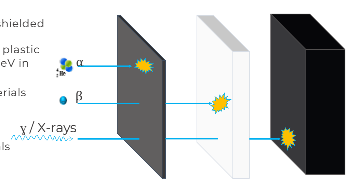
## Ionizing Radiation

Radiation can be in the form of energetic particles.

- Alpha Particles (α)
  - Short range (0.5 cm in air), easily shielded
- Beta Particles ($\beta^-$ or $\beta^+$)
  - Tortuous path, best shielded with plastic
  - Range ~ 10 ft/MeV in air; 0.5 cm/MeV in tissue
  - Bremsstrahlung with high Z materials
- Gamma Rays (γ)
  - Can travel significant distances penetrating
  - Best shielded with high Z materials
- X-rays
  - Byproduct of bremsstrahlung

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## Electromagnetic Radiation

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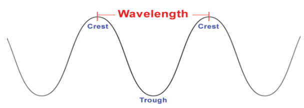
## Wavelength

- The distance between the two crests (or two troughs) of a wave
  - in **meters**.
- Usually denoted by the Greek letter lambda (λ)

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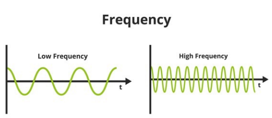
## Frequency

- The number of crests (or troughs) that occur per unit time.
- The unit for frequency is Hertz (Hz) (or cycles per second).
- Usually denoted by the Greek letter Nu (ν) or n.

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## Energy

- The relationship between wavelength, energy and frequency, and speed

$$V = \lambda \upsilon$$

- Electromagnetic waves always travel at the speed of light

$$c = \lambda \upsilon \qquad \upsilon = c/\lambda$$

- Energy of a wave (in electron volt, eV)

$$E = h\upsilon \qquad E = hc/\lambda$$

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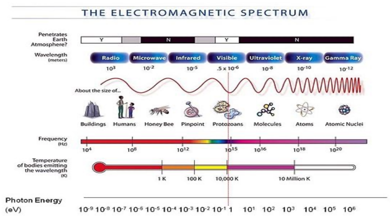


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| Name | Wavelength | Frequency (Hz) | Photon Energy (eV) |
|---|---|---|---|
| Gamma ray | Less than 0.01 nm | more than 10 EHz | 100 kev - 300+ GeV |
| X - ray | 0.01 - 10 nm | 30 EHz - 30 PHz | 120 eV - 120 keV |
| Ultraviolet | 10 nm - 400 nm | 30 PHz - 790 THz | 3 eV - 124 eV |
| Visible | 390 nm - 750 nm | 790 THz - 405 THz | 1.7 eV - 3.3 eV |
| Infrared | 750 nm - 1 mm | 405 THz - 300 GHz | 1.24 meV -1.7 eV |
| Microwave | 1 mm - 1 meter | 300 GHz - 300 MHz | 1.24 $\mu$ eV - 1.24 meV |
| Radio | 1 mm - km | 300 GHz - 3 Hz | 12.4 feV - 1.24 meV |

By convention, long waves are usually displayed in units of frequency, "optical spectrum" are displayed in units of wavelength and ionizing radiation in units of energy.

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## Atomic Model

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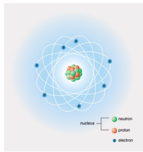
## The Atom – Atomic Structure

- Atoms are the basic building blocks of matter and are extremely small units. The diameter of one atom is in the range of $10^{-10}$ m, or about a million times smaller than human hair.
- In nature, the atom is an electrically neutral particle: it is neither positively nor negatively charged. However, atoms are made up of electrons, protons, and neutrons:
  - An electron has one unit of negative charge.
  - A proton has one unit of positive charge.
  - A neutron is electrically neutral.
- A unit of positive or negative charge is approximately $1.6 \times 10^{-19}$ coulombs (C). The coulomb is the SI unit of charge.
- Protons and neutrons (called nucleons) are fused together through strong nuclear force to form the center of an atom, or nucleus. A nucleus is positively charged.

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## The Atom – Atomic Structure (continued)

- Most of the mass of an atom is from its nucleus.
- The masses of a proton ($m_P$) and neutron ($m_N$) are similar:
  - $m_P$ is about $1.67 \times 10^{-27}$ kg
  - $m_N$ is about $1.69 \times 10^{-27}$ kg
- The mass of an electron ($m_e$) is much less: about $9.11 \times 10^{-31}$ kg, or 1800 times lighter.
- The negatively charged electrons are attracted to and orbit around the positively charged nucleus by electric force.
- Most atomic events are dictated by the mass of the nucleus through attractive forces between the nucleus and electrons.

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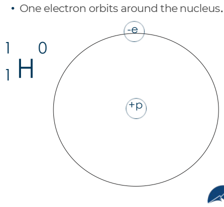
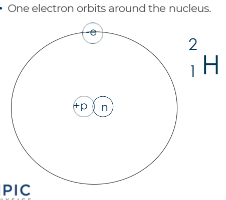
## The Atom – Atomic Structure (continued)

- The hydrogen atom (below left) - with one electron and one proton - is the simplest example of atomic structure:
  - The nucleus contains just one proton.
- One electron orbits around the nucleus.

- The Deuterium atom (below right) - with one electron, one neutron, and one proton
  - is an example of an isotope of Hydrogen:
  - The nucleus contains one proton and one neutron.
  - One electron orbits around the nucleus.

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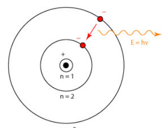
## (Rutherford) - Bohr Model (1913)

- Presented a "solar system" view of atomic structure.
- Atom consists of a dense nucleus with electrons orbiting in discrete quantized "orbits" (electron shell).
- Electrons fill in from the inner shell to the outer shell
- Movement of the an electron from one shell to another requires energy.
- Energy required depends on the binding energy of the shell.

Ernest Rutherford

Niels Bohr

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## Excitation & Ionization

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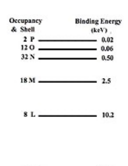
## Electron Binding Energy

- The energy required to remove an electron from an atom.
- Electrons closer to the nucleus require more energy to remove (i.e. inner shell vs. outer shell electrons).
- Electrons from atoms with higher atomic numbers require more energy to remove.
- Electrons can only move to and from specific orbits (quantized locations).




Moving from the K Shell to M shell requires 67 keV of energy (69.5 keV – 2.5 keV)

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## Excitation

- The elevation of an electron from an inner shell to an outer shell
- The energy require is the difference in binding energy between the inner and out shell.
- The charge of the atom / molecule does not change when excitation occurs (i.e. the atom is still neutral, number of electrons = number of protons).
- When the electron returns to it's ground state, energy is release in the form of electromagnetic radiation equivalent to the difference in binding energy between the electron shells.

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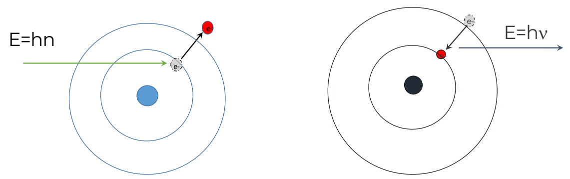
Excitation

De-excitation




Electron elevated to a higher shell due to the absorption of energy

Electron reduced to a lower shell resulting in the emission of energy

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## Ionization

- The removal of an electron from the atom.
- The energy required is equivalent to the binding energy of the electron shell.
- The atom becomes "ionized" and carries a positive charge (due to the removal of the electron).
- For molecules this can result in the breaking of molecular bonds.

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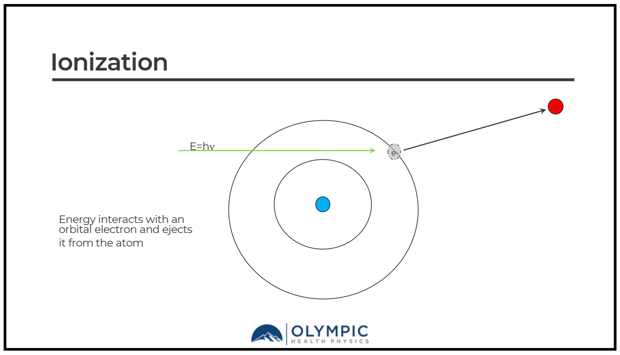
Ionization
E=hv
Energy interacts with an orbital electron and ejects it from the atom
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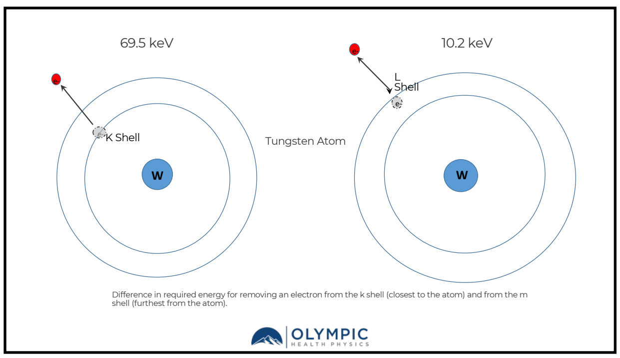
69.5 keV
10.2 keV
L Shell
K Shell
Tungsten Atom
W
W
Difference in required energy for removing an electron from the k shell (closest to the atom) and from the m shell (furthest from the atom).
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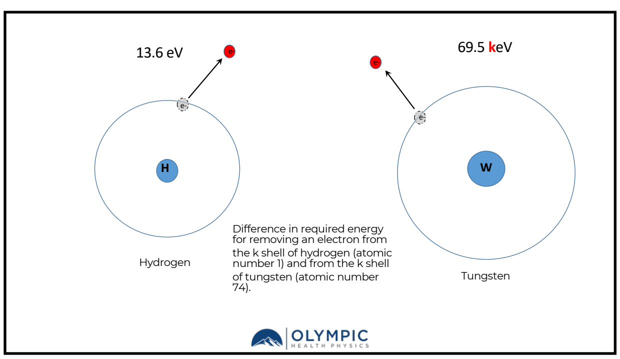
13.6 eV
69.5 keV
H
W
Hydrogen
Difference in required energy for removing an electron from the k shell of hydrogen (atomic number 1) and from the k shell of tungsten (atomic number 74).
Tungsten
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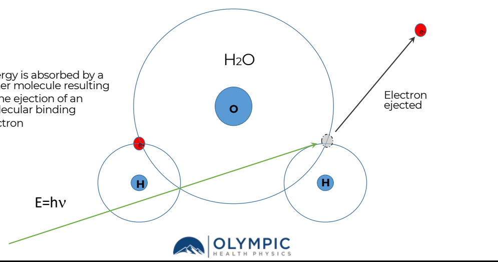
## Ionization of a water molecule

Energy is absorbed by a water molecule resulting in the ejection of an molecular binding electron

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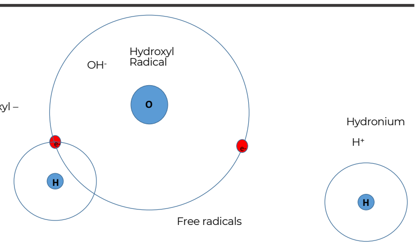
## Ionization of a water molecule

Ionization cause the formation of a Hydroxyl – Hydronium pair

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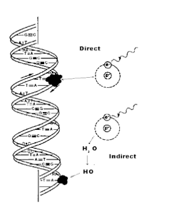
## Biological Significance of Ionization

Ionization does not only occur with water in the body but can be a direct action on the DNA molecule. Since molecular bonds are dependent on the interaction of electrons, removing electrons (ionization) will break those bonds and alter molecular structure.




Hyrdroxyl radiation will interact with DNA

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# X-Ray Interaction with Matter

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## X-Ray (Electromagnetic) Interactions

- There are four principal interactions that can occur when x-rays interact with a material.
  - Absorption
    - Energy deposited
  - Transmission
    - Energy passes through
  - Scatter
    - Energy redirected
  - Attenuation
    - Energy partially deposited

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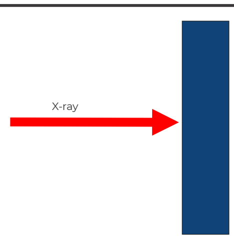
## Absorption




The X-ray is absorbed in the material

The "temperature" of the material will increase, i.e. energy absorbed shows as a temperature rise.

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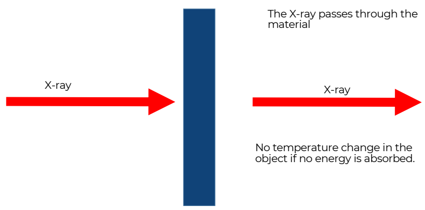
## Transmission

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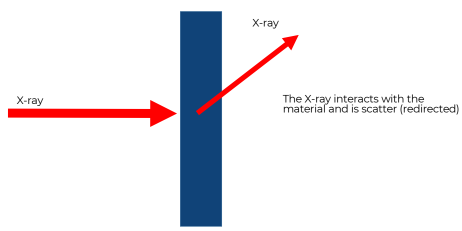
## Scatter

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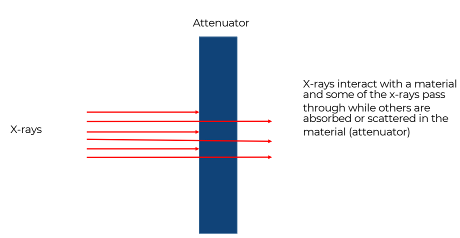
## Attenuation

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# Radiometric Units

Quantifying Radiation

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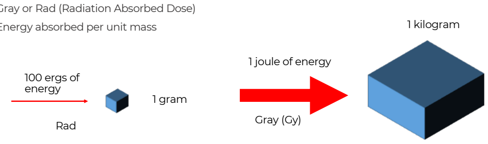
## Absorbed Dose

- Gray or Rad (Radiation Absorbed Dose)
- Energy absorbed per unit mass




1 Gray (Gy) = 100 Rad

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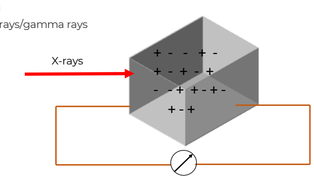
## Radiation Exposure

- Roentgen = 1 esu / cc of dry air
- $2.58 \times 10^{-4}$ C / kg
- Only valid for x-rays/gamma rays

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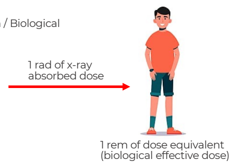
## Dose Equivalent

- Sieverts or Rem (Roentgen Man Equivalent)
- Absorbed Dose x Quality Factor
- Quality Factor = Biological Effect of Radiation / Biological Effect of 250 keV X-rays
- For diagnostic x-ray exposures, QF = 1

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## Roentgen, Rad, & Rem

- 1R of X-ray Exposure results in 0.96 rad of soft tissue absorbed dose.
- The Quality Factor (QF) for x-rays is 1
- 1R of X-ray Exposure = 0.96 rem of equivalent dose.

For diagnostic x-ray radiation exposure

**1 R = 1 Rad = 1 Rem**

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# X-Ray Production

Basics

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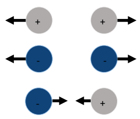
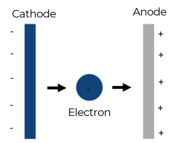
## Law of Attraction

- Opposite charges attract
- Like charges repel



- Anode – Cathode Example

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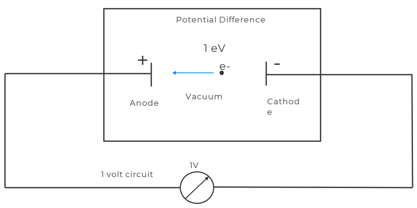
## Electrical Potential

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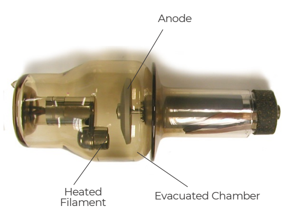
## X-ray Tube

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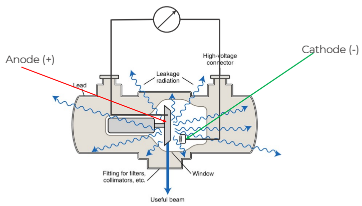
## X-ray tube

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## kVp (Potential)

- The kVp (kilovoltage potential) is a measure of the energy differential between the cathode and anode in an x-ray system.
- This determines the maximum acceleration energy of the electron.
- kVp will affect the energy spectrum of the x-rays that are produced.
- The kVp represents the maximum energy (x-ray energy) that can be generated by a x-ray system

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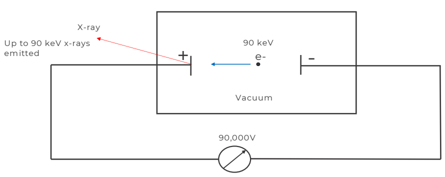
## 90 kVp

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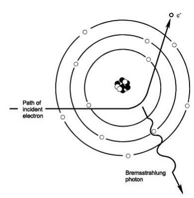
## Bremsstrahlung X-Ray

- Electrons passing near a nucleus can have their path altered due to attractive electromagnetic forces (positive nucleus, negative electron).
- The energy provided to the electron to alter it's path is radiated from the electron as electromagnetic radiation with an energy up to the maximum energy of the electron

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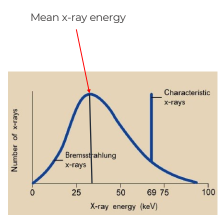
## X-Ray Spectrum

- X-ray systems produce a continuous energy spectrum from 0 to the maximum tube potential (kVp).
- Maximum number of x-rays is produced at approximately 1/3 the maximum tube potential. (i.e. 90 kVp has a peak production of 30 keV x-rays).

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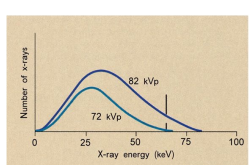
## How kVp Affects X-Ray Spectrum

- Higher kVp results in:
  - Larger number of x-rays (higher radiation dose)
  - Higher maximum energy (greater penetrating ability of the x-ray)
  - Higher average energy

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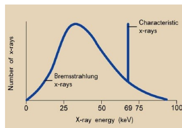
## Characteristic X-Rays

- Characteristic x-rays are also produced due to the interaction with the target material.
- For radiographic x-ray systems this is Tungsten.
- The k-shell electron binding energy is 69.5 keV so a characteristic x-ray is produced at this energy.

Characteristic X-ray peak from k-shell interaction and subsequent electron capture.

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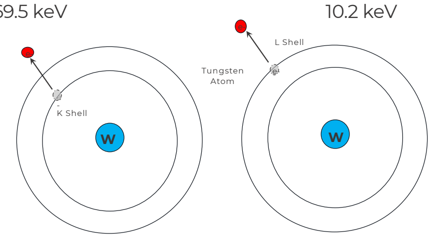
69.5 keV

10.2 keV




Difference in required energy for removing an electron from the k shell (closest to the atom) and from the m shell (furthest from the atom).

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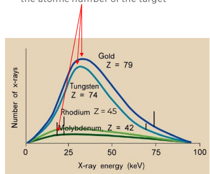
## X-Ray Spectrum Due To Target Material

- Higher atomic number targets (higher Z) will result in both a larger number of x-ray produced and a higher average (peak production) energy.
- Higher atomic number targets will also produce higher energy characteristic x-rays.

Change in peak x-ray production due to the atomic number of the target

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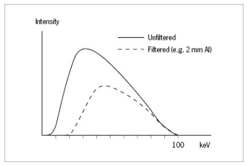
## Filtration

- X-rays below about 20 keV do not have any diagnostic value (all the energy is absorbed in tissue).
- X-ray filtration removes low energy x-rays and shifts the average energy of the x-ray beam higher.
- X-ray filtration also reduces the overall intensity (number of x-rays emitted) of the x-ray beam.

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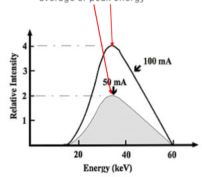
## mA (Current)

- Milliamperes (mA) is the measure of electrical current or the number of electrons "flowing" in a system.
- For x-ray systems, mA represents the intensity or number of x-ray generated.
- The higher the mA (more electrons striking the anode) the greater the number of x-rays.

Note for a given kVp, an increase in mA increase the intensity of the x-ray beam but not the average or peak energy

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## mAs

- Milliamperes-seconds. This is a combination of the current (number of electrons flowing) and the amount of time the x-ray system is activated.
- Multiple combinations of mA and time (seconds) will give the same mAs.
- Not all systems will allow independent control of mA and time.

Note all of these combination are 40 mAs

200 mA & 200 milliseconds
100 mA & 400 milliseconds
400 mA & 100 milliseconds

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## Why have different mA and time combinations?

- X-ray systems are limited in the amount of power that can be produced (e.g. total wattage).
- The maximum amount of power is tied to the combination of kVp and mA. By definition a Watt = Volt x Amp
- Increasing the amount of time an x-ray system is "on" will produce a greater number of x-rays.
- The drawback is the increased time to make an image may result in motion blurring (similar to taking a long exposure with a camera).

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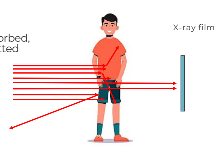
## Basic X-Ray Imaging Physics

X-rays are either absorbed, scattered or transmitted




Absorption – Scatter - Transmission

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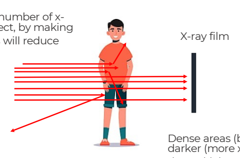
## Increasing kVp

Increasing kVp will increase the number of x-rays transmitted through an object, by making the x-ray more penetrating. This will reduce the contrast in the image




Dense areas (bone) will appear a little darker (more x-rays will pass through), less dense areas will still be dark.

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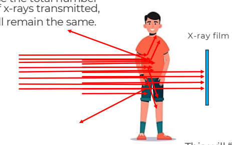
## Increasing mAs

Increasing mAs will increase the total number of x-rays. The proportion of x-rays transmitted, scattered and absorbed will remain the same.




This will "darken" the overall film (and for digital systems reduce noise). The proportion of light vs. dark areas will remain the same

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## Heat Load and Heat Units

- X-Ray generation is an inefficient process.
- The typical efficiency of an X-Ray system is usually less than 1%.
- Most of the energy used to generate X-Ray results in "waste" heat energy.
- For x-ray systems, a Heat Unit is the amount of energy that must be dissipated after the generation of X-Rays.
- If the heat load is too high the system will overheat.

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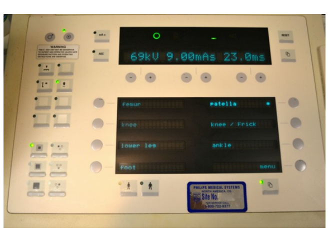
## Basic X-Ray Tube Control




- Tube Potential (kVp)
- Tube Current (mA)
- Timer (sec or ms)
- Other Considerations
  - SID (40" vs 72")
  - AEC
  - Focal Spot Size
  - Collimation & PBL
  - Detector Type (CR/DR)
  - Grids

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# Radiation Safety Considerations

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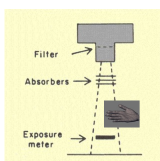
## Primary vs. Scatter Radiation

- Radiation Dose in the primary field is typically about 1000x higher (more intense) that scatter radiation
- Primary field is indicated by the collimator light field.
- When holding patients, it is important to keep the holder's anatomy outside of the primary beam




Primary X-ray Beam

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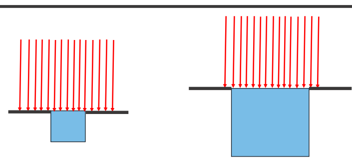
## X-Ray Field Size



Larger field of view (larger irradiated area), large radiation dose to the patient and more scatter radiation

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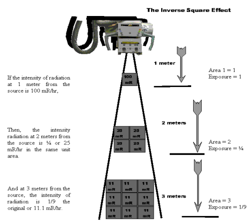
## Inverse Square Law

- Radiation dose and radiation intensity varies as the inverse square of the distance.

Dose = 1 / distance²

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## Settings Affecting Patient Radiation Dose

- Higher / Larger patient radiation doses will result from the following settings:
  - Higher kVp
  - Higher mAs
  - Larger x-ray field size
  - Positioning the patient close to the X-Rray tube

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## Summary

- The significance of X-Rays (ionizing radiation) is its ability to ionize (remove electrons from) matter.
- X-Rays are created by accelerating electrons at high speed (energy) into a target.
- For X-Ray radiation the Rad, Roentgen and Rem are approximately equal.
- kVp, mAs, X-Ray field size and distance from the X-Ray tube all affect the magnitude of radiation dose.

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