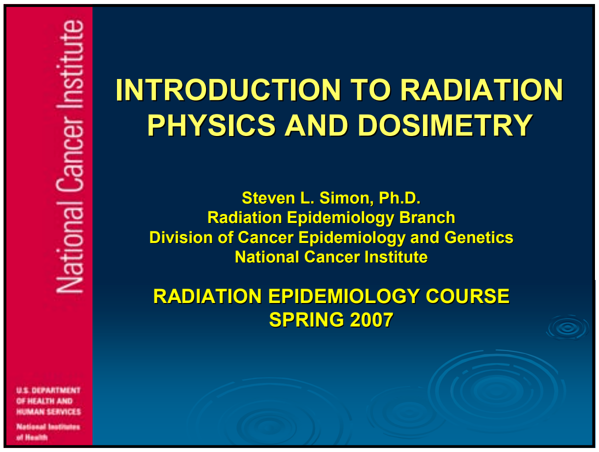

National Cancer Institute

U.S. DEPARTMENT OF HEALTH AND HUMAN SERVICES
National Institutes of Health

INTRODUCTION TO RADIATION PHYSICS AND DOSIMETRY

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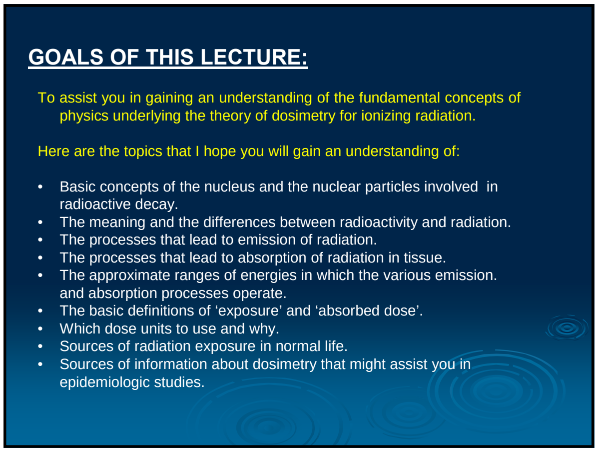
RADIATION EPIDEMIOLOGY COURSE
SPRING 2007

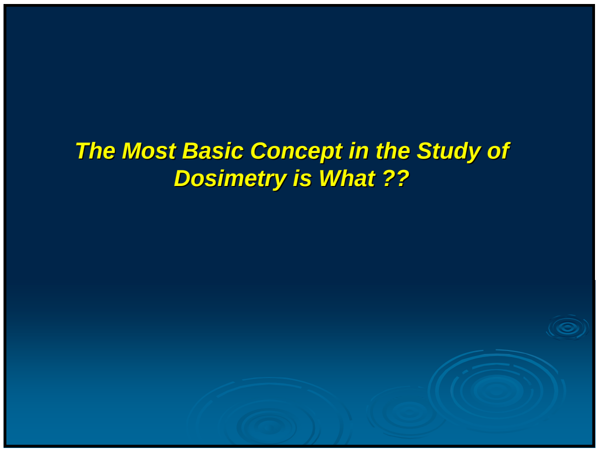


GOALS OF THIS LECTURE:

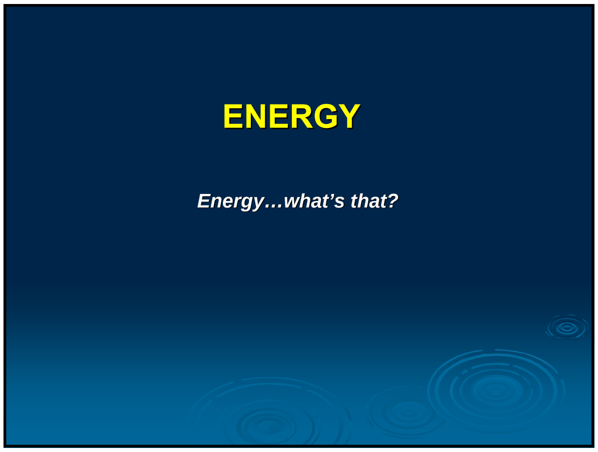
To assist you in gaining an understanding of the fundamental concepts of physics underlying the theory of dosimetry for ionizing radiation.

Here are the topics that I hope you will gain an understanding of:

- Basic concepts of the nucleus and the nuclear particles involved in radioactive decay.
- The meaning and the differences between radioactivity and radiation.
- The processes that lead to emission of radiation.
- The processes that lead to absorption of radiation in tissue.
- The approximate ranges of energies in which the various emission and absorption processes operate.
- The basic definitions of 'exposure' and 'absorbed dose'.
- Which dose units to use and why.
- Sources of radiation exposure in normal life.
- Sources of information about dosimetry that might assist you in epidemiologic studies.

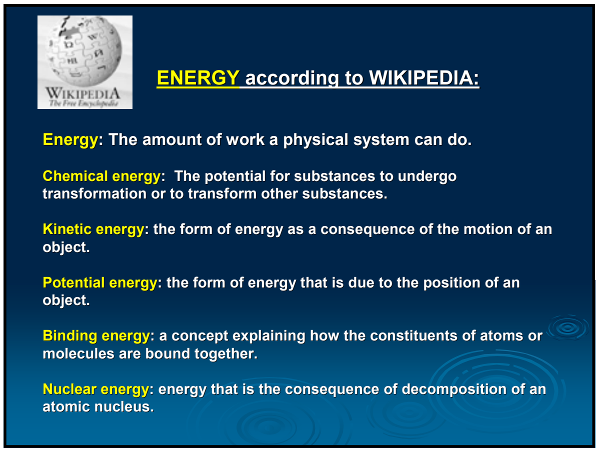


The Most Basic Concept in the Study of Dosimetry is What ??



ENERGY

Energy…what's that?



ENERGY according to WIKIPEDIA:

Energy: The amount of work a physical system can do.

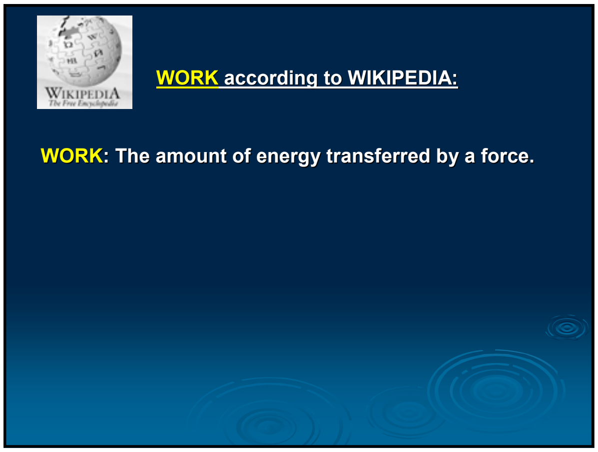
Chemical energy: The potential for substances to undergo transformation or to transform other substances.

Kinetic energy: the form of energy as a consequence of the motion of an object.

Potential energy: the form of energy that is due to the position of an object.

Binding energy: a concept explaining how the constituents of atoms or molecules are bound together.

Nuclear energy: energy that is the consequence of decomposition of an atomic nucleus.



WORK according to WIKIPEDIA:

WORK: The amount of energy transferred by a force.

FORCE according to WIKIPEDIA:

In physics, **force** is an influence that may cause a body to accelerate. It may be experienced as a lift, a push, or a pull.

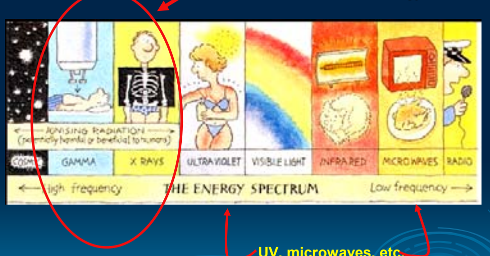
Only four fundamental **forces** are recognized: strong, electromagnetic, weak, and gravitational (in order of decreasing strength). These forces account, for example, for why the nucleus of atoms stays together as well as for radioactive decay.

Why are we interested in understanding ENERGY in Radiation Epidemiology?

A quantitative description of the absorption of energy by biological entities (organisms, tissues, organs) is how radiation dose is defined. And Risk (e.g., Cancer Risk) is defined to be a function of the dose.

Hence, the concepts of Energy and how Energy is transferred as a consequence of radiation exposure provide the logical links between Exposure, Dosimetry, and Radiation Epidemiology.

A reminder that we are discussing ionizing radiation in this lecture…even though other types of radiation are of interest in epidemiology.



**UV, microwaves, etc.
(non-ionizing)**

Some specific definitions:

Energy

A measure of the potential to do work ***(sounds simple doesn't it?)***.

Radiation

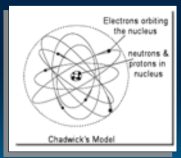
Radiation, in our context, is energy in the form of high speed particles and electromagnetic waves. Radiation is further defined into ionizing and non-ionizing radiation.

- ***Ionizing radiation*** is radiation with enough energy so that during an interaction with an atom, it can remove bound electrons, i.e., it can *ionize* atoms. Examples are X-rays and electrons.
- ***Non-ionizing radiation*** is radiation without enough energy to remove bound electrons from their orbits around atoms. Examples are microwaves and visible light.

Part I.
CONCEPTS OF NUCLEAR AND RADIATION PHYSICS

Nuclear Properties and Terminology

- The atom, for all practical purposes, consists of three basic particles, electrons, neutrons, and protons.
- The nucleus contains protons, which have positive charge, and neutrons, which have no charge.
- Both the proton and neutrons have masses approximately **1836x** that of orbital electrons which are generally described as surrounding the nucleus, either as discrete particles, are part of an electron 'cloud'.



Chadwick's Model

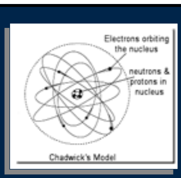
This model of the atom, though obviously simplistic, is sufficient for the purposes here.

Diameter of nucleus ~10^{-12} cm
Diameter of atom ~10^{-8} cm

Number of protons = Z, where Z is called the "atomic number"

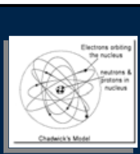
Number of neutrons = N

A = Z + N, where is the "atomic mass"



A nuclide is an atom of a particular atomic mass A

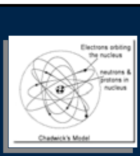
Nuclides are written as: $^{A}_{Z}X$ **(where X is the chemical symbol)**



- The nucleus contains about 99.75% of the mass of an atom.
- 1 mass unit is equivalent to 1/12 a ^{12}C atom.
- The energy equivalent of that mass, determined from $E=mc^2$, is 1.49×10^{-10} Joules (J) or 931×10^6 eV (931 MeV).

Mass and energy equivalence of some nuclear particles

Particle	Mass units 'u'	m_oc^2 (meV)
Electron	5.48597×10^{-4}	0.511007
Neutron	1.008665	939.551
Proton	1.007277	938.258
Alpha particle	4.001506	3727.323



The actual mass of an atomic nucleus is always a little smaller than the sum of the rest masses of all its nucleons (protons and neutrons).

The reason is that some of the mass of the nucleons is changed into energy to form the nucleus (and overcome the electrostatic repulsion among like charges).

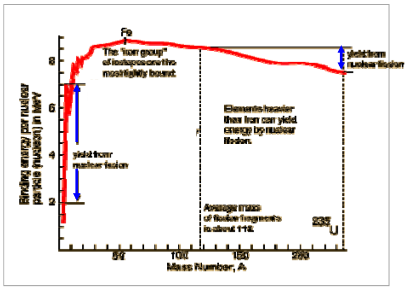
The energy required to assemble the separate parts into a whole nucleus (or atom) is called the **BINDING ENERGY**. The higher the binding energy, the more stable the nucleus is.

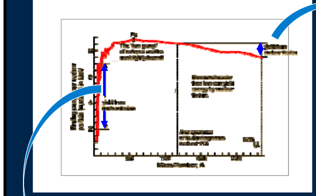
The binding energy explains the source of the energy released by radioactive decay processes. **That energy is of great importance in radiation protection and dosimetry.**

Using the $E=mc^2$ formulation, the **Binding Energy** can be written as difference in the sum of the rest masses of the individual nucleons and the rest mass of the assembled nucleus:

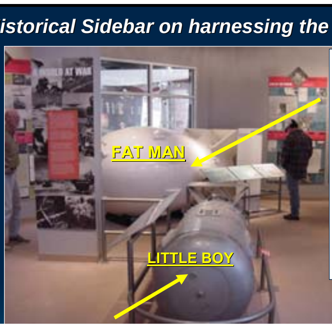
$$BE = [Zm_p + (A-Z)m_n - {}^{A}_{Z}m]\,c^2$$

Binding Energy varies with mass number





Historical Sidebar on harnessing the Binding Energy



NAGASAKI BOMB
Weight: 10,800 lbs
Fuel: Highly enriched Pu-239 (approx. 13.6 lbs; approx. size of a softball)
Plutonium core surrounded by 5,300 lbs of high explosives; plutonium core reduced to size of tennis ball
Efficiency of weapon: 10 times that of Little Boy
Approx 1.176 Kilograms of plutonium converted to energy
Explosive force: ~21,400 tons of TNT equivalent

HIROSHIMA BOMB
Weight: 9,700 lbs
Fuel: Highly enriched uranium (approx. 140 lbs); target - 85 lbs and projectile - 55 lbs
Efficiency of weapon: poor
Approx. 1.38% of the uranium fuel actually fissioned
Explosive force: ~16,000 tons of TNT equivalent

Nuclear Decay Processes

- The process of spontaneous nuclear transformation occurs generally because of instability in the neutron:proton ratio or because the atom is an excited state following a previous transformation.
- This transformation process is termed *radionuclide decay*, *nuclear disintegration*, or *radioactivity*.
- Radioactivity simply refers to the property of unstable atoms to transform themselves and move to a more stable configuration.
- The nuclear transformation process releases energy via photons or emission of particles. The energy and/or particles released are loosely termed *radiation*. (!!!)

Summary of radiation types and selected characteristics

Radiation Type	Charge	Approximate energy range	Approximate range		Primary Source
			In air	In water	
	Energetic Particles				
Alpha (2n+2p)	+2	3 to 9 MeV	2 to 8 cm	20 μm to 100 μm	Some nuclei of high Z
Electron (beta, positron)	± 1	0 to 3 MeV	Up to 12 m	Up to a few mm	Nuclei with high or low n/p ratio
Neutron	0	0 to 10 MeV	Up to 100 m	Up to 1 m	Nuclear reactions
	Electromagnetic Radiation				
X ray	None	A few eV to several MeV	A few mm to 10 m	Up to a few cm	Orbital electron transitions and *Bremsstrahlung*
Gamma ray	None	~10 keV to 10 MeV	A few cm to 100 m	From a few mm to several cm	Nuclear transitions

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We will briefly discuss each decay process that leads to the emission of radiation …

Alpha decay

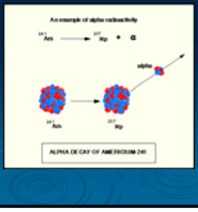
All nuclei heavier than lead are unstable; most decay by alpha emission.

In alpha decay, 2p+2n leave the nucleus as a single 'alpha' (α) particle. For example, natural uranium-238 decays by alpha emission:

$$^{238}_{92}\mathrm{U} \rightarrow ^{234}_{90}\mathrm{Th} + ^{4}_{2}\alpha$$

Energy released = Q_{α} = 4.268 MeV (KE of particle),
$t_{1/2} = 4.51 \times 10^{9}$ years

Another example is the decay of ^{241}Am, which itself is a product of the decay of ^{241}Pu:



Spontaneous fission

Some heavy nuclei can split (fission) into several smaller fragments plus neutrons.

Nuclides that undergo spontaneous fission also are subject to alpha decay. In uranium-238, alpha decay is about 2 million times more probable than is spontaneous fission, whereas in fermium-256, 3 percent of the nuclei undergo alpha decay and 97 percent undergo spontaneous fission.

The fission fragments are generally radioactive and decay by a chain of β emissions toward stable nuclei. Example:

$$^{252}_{98}Cf \rightarrow ^{140}_{54}Xe + ^{108}_{44}Ru + 4\,^{1}_{0}n$$

Beta (β) decay

Beta decay involves a class of particles called 'leptons' which include electrons (e-), positrons (e+), neutrinos (ν), and anti-neutrinos ($\overline{\nu}$). Beta decay processes conserve lepton number as well as charge.

Beta (β) decay

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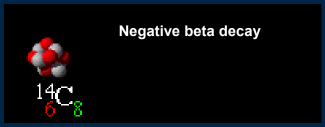
In β decay, there are 3 processes:

$n \rightarrow p + \beta^- + \bar{\nu}$ (β^- decay)

$p \rightarrow n + \beta^+ + \nu$ (β^+ decay)

$p + e^- \rightarrow n + \nu$ (electron capture or 'EC')

Negative beta decay: the decay of a neutron into a proton, which remains in the nucleus, and an electron, which is emitted as a beta particle

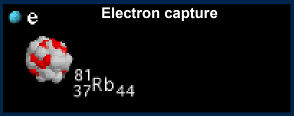


$${}^{14}_{6}C_8 \Rightarrow {}^{14}_{7}N_7 + e + \bar{\nu}_e$$

Positive beta decay: the decay of a proton into a neutron, which remains in the nucleus, and a positive electron, which is emitted as a beta particle

$${}^{18}_{9}F_9 \Rightarrow {}^{18}_{8}O_{10} + e^+ + \nu_e$$

Electron capture: the capture of an electron by the nucleus, resulting in the loss of one proton and the creation of one neutron.



$${}^{81}_{37}Rb_{44} + e \Rightarrow {}^{81}_{36}Kr_{45} + \nu_e$$

Gamma Emission

Nuclei can be in excited states following another type of transformation.

Depending on the available energy, the atoms can emit heavy particles, however, if the energy to be released is below the the binding energy of the last n, p, or α particle, the de-excitation (or movement towards stability) can be by emission of electromagnetic energy (i.e., a photon).

The emitted photon (usually called a 'gamma ray') has a characteristic wavelength determined by its energy. For example, a 0.5 MeV gamma photon has a wavelength on the order of 50 nuclear diameters.

Example: decay of Technetium-99m (the primary radionuclide used in diagnostic nuclear medicine)

$${}^{99m}_{43}Tc \rightarrow {}^{99}_{43}Tc + \gamma$$

E_γ = 142 keV,

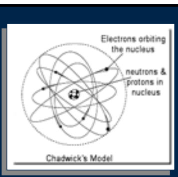
$t_{1/2}$ = 6.02 hr

Note that neither Z or A changes as a result of gamma emission.

Understanding radioactivity….

Some things you should know:

- **What are radionuclides?**
- **What is half-life?**
- **What are the origins of radionuclides?**
- **Which of their properties are relevant to dosimetry?**
- **What is activity?**
- **What is the units of activity?**



REMINDER

\# protons = Z where Z is called the ‘atomic number.’

\# neutrons = N

A = Z + N, where is the ‘atomic mass.’

- A nuclide is an atom of a particular atomic mass A
- Nuclides are written as: $^{A}_{Z}X$ (where X is the chemical symbol)
- A radionuclide is a nuclide which is unstable against radioactive decay.

Nuclides with identical Z are called “isotopes.”
Nuclides with identical A are called “isobars.”
Nuclides with identical N are called “istotones.”
A nuclide in an ‘excited’ (excess energy) state is called an “isomeric” or “metastable” state.

Some examples:

Isotopes: $^{123}_{53}I$, $^{124}_{53}I$, $^{125}_{53}I$, $^{126}_{53}I$, $^{127}_{53}I$, $^{128}_{53}I$, $^{129}_{53}I$, $^{130}_{53}I$, $^{131}_{53}I$, $^{132}_{53}I$

Isobars: $^{131}_{50}Sn$, $^{131}_{51}Sb$, $^{131}_{52}Te$, $^{131}_{53}I$, $^{131}_{54}Xe$, $^{131}_{55}Cs$

Isotones: $^{125}_{48}Cd$, $^{126}_{49}In$, $^{127}_{50}Sn$, $^{128}_{51}Sb$, $^{129}_{52}Te$

Metastable state: $^{130m}_{53}I$ ($t_{1/2}$ = 9 min), $^{132m}_{53}I$ ($t_{1/2}$ = 1.4 hr), $^{137m}_{56}Ba$ ($t_{1/2}$ = 2.5 min),

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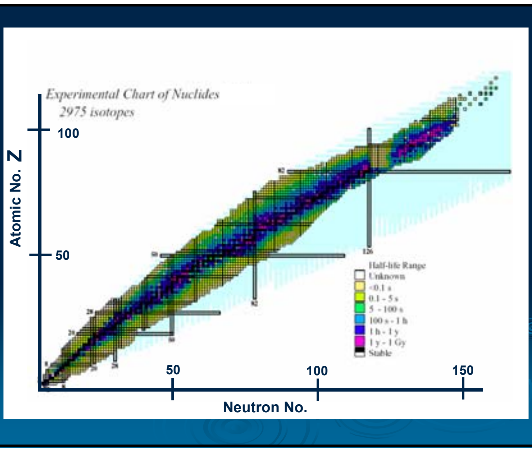
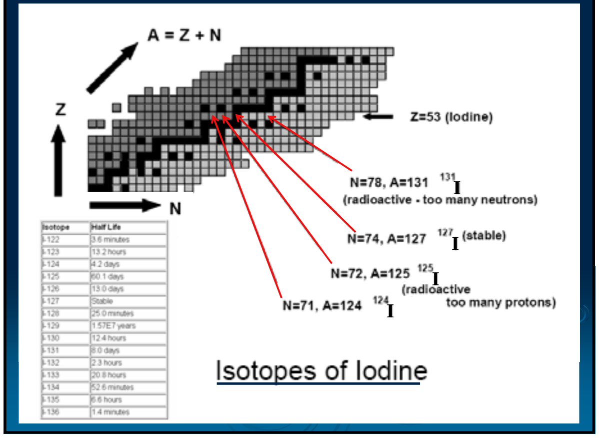
Radionuclides: some important points:

- While there are about 113 known chemical elements, there about 3100 nuclides found in nature.
- About 25 have sufficiently long half-lives to half survived from the formation of the earth until now!!
- Another 35 have shorter half-lives but are being continuously produced by the decay of parent nuclides.
- About 1000 artificially produced nuclides have been discovered. Artificially produced nuclides with Z>92 (uranium) have been produced by bombarding smaller atoms with neutrons and/or α particles.
  - Those artificially produced elements beyond U are called ‘transuranics.’
- Possibly the most important *transuranic* is ^{239}Pu which is produced by bombardment of ^{238}U with neutrons. Plutonium-239 can be induced to fission and thus constitutes the primary fuel for fission-type nuclear weapons.
- Exposure to transuranics is generally related to activities associated with the nuclear weapons program. The importance of transuranics to doses received from nuclear power is usually minor.





Isotope	Half Life
I-122	3.6 minutes
I-123	13.2 hours
I-124	4.2 days
I-125	60.1 days
I-126	13.0 days
I-127	Stable
I-128	25.0 minutes
I-129	1.57E7 years
I-130	12.4 hours
I-131	8.0 days
I-132	2.3 hours
I-133	20.8 hours
I-134	52.6 minutes
I-135	6.6 hours
I-136	1.4 minutes

Isotopes of Iodine

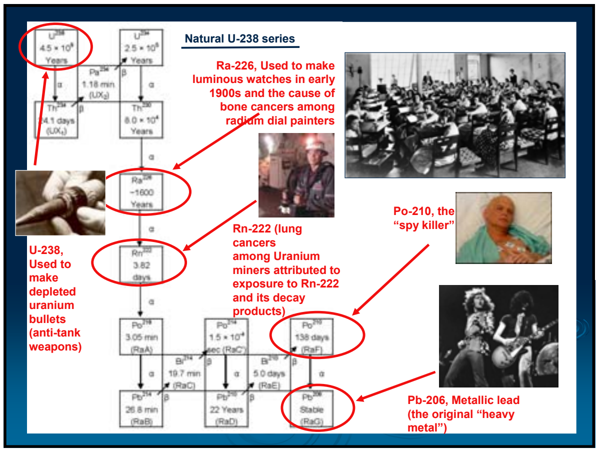
There are 4 families of naturally occurring radionuclides.

Each family begins with a parent radionuclide that decays through a number of progeny nuclides to a final stable nuclide.

The transition between each successive nuclide is by one (or more) of the decay processes just discussed: primarily alpha and beta decay.

Two series are important: ^{238}U and ^{232}Th:
The uranium series begins with ^{238}U and ends with ^{206}Pb.
The thorium series begins with ^{232}Th and ends with the stable nuclide ^{208}Pb.

The most important nuclide in these series, in terms of public exposure, is ^{222}Rn (radon-222).



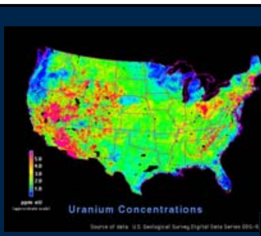
Ra-226, Used to make luminous watches in early 1900s and the cause of bone cancers among radium dial painters

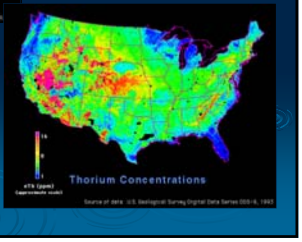
U-238, Used to make depleted uranium bullets (anti-tank weapons)

Rn-222 (lung cancers among Uranium miners attributed to exposure to Rn-222 and its decay products)

Po-210, the "spy killer"

Pb-206, Metallic lead (the original "heavy metal")





Natural radionuclides in are ubiquitous in the environment and contribute to background radiation dose.

"**Activity**" is simply a measure of the **rate of decay** (i.e., rate of spontaneous disintegration) of the atoms of a nuclide.

The unit of radioactivity historically was the Curie and was defined to be equal to the disintegration rate of 1 gm of ^{226}Ra, or 3.7×10^{10} disintegrations per second (d/s).

You can have subunits of mCi (10^{-3} Ci), µCi (10^{-6} Ci), nCi (10^{-9} Ci), pCi (10^{-12} Ci), etc.

All other nuclides also used the definition of 3.7×10^{10} d/s to define a Ci.

The units of radioactivity in the international system of units (SI units) is the Becquerel (Bq) which is simply equal to 1 d/s. Hence, 1 Bq ≈ 27 pCi.

In an ensemble of atoms of a single nuclide, the number of atoms that decay in a unit time interval is proportional to the number available. Hence, the rate of decay is exponential:

$$N(t) = N_o e^{-\lambda t}$$

where λ is a constant = $\log_e(2)$/half-life

Half-Life

Half-life is the length of time for half of the atoms of a given nuclide to decay.

The half-life a unique characteristic of each nuclide.

Half-lives range from millionths of a second to millions of years.

The half-life determines the rate at which the nuclide releases energy, thus, **doses received from individual nuclides within a unit time are a function of the half-life as well as the energy released in each decay.**

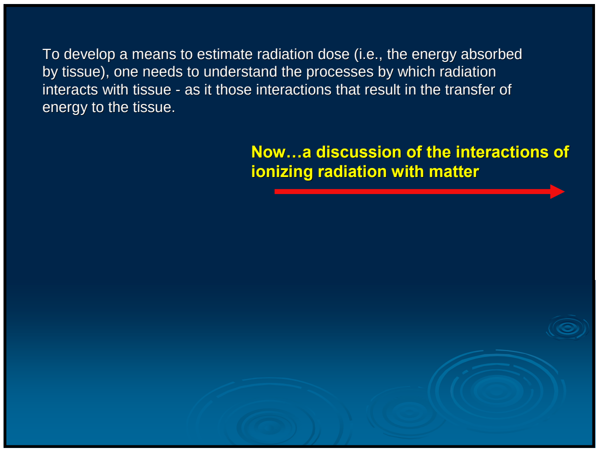
Radionuclides are thus uniquely distinguished by:

- Half-life
- Type of radiations emitted
- Energy of emitted radiations

The number of atoms of the nuclide determines the "activity" at any moment.

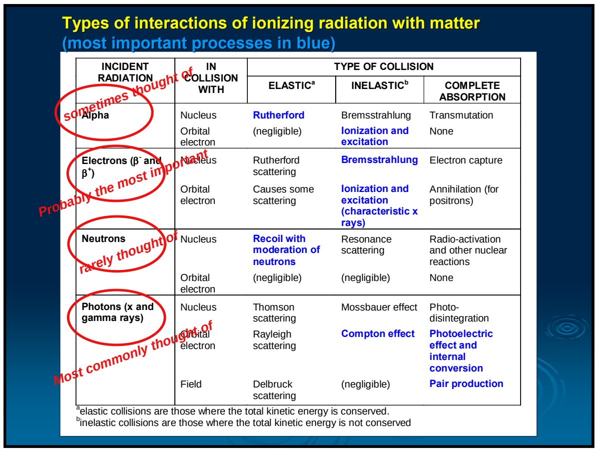
The "radiation dose" that a nuclide can deliver is determined, in part, by all of these factors.

Part II.
INTERACTIONS OF RADIATION AND MATTER



To develop a means to estimate radiation dose (i.e., the energy absorbed by tissue), one needs to understand the processes by which radiation interacts with tissue - as it those interactions that result in the transfer of energy to the tissue.

Now…a discussion of the interactions of ionizing radiation with matter

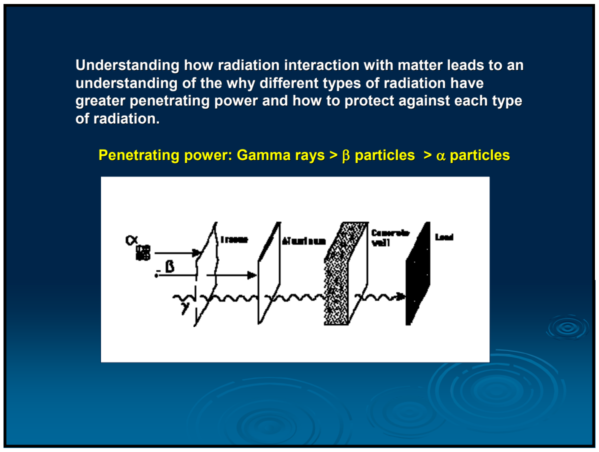


Types of interactions of ionizing radiation with matter
(most important processes in blue)

INCIDENT RADIATION	IN COLLISION WITH	TYPE OF COLLISION		
		ELASTIC[a]	INELASTIC[b]	COMPLETE ABSORPTION
Alpha	Nucleus	**Rutherford**	Bremsstrahlung	Transmutation
	Orbital electron	(negligible)	**Ionization and excitation**	None
Electrons (β^- and β^+)	Nucleus	Rutherford scattering	**Bremsstrahlung**	Electron capture
	Orbital electron	Causes some scattering	**Ionization and excitation (characteristic x rays)**	Annihilation (for positrons)
Neutrons	Nucleus	**Recoil with moderation of neutrons**	Resonance scattering	Radio-activation and other nuclear reactions
	Orbital electron	(negligible)	(negligible)	None
Photons (x and gamma rays)	Nucleus	Thomson scattering	Mossbauer effect	Photo-disintegration
	Orbital electron	Rayleigh scattering	**Compton effect**	**Photoelectric effect and internal conversion**
	Field	Delbruck scattering	(negligible)	**Pair production**

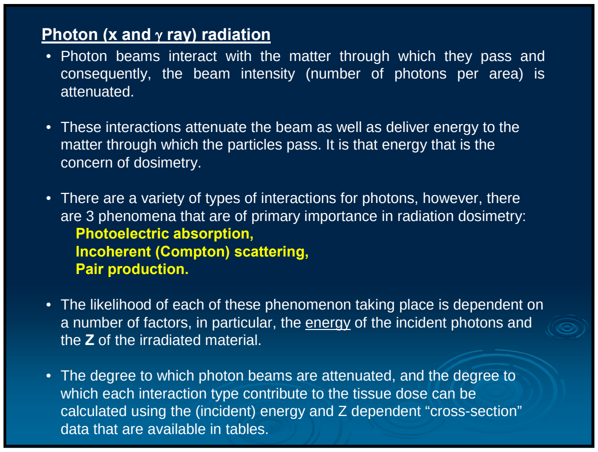
[a] elastic collisions are those where the total kinetic energy is conserved.

[b] inelastic collisions are those where the total kinetic energy is not conserved



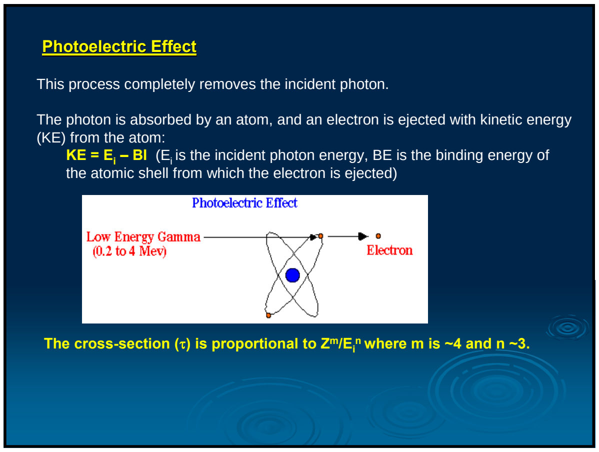
Understanding how radiation interaction with matter leads to an understanding of the why different types of radiation have greater penetrating power and how to protect against each type of radiation.

Penetrating power: Gamma rays > β particles > α particles



Photon (x and γ ray) radiation

- Photon beams interact with the matter through which they pass and consequently, the beam intensity (number of photons per area) is attenuated.
- These interactions attenuate the beam as well as deliver energy to the matter through which the particles pass. It is that energy that is the concern of dosimetry.
- There are a variety of types of interactions for photons, however, there are 3 phenomena that are of primary importance in radiation dosimetry:
  Photoelectric absorption,
  Incoherent (Compton) scattering,
  Pair production.
- The likelihood of each of these phenomenon taking place is dependent on a number of factors, in particular, the energy of the incident photons and the **Z** of the irradiated material.
- The degree to which photon beams are attenuated, and the degree to which each interaction type contribute to the tissue dose can be calculated using the (incident) energy and Z dependent "cross-section" data that are available in tables.



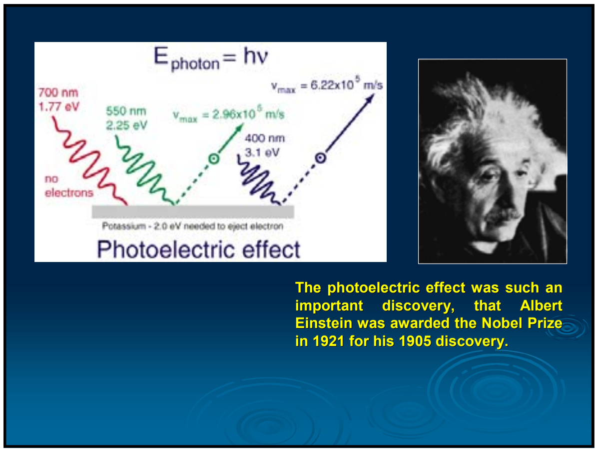
Photoelectric Effect

This process completely removes the incident photon.

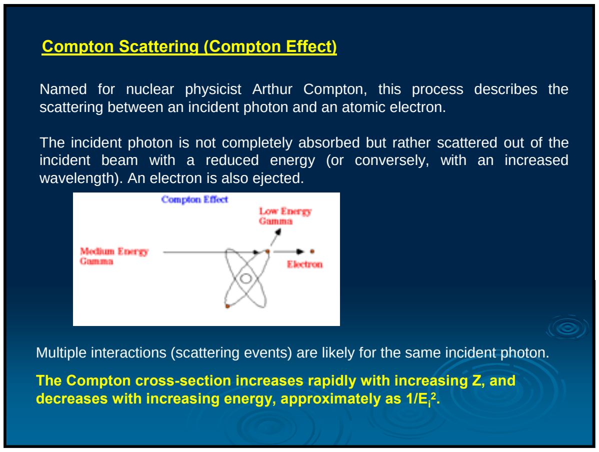
The photon is absorbed by an atom, and an electron is ejected with kinetic energy (KE) from the atom:

KE = E_i – BI (E_i is the incident photon energy, BE is the binding energy of the atomic shell from which the electron is ejected)

The cross-section (τ) is proportional to Z^m/E_i^n where m is ~4 and n ~3.



The photoelectric effect was such an important discovery, that Albert Einstein was awarded the Nobel Prize in 1921 for his 1905 discovery.



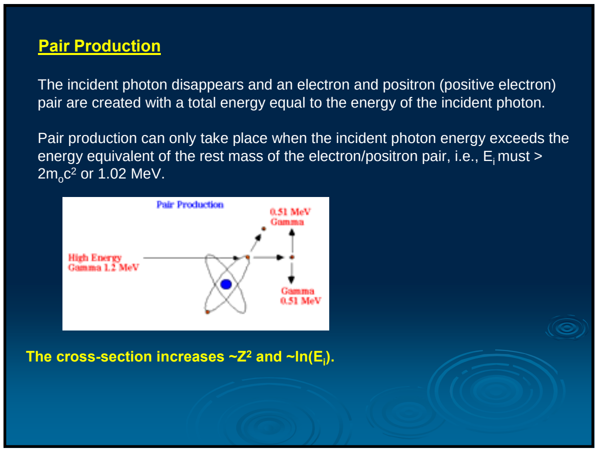
Compton Scattering (Compton Effect)

Named for nuclear physicist Arthur Compton, this process describes the scattering between an incident photon and an atomic electron.

The incident photon is not completely absorbed but rather scattered out of the incident beam with a reduced energy (or conversely, with an increased wavelength). An electron is also ejected.

Multiple interactions (scattering events) are likely for the same incident photon.

The Compton cross-section increases rapidly with increasing Z, and decreases with increasing energy, approximately as $1/E_i^2$.

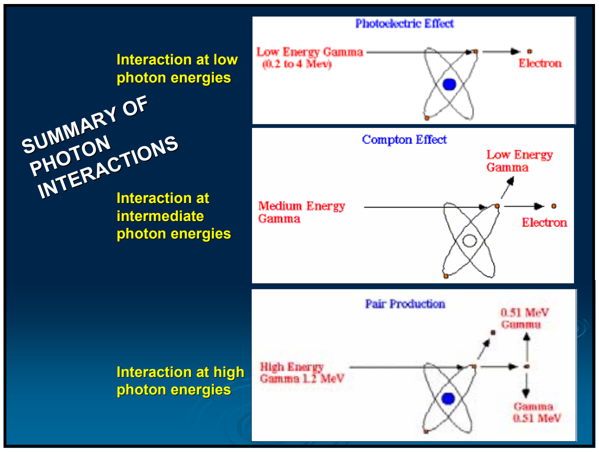


Pair Production

The incident photon disappears and an electron and positron (positive electron) pair are created with a total energy equal to the energy of the incident photon.

Pair production can only take place when the incident photon energy exceeds the energy equivalent of the rest mass of the electron/positron pair, i.e., E_i must > $2m_oc^2$ or 1.02 MeV.

The cross-section increases ~Z^2 and ~$\ln(E_i)$.

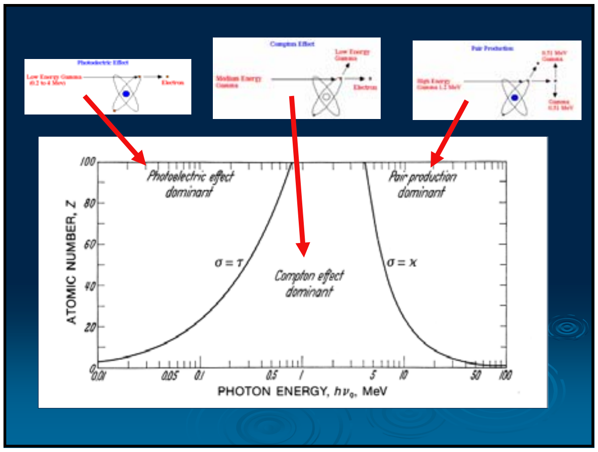


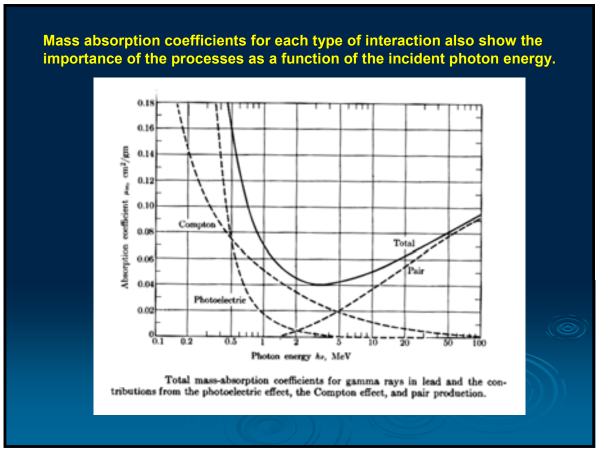
SUMMARY OF PHOTON INTERACTIONS

Interaction at low photon energies

Interaction at intermediate photon energies

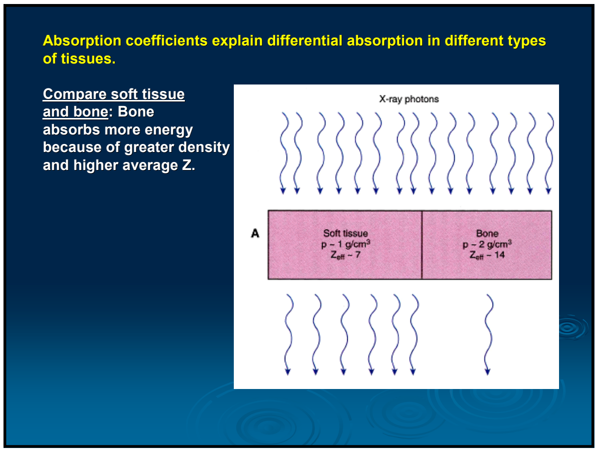
Interaction at high photon energies





Mass absorption coefficients for each type of interaction also show the importance of the processes as a function of the incident photon energy.

Total mass-absorption coefficients for gamma rays in lead and the contributions from the photoelectric effect, the Compton effect, and pair production.

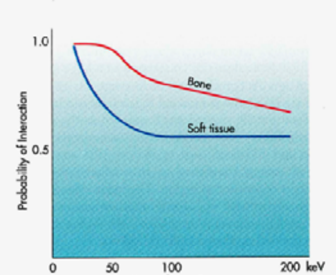


Absorption coefficients explain differential absorption in different types of tissues.

<u>Compare soft tissue and bone</u>: Bone absorbs more energy because of greater density and higher average Z.

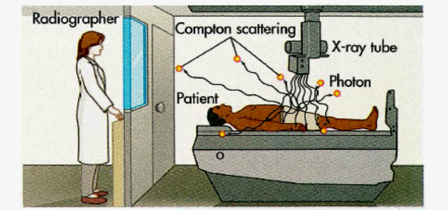
Absorption coefficients explain differential absorption in different types of tissues (con't.).

The likelihood of a photon interaction in bone is several times greater at energies typical of medical diagnostic X ray procedures, but the differences decrease at higher energies typical of ortho-voltage therapies.



These phenomena, e.g., Compton scatter, have practical as well as theoretical implications in radiation protection and dosimetry.

For example, the exposure near (but not within) x-ray beams is largely an outcome of Compton scatter:



Now, remember that the single common outcome of the photon interactions in materials was the release of <u>electrons</u>!

What happens to those <u>electrons</u>?

INCIDENT RADIATION	IN COLLISION WITH	TYPE OF COLLISION		
		ELASTIC[a]	INELASTIC[b]	COMPLETE ABSORPTION
Alpha	Nucleus	**Rutherford**	Bremsstrahlung	Transmutation
	Orbital electron	(negligible)	**Ionization and excitation**	None
Electrons (β^- and β^+)	Nucleus	Rutherford scattering	**Bremsstrahlung**	Electron capture
	Orbital electron	Causes some scattering	**Ionization and excitation (characteristic x rays)**	Annihilation (for positrons)
Neutrons	Nucleus	**Recoil with moderation of neutrons**	Resonance scattering	Radio-activation and other nuclear reactions
	Orbital electron	(negligible)	(negligible)	None
Photons (x and gamma rays)	Nucleus	Thomson scattering	Mossbauer effect	Photo-disintegration
	Orbital electron	Rayleigh scattering	**Compton effect**	**Photoelectric effect and internal conversion**
	Field	Delbruck scattering	(negligible)	**Pair production**

[a] elastic collisions are those where the total kinetic energy is conserved.
[b] inelastic collisions are those where the total kinetic energy is not conserved

WHAT HAPPENS TO THOSE PARTICLES IS TERMED PARTICLE INTERACTIONS

- Particles, unlike photons, have mass, and some have charge.
- Hence, the processes that govern what happens to particles differ from those than govern what happens to photons
- Understanding particle interactions in matter (e.g., tissue) is the last major requirement to understanding the phenomenon that contribute to radiation dose.

Particles (except for neutrons) are charged and cause atomic ionization or excitation as they move through matter as a result of Coulomb forces (repulsion of like electric charges).

Particles (except for neutrons) are charged and cause atomic ionization or excitation as they move through matter as a result of Coulomb forces (repulsion of like electric charges).

$$F = \frac{kq_1q_2}{r^2} = \frac{q_1q_2}{4\pi\varepsilon_0 r^2}$$

Coulomb's Law

The electrons released by photon interactions will eventually stop because each Coulomb interaction results in a transfer of energy to atomic electrons of the material irradiated.

The processes that slow down the incident particles are of importance to the theory of radiation dosimetry because it is those processes that impart energy to the material irradiated.

Electrons

Remember that electrons are released by all photon interactions and from β decay and will be moving in the tissue with some kinetic energy.

Coulomb interactions with neighboring atoms will gradually slow them down.

Rate of energy loss with distance is proportional to *e* (electron charge), and electron density (NZ) of the material.

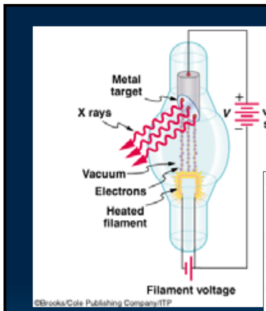
The important point is the electrons cause ionization and excitation and as they lose their energy in the material, energy is imparted to the material through which they pass, and the “dose” is delivered.

Electrons not only cause ionization…but also re-radiate some energy through ***brehmsstrahlung***

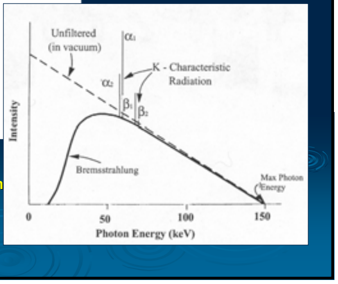
Charged particles (e.g. electrons) when (de)accelerated in the electric field of the nucleus or of the orbital electrons will radiate energy, known as “braking” or “brehmsstrahlung” radiation.

The radiation loss is proportional to the kinetic energy (K.E.) of the incident electron: $-dE/dx \approx Z\ e\ KE$.

Brehmsstrahlung is the mechanism used in medicine to produce x-rays for diagnosis and treatment



Brehmsstrahlung is the mechanism used to generate x-rays for medical use.



Typical x-ray spectrum (example is for 150 kV peak)

What about the interactions of other types of particles with matter?

Alpha particles

Alpha particles are relatively heavy (~7300x that of electron) and have 2 units of charge, thus, they have much shorter range…because each Coloumb interaction is greater.

Typical range of alpha particles in tissue is 40 μm. This explains why alpha particles are normally only a hazard of “internal emitters.”

Neutrons

The processes for slowing of neutrons in matter is the reverse of that of charged particles.

Because neutrons are of neutral charge, there is no Coulomb interaction.

Neutrons are primarily slowed as a result of ‘collisions’ and scattering from nuclei and are eventually absorbed in by the nuclei in neutron-capture reactions.

In elastic scattering (this is where the kinetic energy is conserved through the collision), the maximum energy (Q_{max}) that a particle of mass M and energy E can transfer to a free particle of mass m is

$Q_{max} = 4mM/(M+m)^2$

Since neutrons and protons have near equal mass, large energy transfers are possible in proton rich material, e.g., water or tissue. Less energy is transferred (per collision) to ^{12}C or heavier atoms (because their mass m is larger).

Not all energy is transferred, however, in all neutron interactions.

There is a distribution of energy transferred per interaction and multiple interactions may be necessary before the neutron is 'thermalized' (moving at speeds representative of typical thermal energy, i.e. within the 'eV' range) where the neutron can be captured by a nucleus.

A common neutron capture reaction is: $^{1}H\ (n,\ \gamma)\ ^{2}H$ which releases a 2.22 MeV γ photon that can irradiate surrounding tissue.

Another neutron capture reaction is: $^{23}Na(n,\ \gamma)^{24}Na$ results in the production of ^{24}Na which is radioactive ($t_{1/2}$ = 15 hr).

^{24}Na releases 2 γ's, one each of 1.37 and 2.75 MeV. This 'activation' of sodium in human blood can be used to indicate personnel exposures after a nuclear criticality accident.

Comparing Interactions of Photons and Other Charged Particles

Comparing Interactions of Photons and Other Charged Particles

Photons

- Not charged
- Zero rest mass
- V = c
- No Coulomb force
- Random and rare interactions
- Infinite range (in theory)

Comparing Interactions of Photons and Other Charged Particles

Photons	Electrons
Not charged	Charged
Zero rest mass	Finite mass
V = c (speed of light)	V < c
No Coulomb force	Coulomb force
Random and rare interactions	Continuous interactions
Infinite range (in theory)	Finite range

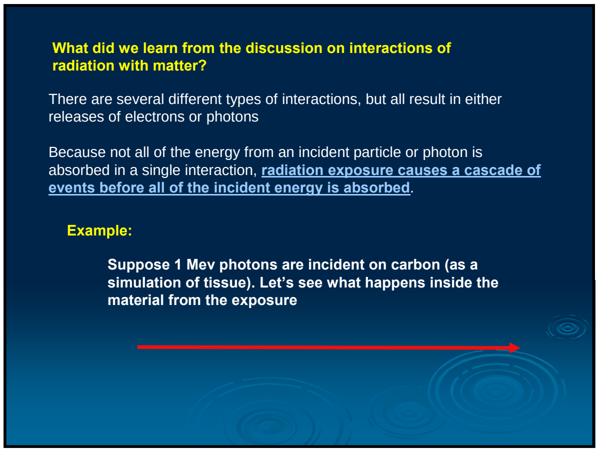
Part III.
CONCEPTS OF RADIATION DOSIMETRY

TAKE NOTE:

Dosimetry is not a basic science, but is simply applied physics.

The primary goal goal of radiation dosimetry in the context of this lecture is a quantitative estimation of the absorption of energy in tissue.

To make estimates of radiation dose (i.e., the energy absorbed by tissue), one needs to understand the processes by which radiation interacts with tissue as it those interactions that result in the transfer of energy to the tissue.



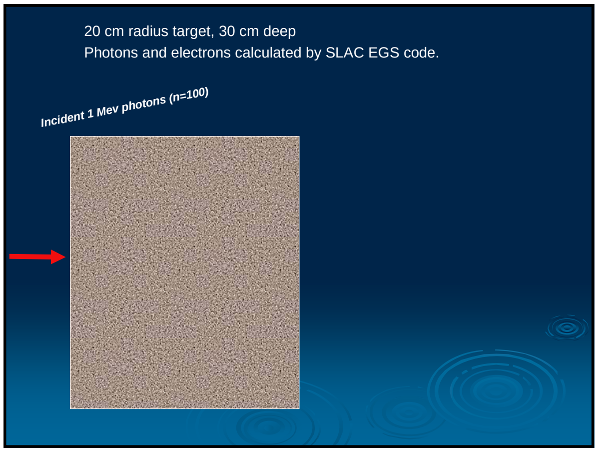
What did we learn from the discussion on interactions of radiation with matter?

There are several different types of interactions, but all result in either releases of electrons or photons

Because not all of the energy from an incident particle or photon is absorbed in a single interaction, radiation exposure causes a cascade of events before all of the incident energy is absorbed.

Example:

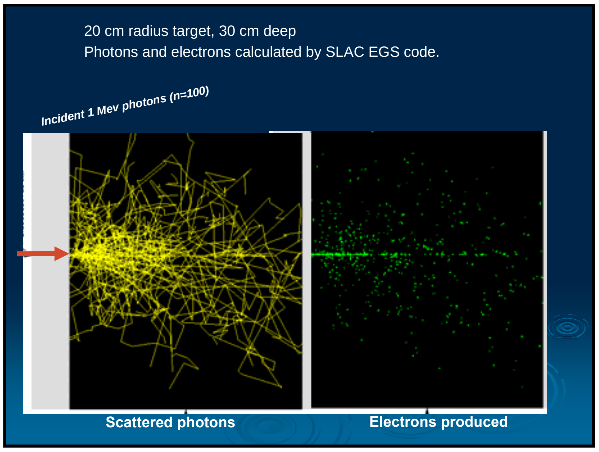
Suppose 1 Mev photons are incident on carbon (as a simulation of tissue). Let's see what happens inside the material from the exposure



20 cm radius target, 30 cm deep

Photons and electrons calculated by SLAC EGS code.

Incident 1 Mev photons (n=100)

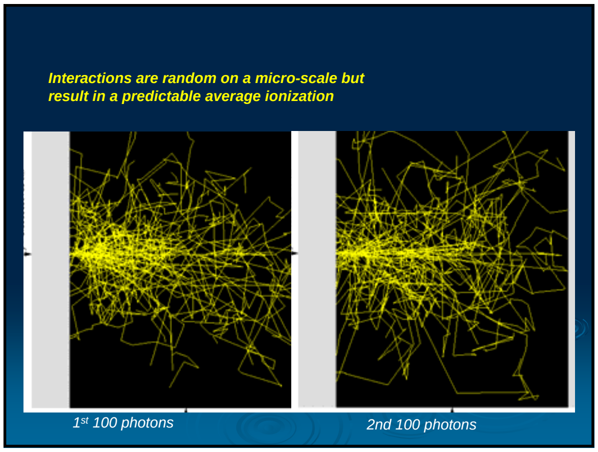


20 cm radius target, 30 cm deep

Photons and electrons calculated by SLAC EGS code.

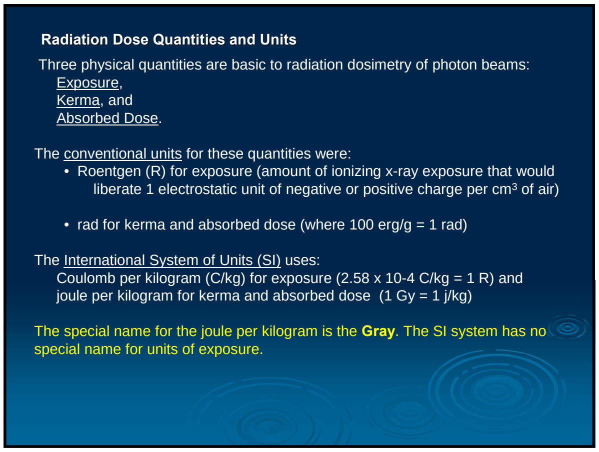
Incident 1 Mev photons (n=100)

Scattered photons **Electrons produced**



Interactions are random on a micro-scale but result in a predictable average ionization

1st 100 photons *2nd 100 photons*



Radiation Dose Quantities and Units

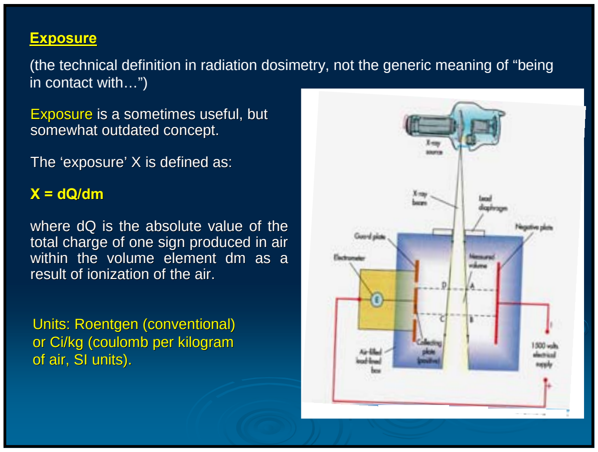
Three physical quantities are basic to radiation dosimetry of photon beams:
Exposure,
Kerma, and
Absorbed Dose.

The conventional units for these quantities were:

- Roentgen (R) for exposure (amount of ionizing x-ray exposure that would liberate 1 electrostatic unit of negative or positive charge per cm^3 of air)
- rad for kerma and absorbed dose (where 100 erg/g = 1 rad)

The International System of Units (SI) uses:
Coulomb per kilogram (C/kg) for exposure (2.58 x 10-4 C/kg = 1 R) and
joule per kilogram for kerma and absorbed dose (1 Gy = 1 j/kg)

The special name for the joule per kilogram is the **Gray**. The SI system has no special name for units of exposure.



Exposure

(the technical definition in radiation dosimetry, not the generic meaning of "being in contact with…")

Exposure is a sometimes useful, but somewhat outdated concept.

The 'exposure' X is defined as:

X = dQ/dm

where dQ is the absolute value of the total charge of one sign produced in air within the volume element dm as a result of ionization of the air.

Units: Roentgen (conventional) or Ci/kg (coulomb per kilogram of air, SI units).

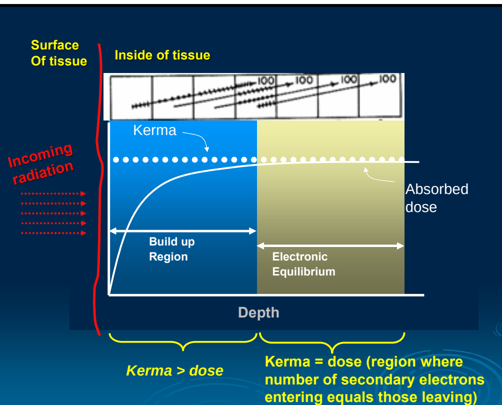
KERMA

The ‘kerma’ (‘kinetic energy released in medium’) K is defined as:

the sum of the initial kinetic energies of the charged particles liberated by the photons (photons are often called ‘indirectly ionizing particles’ whereas electrons are called ‘directly ionizing’ particles) in the volume element.

Units: joule/kg (SI with special name Gray), erg/gm (conventional with special name rad)

Kerma is closely related, but not exactly the same as absorbed dose



Kerma > dose

Kerma = dose (region where number of secondary electrons entering equals those leaving)

Fundamental to understanding ‘absorbed dose’ is the concept of the ‘energy imparted’, ε, within a volume:

$$\varepsilon = R_{in} - R_{out} + \Sigma Q$$

where,

R_{in} is the incident energy on the volume, i.e., the sum of the energies (including ‘rest energies’) of the charged and uncharged ionizing particles that enter the volume,

R_{out} is the energy emerging from the volume, i.e., the sum of the energies (including ‘rest energies’) of the charged and uncharged ionizing particles that leave the volume,

ΣQ is the sum of the all changes of the rest mass energy of the nuclei and particles in any interactions which occur in the volume.

The absorbed dose D is:

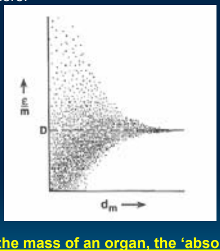
$$D = k_1 \frac{d\bar{\varepsilon}}{dm}$$

where $d\varepsilon$ is the mean (average) energy imparted by ionizing radiation to matter in a volume element dm. As the volume approaches zero, the absorbed dose is defined at that point.

Note: The coefficient k_1 has the value of 1.0 for SI absorbed dose units (joule/kg with the special name of Gray [Gy]) and a value of 100 for conventional dose units (ergs/gram with the special name of rad).

For small volumes, there is statistical variation of the absorbed dose since the likelihood of interaction per unit distance is characterized by a probability.

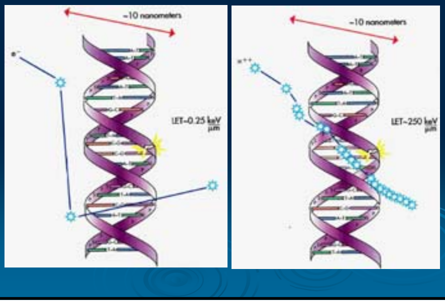
The stochastic (random) variation of absorbed dose as a function of volume is shown here.



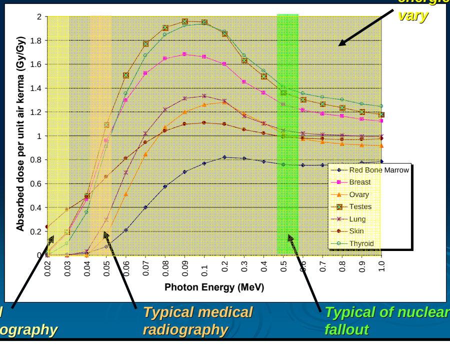
When averaged over the mass of an organ, the ‘absorbed dose’ is probably the most useful measure of radiation dose for epidemiologic studies.

Absorbed dose *is defined by the* ***energy absorbed per gram*** *and is generally viewed, particularly in epidemiology, as a macroscopic quantity.*

The damage to living tissues, on a microscopic level can vary depending on a number of physical and biological parameters, and while can be described by microdosimetry, it will be discussed by the next speakers in the context of radiobiology.



EXTERNAL RADIATION DOSE to different body tissues depends greatly on energy of radiation and geometry of exposure (data below is for exposure from anterior direction.)



Industrial energies can vary

Typical mammography

Typical medical radiography

Typical of nuclear fallout

INTERNAL RADIATION DOSE is a more complex subject because it ALSO depends greatly on a number of factors:

- **Specific Radionuclide**
- **Type of radiation emitted**
- **Half-life**
- **Energy of radiation**
- **Chemical form of radionclide**
- **Residence time in the body**
- **Specifics about the exposed individual (age, health status), etc.**

EXAMPLE: Iodine-131

The general equation to determine the internal dose following an accidental intake or following an oral medical administration of ^{131}I is:

$$D = \int_0^{\infty} \frac{A\ f_1\ f_2\ R(t)}{M_T(a)} \left[\sum_{i=1}^{n} Y_i\ E_i\ AF_i(T \leftarrow S, a) \right] dt$$

where,

A is the activity intake (or the administered activity of ^{131}I (Bq),

f_1 is the fraction of the iodine intake that is transferred to blood (generally assumed to be close to 100%)

f_2 is the fraction of the iodine intake that is absorbed by the thyroid (the rest is excreted primarily through urine),

R(t) is the fraction of the amount that enters the thyroid that is retained at any time, t,

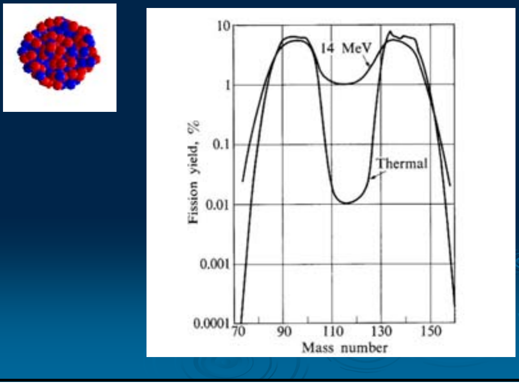
Y_i is the fractional yield of radiation type i, per nuclear transformation,

E_i is the energy released per decay (~0.19 MeV β and ~0.38 MeV γ per nuclear transformation).

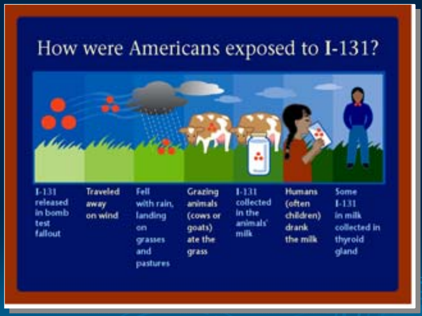
$AF_i(T \leftarrow S,a)$ is the fraction of the energy emitted in the source organ S that is absorbed, in the target organ T, and is a function of age, a,

$M_{th}(a)$ is the mass of the thyroid in this case) and is a function of age, *a*

Why is I-131 so important?



Why is I-131 so important?



How were Americans exposed to I-131?

I-131 released in bomb test fallout

Traveled away on wind

Fell with rain, landing on grasses and pastures

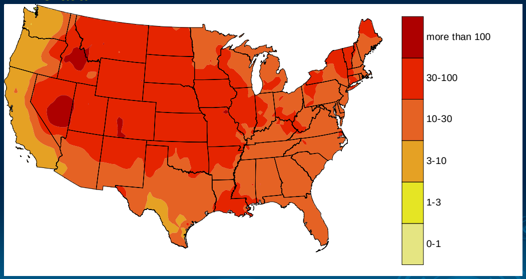
Grazing animals (cows or goats) ate the grass

I-131 collected in the animals' milk

Humans (often children) drank the milk

Some I-131 in milk collected in thyroid gland

Geographic pattern of average internal dose (mGy) to the thyroid of children born January 1, 1951 from ^{131}I released from all nuclear tests in Nevada.



Source: NCI

Up to this point, we've discussed dosimetry on a theoretical level, emphasizing the processes leading to the release and absorption of energy.

However, dosimetry, for the purposes of epidemiologic studies, is primarily the application of the principles discussed.

Applied Dosimetry can be loosely subdivided into:

- '**Internal Dosimetry**' where the energy delivered to tissue from sources within the body, e.g., radionuclides, and
- '**External Dosimetry**' where the energy delivered to tissue originates from sources of radiation outside the body.

Though there are specific techniques in dosimetry for medical, occupational, and/or environmental exposures, the basic physics remains the same.

Almost all of the differences in medical, occupational, and environmental dosimetry can be attributed to:

- Differences in the sources of the radiation,
- Whether the radiation received by individuals was completely controlled, as in medical exposures,
- Whether the radiation was received with moderate control but with some monitoring (typical of occupational exposures), or
- Or if the radiation was received with no control and no monitoring on the individual level (typical of environmental exposures).

The major technical challenge of dosimetry for epidemiologic purposes is not in the physics of radiation interactions (something already well understood), but in determining how much of the radioactive material and/or the radiation the individual was exposed to.

Dosimetry for purposes of epidemiologic studies requires both the concepts of physics and the concepts of exposure analysis.

Dosimetry + Exposure Assessment = Dose Assessment

Because most dosimetry conducted for epidemiologic studies is retrospective (i.e., doses are estimated that were received in the past), most of the difficulties are associated with determining the specifics of the exposure conditions and not the application of the physical principles.

Examples of Problems in Reconstructing Radiation Doses and Relative Difficulty:

Relatively easy (exposure conditions are known):

- Medical external beam radiation therapy
- Medical x-ray procedures (therapeutic and diagnostic)

More difficult (exposure conditions are less well known, but relatively good information is still available):

- Internal medical radioisotope procedures for recent decades.
- Occupational dose for medical radiation workers

Still more difficult:

- Occupational doses for industrial situations, particularly for poorly monitored working conditions
- Nuclear fallout related external doses

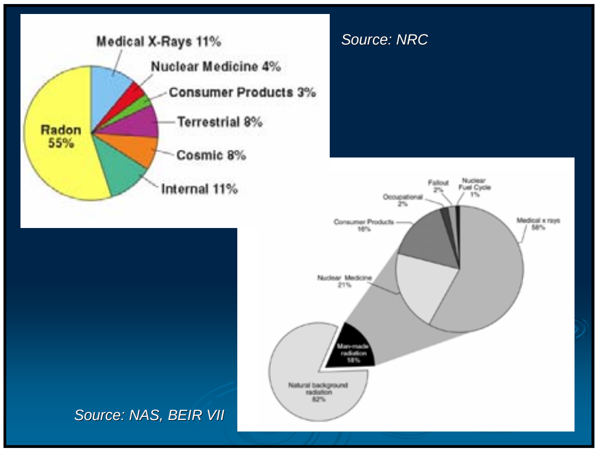
Examples of Problems in Reconstructing Radiation Doses and Relative Difficulty (con't.):

Very difficult:

- Occupational doses for industrial situations, without radiation monitoring data
- A-bomb survivor dosimetry
- Nuclear fallout related internal doses
- Any situation without an adequate description of the source of radiation (energy and geometry) and the exposure conditions (e.g., location of individual with respect to the source, the amount of radioactivity accidentally taken into the body, etc.)

Part IV. Sources of Radiation Exposure:

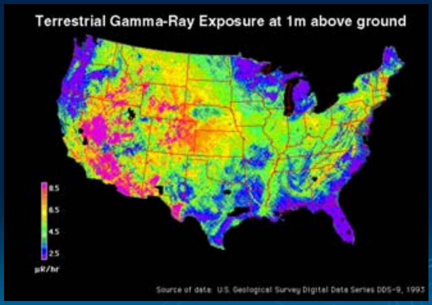
- Medical practices (diagnostic and therapeutic medicine)
- Occupations (industrial practices)
- Consumer products
- Environmental (natural sources)
- Accidental exposures and releases



Source: NRC

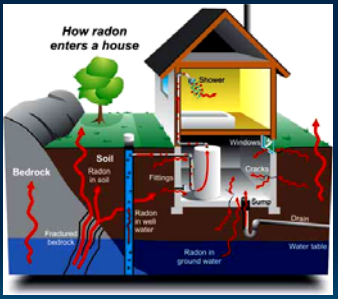
Source: NAS, BEIR VII

Dose from natural terrestrial sources depends partly on mineral content of ground.

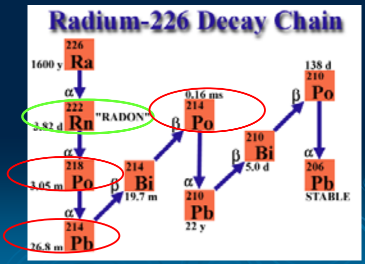


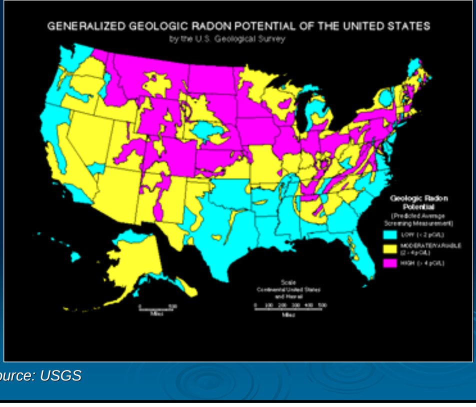
Source: USGS

RADON: a part of the natural radiation environment.



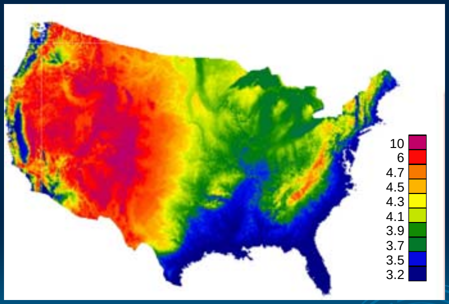
Sidebar on Radon: Dosimetry is difficult because determining the amount of exposure of sensitive cells in the lung by low-penetrating alpha particles is difficult.





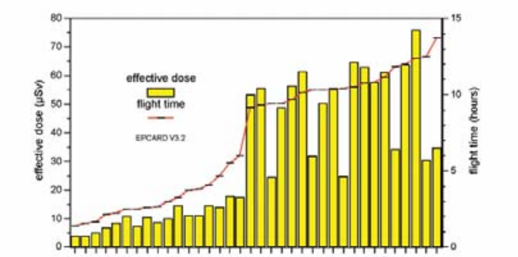
Source: USGS

Ground level cosmic ray dose in the U.S.



Total dose (mGy) to red bone marrow of representative persons from 10 years of exposure to cosmic ray radiation (map courtesy of Geological Survey of Canada).

Cosmic ray dose increases with elevation or altitude and with time spent at high altitudes.



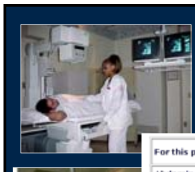
Data: GSF

Average Radiation Dose (effective) from Natural Sources

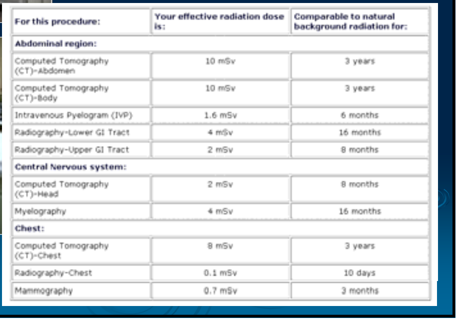
Source	*Worldwide average annual effective dose (mSv)*	*Typical range (mSv)*
External exposure Cosmic rays Terrestrial gamma rays	 0.4 0.5	 0.3 – 1.0^{a} 0.3 – 0.6^{b}
Internal exposure Inhalation (mainly radon) Ingestion	 1.2 0.3	 0.2 – 10^{c} 0.2 – 0.8^{d}
Total	2.4	1 - 10

[a] Sea level to high ground elevation
[b] Depending on radionuclide composition of soil and building materials
[c] Depending on indoor accumulation of radon gas
[d] Depending on radionuclide composition of foods and water

Source: UNSCEAR

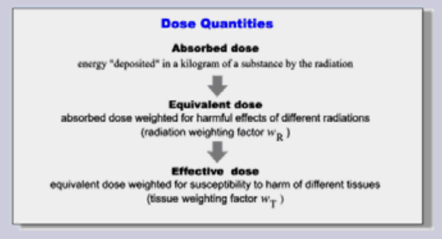


Medical diagnosis and treatments has obvious benefits to the public and to individual patients. The inevitable radiation exposure is usually considered as part of the cost for that benefit.



For this procedure:	Your effective radiation dose is:	Comparable to natural background radiation for:
Abdominal region:		
Computed Tomography (CT)-Abdomen	10 mSv	3 years
Computed Tomography (CT)-Body	10 mSv	3 years
Intravenous Pyelogram (IVP)	1.6 mSv	6 months
Radiography-Lower GI Tract	4 mSv	16 months
Radiography-Upper GI Tract	2 mSv	8 months
Central Nervous system:		
Computed Tomography (CT)-Head	2 mSv	8 months
Myelography	4 mSv	16 months
Chest:		
Computed Tomography (CT)-Chest	8 mSv	3 years
Radiography-Chest	0.1 mSv	10 days
Mammography	0.7 mSv	3 months

Part V. Dose Units for Radiation Epidemiology



Dose Quantities

Absorbed dose
energy "deposited" in a kilogram of a substance by the radiation

Equivalent dose
absorbed dose weighted for harmful effects of different radiations
(radiation weighting factor w_R)

Effective dose
equivalent dose weighted for susceptibility to harm of different tissues
(tissue weighting factor w_T)

Absorbed dose: rad or Gray (1 Gy = 100 rad, for photons)
Equivalent dose: rem or Sievert (1 Sv = 100 rem for photons
Effective dose: rem or Sievert (1 Sv = 100 rem for photons)

But equivalent dose is conceptually not the same as effective dose

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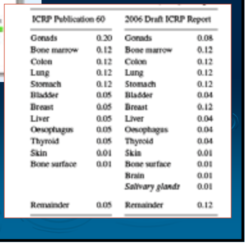
Effective Dose is a "radiation protection" quantity, not a scientific unit intended for scientific analyses. **Do not use for epidemiology, in particular studies to estimate radiation risk.**



ICRP Publication 60		2006 Draft ICRP Report	
Gonads	0.20	Gonads	0.08
Bone marrow	0.12	Bone marrow	0.12
Colon	0.12	Colon	0.12
Lung	0.12	Lung	0.12
Stomach	0.12	Stomach	0.12
Bladder	0.05	Bladder	0.04
Breast	0.05	Breast	0.12
Liver	0.05	Liver	0.04
Oesophagus	0.05	Oesophagus	0.04
Thyroid	0.05	Thyroid	0.04
Skin	0.01	Skin	0.01
Bone surface	0.01	Bone surface	0.01
		Brain	0.01
		Salivary glands	0.01
Remainder	0.05	Remainder	0.12

Closing Remarks for Epidemiologists

There are a variety of 'types' of doses used in the literature including:

shallow dose,
deep dose,
deep equivalent dose,
absorbed dose,
dose equivalent,
equivalent dose,
effective dose,
effective dose equivalent,
committed dose,
committed effective dose,
committed effective dose equivalent, etc.

My advice is…

- Be wary of the many convoluted dose-related terms and dose estimates available in historical literature, particularly if no contact with the original investigators has been made.
- Understand that:
  - Some dose estimates serve purposes that are probably not of interest to you, such as for establishing compliance in radiation protection activities, etc.
  - Some dose estimates may have been calculated by methods, models, or with definitions that are no longer in use or accepted.
  - Doses may be averages over multiple organs or weighted by factors unknown to you or are irrelevant to you.
- Dose estimates other than **organ absorbed dose** will likely not be what is needed for your research purposes.
  - Stick with Gy (or rad) in epidemiology.
- When collaborating with other scientists who might not appreciate the requirements of epidemiology, seek clarification on exactly what *kind* of dose is being provided.
- Finally, ask for legitimate statements of uncertainty (or conversely, the precision) of dose estimates and never assume that doses are known with absolute certainty.

Where can you go for reliable information on dosimetry, dose estimation, dose limitation guidelines, etc. ?

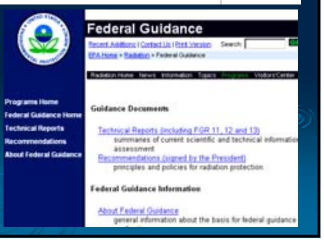
Sources of information: EPA (Federal Guidance, Dose Coefficients, Limiting Values of Exposure)


U.S. Environmental Protection Agency

Federal Guidance

Technical Reports

http://www.epa.gov/radiation/federal/


Federal Guidance

Guidance Documents

Technical Reports (including FGR 11, 12 and 13)
summaries of current scientific and technical informatio
assessment
Recommendations (signed by the President)
principles and policies for radiation protection

Federal Guidance Information

About Federal Guidance
general information about the basis for federal guidance

Sources of information (con't.): International Organizations (see NCI website for links)

http://dceg.cancer.gov/radia/links.html


Radiation Epidemiology Branch Useful Links

- ICRP: International Commission on Radiological Protection
- NIAID: Medical Countermeasures Against Radiological and Nuclear Threats
- HPA: Health Protection Agency (UK)
- IAEA: International Atomic Energy Agency
- ICRU: International Commission on Radiation Units and Measurements
- International Agency for Research on Cancer
- International Commission on Non-Ionizing Radiation Protection
- NAS-BEIR
- NCRP: National Council on Radiation Protection and Measurements
- RERF Publications: Radiation Effects Research Foundation
- UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation
- WHO, Ionizing Radiation Section: World Health Organization

Websites with additional Radiation related links

- Radiation Research Society
- Health Physics Society
- The Radiation Information Network

Sources of information (con't.): Applications of Dosimetry to Epidemiology – Radiation Research (July, 2006)


National Cancer Institute

Division of Cancer Epidemiology and Genetics

Radiation Dosimetry Monograph

http://dceg.cancer.gov/radia/res35.html


Radiation Research

An International Journal

Sources of information (con't.): Radiological Terrorism

http://remm.nlm.gov/

http://www.afrri.usuhs.mil/

Radiation Emergency Assistance Center/Training Site (REAC/TS)

http://orise.orau.gov/reacts/

THE END