Introduction to Radiation, Radioactivity, Risks and Effects

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Learning Objectives

• Understand the causes and properties of radiation and radioactivity.
• Review radiation units of measurement and comprehend typical versus dangerous radiation doses.
• Discuss how radiation interacts with human tissues, and what the possible consequences are.
• Describe the risks associated with radiation.

Atomic Structure

Atomic Structure – The Nucleus

Helium-4 Nucleus

Atomic Structure – Nuclear Forces

Atomic Structure – Nuclear Forces

Electrostatic Repulsion Forces
Atomic Structure – Nuclear Forces

- Nuclear Stability

- Known Nuclides
  - More than 3,400 nuclides have been discovered; number increases every year
  - **STABLE**
    - $^2_1$He, $^{28}_{12}$Si, $^{39}_{17}$K, $^{88}_{36}$Sr, $^{96}_{40}$Zr, $^{136}_{54}$Ba, $^{190}_{78}$Pt, $^{238}_{90}$U, $^{235}_{92}$U, $^{234}_{92}$U, $^{232}_{92}$Th
  - **RADIOACTIVE**
    - $^1$H, $^{129}$I, $^{141}$Ce, $^{143}$Ce, $^{150}$Nd, $^{181}$Ta, $^{183}$W, $^{210}$Po, $^{222}$Rn, $^{226}$Ra, $^{228}$Th
  - Actinium, Thorium, Uranium series nuclides

- Natural Radionuclides
  - Primordial
  - Born with the earth
  - Actinium, Thorium, Uranium series nuclides

- Cosmogenic
  - Continuously created by cosmic ray induced nuclear reactions

- Manmade Radioactivity
  - Bombard the nucleus of atoms with protons, neutrons, helium nuclei
  - Nuclear reactor – neutron source
  - Cyclotron – proton source
  - Accelerators – various particles
  - Natural products of nuclear fission in a nuclear reactor
Isotopes of Carbon and Their Half-Lives

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<th>Protons</th>
<th>Neutrons</th>
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Types of Radioactive Decay

Alpha Particle Decay

- **Radium-226** (88 protons, 138 neutrons)
- **Radon-222** (86 protons, 136 neutrons)

**Alpha Particle**

- **Characteristics**
  - +2 charge
  - 2 protons
  - 2 neutrons
  - Large mass
- **Range**
  - Very short range
  - 1" - 2" in air

Alpha Particle Sources

- Plutonium
- Uranium
- Radium
- Thorium
- Americium

Example of Beta Particle Decay

- **Carbon - 14** (6 protons, 8 neutrons)
- **Nitrogen - 14** (7 protons, 7 neutrons)
**Characteristics**
- 1 charge
- Small mass

**Range**
- Short range
- About 10 ft in air

**Shielding**
- Plastic safety glasses
- Thin metal

**Hazards**
- Skin and eyes
- Can be internal

**Sources**
- Radioisotopes
- Activation Products
- Sealed sources

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**Electromagnetic Radiation**

*Graph showing frequency (cycles per second) with labels for different types of radiation.*

**Radiation Generating (X-ray) Equipment**

- X-ray machines also produce the same type of electromagnetic radiation.
- Uses: medical, industry, airports.
- X-ray machines can be turned off by removing the power source. They leave no residual radiation in the room.
- Unlike x-ray machines, gamma radiation sources are always “on”, until they decay away naturally.

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**Neutron Particle**

- Does not occur in radioactive decay processes
- Is normally found in nuclear reactors and some particle accelerators
- Can be generated using alpha particles with certain metals, used in some research labs and industry

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**Carnotite Rock Sample (Beta)**

*Image of a rock sample with labeling.*
Radioisotope Half-Lives

Natural Materials
- Uranium-238 (in soils) – 4.5 Billion years
- Potassium-40 (in soil and all living tissues) – 1.3 Billion years
- Carbon-14 (in all living tissue) – 5730 years
- Hydrogen-3 (in all water) – 12 years

Terrorist Threat Materials
- Plutonium-239 – 24,100 years α, β, γ
- Radium-226 – 1,600 years α, β, γ
- Americium-241 – 1,432 years α
- Cesium-137 – 30 years γ
- Strontium-90 – 28 years β
- Cobalt-60 – 5.26 years γ
- Iridium-192 – 74.2 days γ

Radioactive Decay Units
- 1 Ci = 1 Curie = 3.7 x 10^{10} disintegrations per second. This is the approximate activity of one gram of pure radium.
- 1 Bq = 1 Becquerel = 1 disintegration per second. This is the new S.I. (metric system) unit for radioactivity.
- 1 Ci = 37 GBq (gigaBecquerels)
- 1 milliCurie (mCi) = 37,000,000 dps = 37 MBq
- 1 microCurie (µCi) = 37,000 dps = 37 kBq
- 1 picoCurie (pCi) = 0.037 dps = 2 decays/minute
Curie - Unit of Radioactivity

• 1 Ci = 37,000,000,000 disintegrations/sec
• 1 uCi = 37,000 DPS = 37 kBq

Manmade Radioactive Sources

• Medical diagnosis – 1 uCi to 30 mCi
• Industrial gauges and test equipment – 0.01 – 100 Ci
• Radiation therapy (cobalt-60 machines) – 5,000 – 10,000 Ci
• Food Irradiation – 100,000 - 500,000 Ci

Radiation Quantities and Units

• rad or Gray - unit of absorbed dose. It is a measure of how much energy is deposited in a mass of tissue. 1 Gy = 100 rads = 1 J/kg
• rem or Sievert - It is the a measure of the biological effect of the absorbed radiation on tissues. 1 Sv = 100 rem

Dose Equivalent

• For the same absorbed dose, different forms of radiation (e.g., alpha, beta, gamma) cause differing degrees of biological harm.
• Recognizing this, a unit for dose equivalent was created, incorporating a quality factor to take into account the biological effects.
• Dose equivalent = QF times absorbed dose

Dose Equivalent

• The units for dose equivalent are:
  • rem = QF x rads, or:
  • Sv = Sievert = QF x Gy (S.I. units)
• QF depends on the type of radiation:
  • QF=1 for x-rays and beta particles
  • QF=5-20 for neutrons and alpha particles
  • 1 Sv = 100 rem

Quality Factor: X-rays Vs. Neutrons
Radiation Quantities and Units

- The rad and rem describe large quantities of radiation. The Gray and Sievert describe even larger quantities. Smaller units are the millirad (mrad), and millirem (mrem).
  - $1 \text{ rem} = 1,000 \text{ mrem}$
  - $1 \text{ mrem} = 1/1,000 \text{ rem}$
  - $1 \text{ Sievert} = 100,000 \text{ mrem}$

Interactions With Matter

- Alpha and beta particles and gamma rays deposit their energy through multiple ionizations. The degree of harm depends on how many ions are formed per unit volume of material.
- Physical analogy:
  - Gamma rays, flashlight
  - Beta particles = fine sand
  - Alpha particles = a rock
- For equivalent masses striking a target, the rocks do far more damage.

Relative Penetrating Power

- Alpha and beta particles deposit their energy through multiple ionizations.
- Gamma rays deposit energy with no multiple ionizations.

Spark Chamber

Radiation Exposure Protection

- Time, Distance and Shielding
  - These factors are the most important in reducing radiation exposure.
  - 1. Minimize the time you are near a radiation source.
  - 2. Step back! Radiation intensity falls off quickly with distance from the source.
  - 3. Use shielding when appropriate. Cover alpha or beta sources. Be aware that even lead may not be effective in reducing high energy gamma radiation sources.

Radiation Shielding Materials
Penetrating Properties of Radioactive Particles

- Alpha
- Beta
- Gamma

Radiation Falloff With Distance

- Effect of distance on radiation dose.

Reducing Radiation Dose

- Three ways of reducing radiation dose:
  - Shielding
  - Distance
  - Time

Mechanisms of Damage

- The absorption of radiation can cause two effects at the atomic level:
  - Ionization
    - Orbital electrons are ejected, and the atom is left positively charged. The atom and electron are called an ion pair.
  - Excitation
    - Orbital electrons move to a higher (outer) orbit, becoming susceptible to later chemical bond breakage.

Ionizing Radiation

- Neutrons and Protons
- Ejected Electron
- Ionization Radiation - radiation with enough energy to remove an electron from its atom.
**Excitation**

- Energy is transferred to an orbital electron, but not enough to free it.
- Electron is left in an excited state, and subsequently returns to lowest available state, giving off lower-energy electromagnetic radiation ("fluorescent x rays").

**Mechanisms of Damage**

**Direct Effects**

- The radiation may directly affect an important molecule, like DNA or a cell membrane component.
- The general scheme is:
  - $A + \text{energy} \rightarrow A^+ + e^-$, where $A$ is a molecule which is critical to the proper functioning or reproduction of the cell.

**Indirect Effects**

- The damage may occur indirectly.
- The radiation may result in the production of a free radical.
- Free radicals are chemically very reactive with other molecules.
- The result of the interaction of the free radical with other molecules causes the actual damage.

**Indirect Effects (Free Radicals)**

**Direct Radiation Effect**

- The energy from a gamma ray interacts with DNA, possibly causing damage to the DNA molecules.
DNA Radiation Damage

- Possible scenarios:
  - Damage is repairable.
  - Damage leads to chromosome aberrations and possible mutations.
  - Unrepaired DNA leads to cell death.
- DNA is essential for cell growth and reproduction.
Direct and Indirect Effects

Law of Bergonie and Tribondeau

- First proposed in 1906, the law states that "the more rapidly a cell is dividing, the greater its radiosensitivity".
- Cells at greatest risk are those which are rapidly dividing, or are likely to undergo mitosis in the future.
- Those cells which infrequently undergo cell division are more radioresistant.

Radiosensitive Tissues

- Rapidly dividing cells are most susceptible to radiation damage, including:
  - blood forming cells (bone marrow)
  - cells lining the gastrointestinal tract
  - fetal cells
- Muscle, brain, liver and nerves are relatively radioresistant, due to their slow rates of cell division.

Dose-Effect Relationships

- The human body has free radical scavengers which can prevent or repair free radical damage.
- If the body is overloaded with free radicals, repair is impossible.
- A high dose rate is more damaging than a low dose rate. In nuclear medicine, a higher total dose is given, but at a lower dose rate than x-rays.

Factors Affecting Biological Damage

- Total Radiation Dose.
- Dose Rate (affects ability to repair).
- Type of Radiation (x-rays, neutrons).
- Type and amount of tissue affected (rapidly dividing cells are at greater risk).
- Chemical modifiers (free radical scavengers, radioprotectors).
**Natural Background Radiation**

- **Terrestrial Radiation**
  - Primary exposure is due to uranium and radium, especially in granite bearing soils and rock.
  - It varies from about 15 mrem/year to 140 mrem/year in the U.S.
  - High readings are from Reading Prong (eastern PA, NJ) and Colorado uranium mining areas.

- **Cosmic Radiation**
  - Comes from outer space, doubles for every 2000 meters in elevation.
  - The range is about 24 mrem/year at sea level, to 125 mrem/year in Colorado at high elevation (3,200 meters above sea level).
  - In Cleveland, it is about 27 mrem/year.
  - Airline pilots receive about 600 mrem/year.
  - In a jet, you get about 0.5 millirem/hour.

- **Internal Radiation**
  - The body contains naturally radioactive potassium-40, carbon-14, uranium daughter products and other elements. There are over 7000 radioactive decays per second inside the human body.
  - Internal isotopes contribute 40 mrem/year.
  - Smokers inhale traces of polonium-210 and lead-210 in tobacco (adds 200 mrem/year).

- **Man-Made Radiation**
  - Most man-made radiation is due to the medical use of radiation. X-rays contribute about 40 mrem/year, and Nuclear Medicine about 14 mrem/year.
  - Consumer products contribute about 11 mrem/year from TV, smoke detectors, etc.
  - Trace amounts come from fallout, nuclear power plants, etc.
Manmade Radiation Sources

Background Radiation
- Overall Total: 360 mrem/year in Cleveland
- It varies from about 250 to 600 mrem/year across the United States.
- Worldwide, it varies from about 200 mrem/year to 10,000 mrem/year.
- Epidemiological studies in areas of high background radiation levels demonstrate no increase in cancer rates in these areas.

Radiation Effects Observed in Humans
- Early radiologists demonstrated skin burns, cataracts, leukemias and life shortening.
- A number of cancers are associated with high doses of radiation: leukemias, breast cancer, lung cancer, bone cancer, thyroid cancer and skin cancer.
- Prolonged fluoroscopy has been associated with epilation and erythema.

Radiation As a Carcinogen
- A carcinogen is an agent which causes cancers which may not have otherwise developed.
- Spontaneous cancer development in humans is high. About 22% of us will get cancer.
- Radiation is known to increase the likelihood of cancer induction at high doses.

Radiation As a Carcinogen
- Cancers exhibit a long latent period between exposure to the agent and manifestation of the disease.
- Leukemias: 2-20 years, 10 year average
- Solid tumors: 10-50 years, 20-30 year avg.
- This greatly confounds the association between radiation and cancer, since there are many other causative agents.

Cancer Induction
- High doses of radiation are known to cause cancers.
- Leukemia, thyroid, lung, bone and breast cancers are caused by a number of agents, but are also associated with high doses of radiation.
- Hiroshima and Nagasaki survivors showed a 2-4% excess incidence of cancers.
Hormesis

- Hormesis is a reduction in the baseline cancer rate due to enhancement of repair mechanisms in the body and immune system stimulation.
- A-bomb survivors live longer than non-exposed individuals.
- People living in high background radiation areas have less cancer than those living in low background radiation areas.
- An aspirin a day is known to be beneficial. Many aspirin taken at the same time can be lethal. So, too, with radiation.

Radiation-Induced Cataract

Epilation (Hair Loss) Following 1000 rem (10 Sv) Skin Dose

Radium Dial Painters

Dr. Kassabian, Early Radiologist

Is Chronic Radiation an Effective Prophylaxis Against Cancer?


ABSTRACT

An prospective, nested case-control study was carried out in a group of 15,000 people who had been exposed to radiation in the course of their employment in the nuclear industry. The study was designed to evaluate the relationship between chronic low-level radiation exposure and the development of cancer. The results of the study indicate that chronic low-level radiation exposure is not associated with an increased risk of cancer. In fact, the results suggest that chronic low-level radiation exposure may be protective against the development of cancer. This finding is consistent with previous studies that have suggested a possible protective effect of chronic low-level radiation exposure.
Typical Effective Doses From Medical X-Rays

- Chest X-ray: 8 mrem (0.08 mSv)
- Head CT scan: 100 mrem (1 mSv)
- Barium Enema: 400 mrem (4 mSv)
- Extremity X-ray: 1 mrem (0.01 mSv)

» Source: NCRP Report 100

Acute Radiation Sickness Due to Whole Body Irradiation

Acute Radiation Syndrome Time Line

- 1. Massive Radiation Exposure
  - The body is overwhelmed with free radicals.
- 2. Prodromal period
  - Free radicals form peroxides and other end products which are toxic to the body.
  - The body responds accordingly.
  - This phase lasts several minutes to several days, depending on dose.
- 3. Latency period
  - Once the free radical products are removed from the body, the patient feels fine for days to weeks. This period of feeling okay is dose dependent and disappears at high doses.
- 4. Manifestation illness period
  - No new cells are generated, so blood components disappear over a period of several weeks.
- 5. Recovery period (or death)
  - If the patient doesn’t die due to immune system shutdown (infection) and low platelet counts (hemorrhaging), slow recovery ensues.
  - If the dose is overwhelming, the patient expires.

Platelet Counts After Radiation Accidents

Comparison of platelet counts in the T-15 patients and in a victim of the Vrča accident.
**Acute Radiation Effects (Whole Body Exposure)**

- 0-50 rem (0.5 Sv, 50,000 millirem) - no visible effects are manifested.
- 50-100 rem (0.5-1 Sv) - possible nausea and vomiting due to free radical toxicity.
- 150-400 rem (1.5-4 Sv) - transient nausea and vomiting, hematopoietic (blood cells) system damage, suppressed immune system, with recovery possible in 1-2 months.

**Acute Radiation Effects (Whole Body Exposure)**

- 350-450 rem (3.5 - 4.5 Sv) - 50% fatalities.
- 300-800 rem - severe damage to hemopoietic system, bone marrow transplant needed, survival chance 50%.
- 550-1000 rem - gastrointestinal tract lining damage, severe nausea and vomiting, diarrhea, very small chance of recovery, death in 10-24 days.
- >10,000 rem - confusion, shock, coma, death follows within hours.

**Deterministic Radiation Effects**

- Substantial minimum dose threshold.
- Certainty of effect (not probability based).
- Severity is a function of dose.
- High dose risks are: hair loss, skin damage, cataracts and congenital abnormalities. These are normally observed only during prolonged fluoroscopy procedures (greater than one hour total fluoroscopy time).

**Deterministic Effects**

- Temporary hair loss - 300,000 mrem
- Permanent hair loss - 700,000 mrem
- Transient skin effects - 250,000 mrem
- Main erythema (skin damage) - 600,000 mrem (600 rem, 6 Sv)
- Cataract - 200,000 mrem, single dose
- Male sterility - 500,000 mrem

**Genetic Effects**

- Chromosome damage was seen in early radiologists, who worked around unshielded radiation sources for long time periods.
- A-bomb survivor progeny have been followed for three generations now with no manifestation of genetic effects.
- Individuals living in high background radiation areas do not demonstrate genetic effects.

**Late Radiation Effects**

- Radiation exposure is known to cause leukemia and cancer.
- The severity of the disease is not linked to the dose level, but the risk of disease is dose dependent.
- Other effects are dose dependent, like cataracts and hair loss. These effects are not seen below some threshold dose.
Radiation Dose Response Models

Carcinogenesis
- Epidemiological studies identify an increased risk of cancers due to radiation exposure.
- Disease manifestation may take 10-50 years following irradiation.
- 2-4% increase in lifetime cancer risk following 100 rem (1 Sv) dose, using the most conservative dose-effect model.

Radiation Risks
- Fatal cancer: 4 / 10,000 per rem
- Nonfatal cancer: 8 / 100,000 per rem
- Severe genetic effects: 8 / 100,000 per rem
- Total detriment: 5.6 / 10,000 per rem
- This assumes that the linear no-threshold model applies (no time for cell repair, large dose delivered at a high dose rate).
  - From NCRP Report 116

Radiation Exposure
- How much radiation is dangerous?
- First, examine natural background radiation levels around the world.
- These levels vary from about 0.2 rem (2 mSv) to 10 rem (0.1 Sv) per year depending on elevation and local soil content. Cancer incidence does not correlate with these background levels.

Permissible Radiation Doses
- Radiation workers (considered a safe occupation), are permitted to receive no more than .05 Sieverts/year (5 rem/yr).
- Members of the public are allowed to receive no more than 0.005 Sieverts / year (0.5 rem/yr). This does not include tests necessary for medical purposes.
- Permitted individual organ dose limits are significantly higher (15-50 rem/yr).

Relative Risk of Dying: 1 in a Million Odds
- Smoking 1.4 cigarettes (lung cancer)
- Eating 40 tablespoons of peanut butter
- Eating 100 charcoal broiled steaks
- 2 days living in New York City (air pollution)
- Driving 40 miles in a car (accident)
- Flying 2500 miles in a jet (accident)
- Canoeing for 6 miles
- Receiving 10 mrem radiation dose (cancer)
Conclusions

- One must understand the type and properties of radiations to properly protect oneself.
- The concepts of time, distance and shielding can be employed to minimize your radiation dose.
- Radiation is a relatively weak carcinogen, but it can cause severe acute effects at very high dose levels.