# Biological Effect of Radiation

**ACADs (08-006) Covered**

| | | | | | |
|---|---|---|---|---|---|
| 1.1.4.5 | 1.1.8.2 | 1.1.8.3 | 1.1.8.3.1 | 1.1.8.3.2 | 1.1.8.3.3 |
| 3.3.2.1 | 3.3.2.2 | 3.3.4.4.1 | 3.3.4.4.2 | 3.3.4.4.5 | 3.3.4.4.6 |
| 4.10.1.1 | 4.10.1.2 | 4.10.1.3 | 4.10.1.4 | 4.10.2 | 4.12.1.1 |
| 4.12.1.2 | 4.12.1.3 | 4.12.1.4 | 4.12.2 | | |

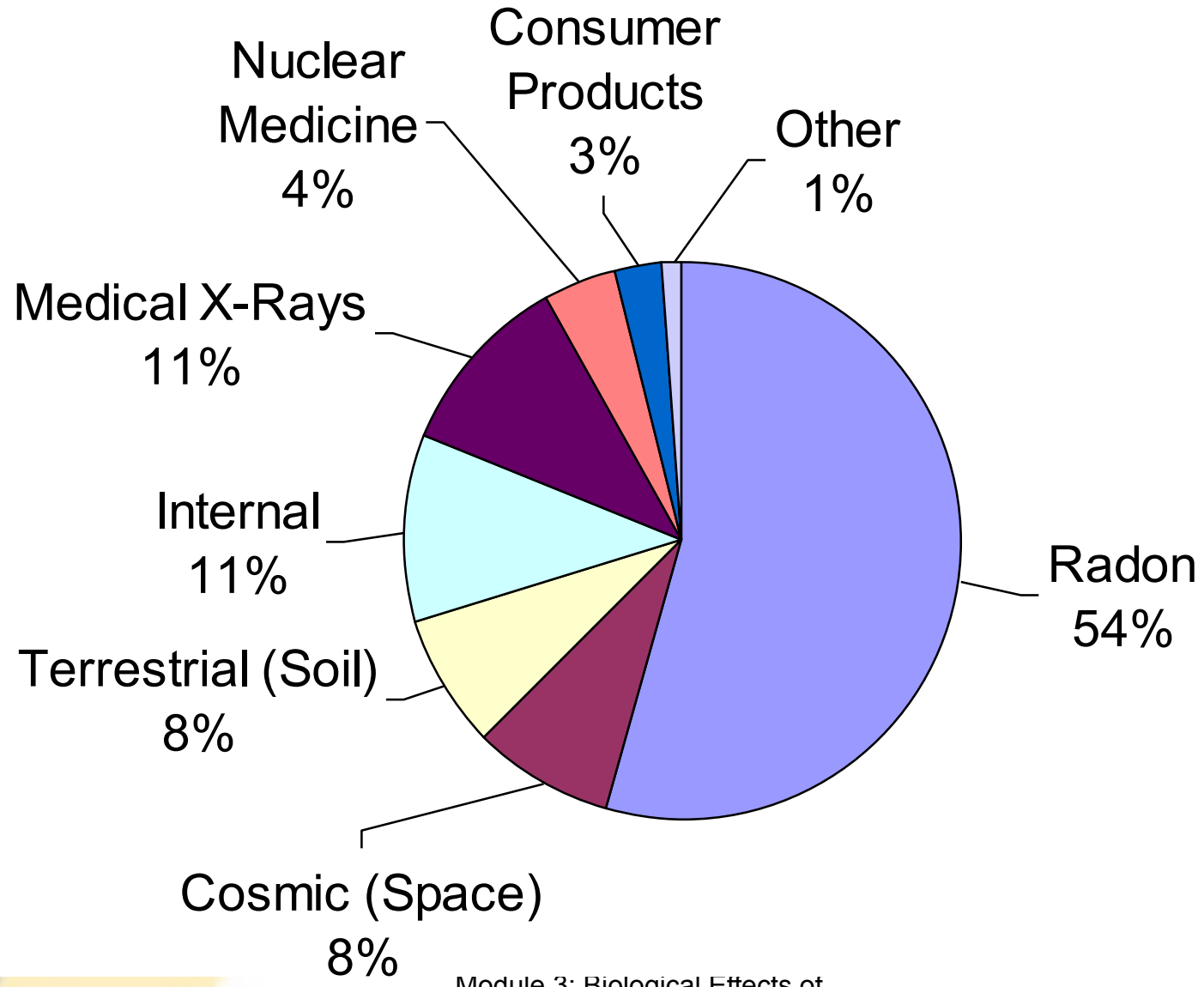
**Keywords** cosmic terrestrial internal radiation, uranium, thorium, radium, curie, becquerel, roentgen, dose, RAD, REM, x-rays, gamma, beta, alpha, fission fragments, mrad, tissue, organ, affect on cells, blood, whole body exposure, acute, chronic, genetic, body burden, time distance shielding, gonads

**Description** This module examines the affects of short and long term exposure to all types of radiation.

**Supporting Material**

RCNET
Regional Center for Nuclear Education & Training

# Sources of Radiation Exposure in the US



# Natural Sources of Radiation

- Natural background radiation comes from three sources:
  - Cosmic Radiation
  - Terrestrial Radiation
  - Internal Radiation

# Natural Sources of Radiation

- Cosmic Radiation
  - Sun and stars send constant stream of cosmic radiation to Earth
    - Like steady drizzle of rain
  - Differences in certain variables can change the amount (or dose) of cosmic radiation that we receive.
    - Elevation
    - Atmospheric conditions
    - Earth's magnetic field

# Natural Sources of Radiation

- Terrestrial Radiation
  - The Earth itself is a source of terrestrial radiation
  - Radioactive materials exist naturally in soil and rock
    - Uranium
    - Thorium
    - Radium
  - Water contains small amounts of dissolved uranium and thorium
  - All organic matter (both plant and animal) contains radioactive carbon and potassium.

# Natural Sources of Radiation

- Internal Radiation
  - All animals (including people) have internal radiation
  - Comes from radioactive potassium-40 and carbon-14 inside their bodies
    - Present from birth
    - Very minor sources of exposure to others

# Man-Made Sources of Radiation

- All living things are exposed to natural background radiation
- Exposure to man-made radiation sources differs by group:
  1. Members of the Public
  2. Occupationally Exposed Individuals (Workers)

# Man-Made Sources of Radiation

- Members of the Public
  - Medical Sources (by far, the most significant man-made source)
    - Diagnostic x-rays
    - Nuclear medicine procedures (iodine-131, cesium-137, and others)

# Man-Made Sources of Radiation

- Consumer Products
  - Building and road construction materials
  - Combustible fuels, including gas and coal
  - X-ray security systems
  - Televisions
  - Fluorescent lamp starters
  - Smoke detectors (americium)

# Man-Made Sources of Radiation

- Consumer Products
  - Luminous watches (tritium)
  - Lantern mantles (thorium)
  - Tobacco (polonium-210)
  - Ophthalmic glass used in eyeglasses
  - Some ceramics

# Man-Made Sources of Radiation

- Occupationally Exposed Individuals (Workers)
  - Industrial radiography (X-ray imaging)
  - Nuclear medicine departments
    - Radiology (medical imaging, X-rays, etc)
    - Radiation oncology (cancer treatment)
  - Nuclear power plants
  - Nuclear fuel cycle facilities
    - Production
    - Disposal
  - Government and university research laboratories

# Radiation Measurement Units

- Radioactive Material Quantity
  - Curie :: the amount of radioactive material decaying at 2.22 X $10^{12}$ atoms per minute or 3.7 X $10^{10}$ atoms per second
    - 1 ci = 3.7 X$10^{10}$ decays per second (dps)
  - Becquerel :: the amount of radioactive material decaying at 1 decay per second
    - 1 ci = 3.7 × $10^{10}$ Bq
    - 1Bq = 1 dps

# Radiation Measurement Units

- Biological Effects
  - Not fully described by decay rate of radioactive material
  - Additional factors must considered
    - Radiation type
    - Radiation energy

# Radiation Measurement Units: Roentgen (R)

- Relates to gamma or x-ray interactions in air
- Relates to energy deposition in air
- Qty of x-ray or gamma radiation producing 1 esu of charge (positive or negative) in 1 cc ($cm^3$) of dry air
  - esu = electrostatic unit of charge
  - 1 ionizing event = addition or removal of 1 electron = $\pm 4.8 \times 10^{-10}$ esu
  - 1 R = $2.08 \times 10^{9}$ ion pairs
  - 1 R = 88 erg/gram energy deposition in air
    - erg = unit of work or energy

- Problem: Doesn't relate to biological damage.

# Radiation Measurement Units: Radiation Absorbed Dose (RAD)

- Dose = Total amount of energy delivered to a specific area or organ by radiation.
- Dose rate = dose units per unit of time

- 1 RAD is an amount of any type of ionizing radiation that deposits 100 ergs/gram in tissue.

- 1 RAD = 100 ergs/gram energy deposition (tissue)

- Problem: Different types of ionizing radiation might have the same energy, but have totally different effects on tissue.

# Radiation Measurement Units:
# Roentgen Equivalent Man (REM)

- The amount of ionizing radiation required to produce the same biological effect as one rad of high-penetration x-rays.
- Radiation dose in rem is referred to as the dose equivalent (DE)

  DE (rem) = Dose (rad) x QF

- Quality Factor (QF)
  - Accounts for differences in biological effect for different types of radiation

# Quality Factor

- Gamma, X-Rays, and High-Energy Beta
  - 1 rad = 1 rem
- Alpha, Proton, Neutron, and Low-Energy Beta
  - 1 rad ≠ 1 rem
  - 1 rem = 1 rad * QF

| RADIATION | QUALITY FACTOR |
|---|---|
| GAMMA | 1 |
| X | 1 |
| BETA, ELECTRON>0.03 MeV | 1 |
| BETA, ELECTRON < 0.03 MeV | 1.7 |
| THERMAL NEUTRONS | 3 |
| FAST NEUTRONS | 10 |
| PROTONS | 10 |
| ALPHA | 10 |
| HEAVY IONS | 20 |

# Different Radiation Types

- Biological effect of any radiation is related to rate at which radiation transfers energy to tissue
- Linear Energy Transfer (LET)
  - Measure of the interaction density along radiation travel path
  - Equivalent to ionization potential or stopping power of body tissue
  - Inversely proportional to radiation range
    - Short range particles like alphas have a high LET
- Most damaging types of radiation to a biological system are those with a high LET.
- High LET radiation deposits all of its energy in a short distance of travel.

# Different Radiation Types

- LET increases with:
  - Increasing mass of incident radiation
  - Increasing charge of incident radiation
  - Decreasing energy of incident radiation
- In order of decreasing LET:
  - Fission fragments
  - Low mass number nuclei
  - Alpha particles
  - Protons
  - Neutrons
  - Low energy Beta, x-ray and gamma
  - High energy beta, x-ray and gamma

# Relationship between LET and QF

| LINEAR ENERGY TRANSFER (LET) (KeV/micron in water) | QUALITY FACTOR (QF) |
|---|---|
| 3.5 or less | 1 |
| 3.5 – 7.0 | 1 – 2 |
| 7.0 – 23 | 2 – 5 |
| 23 - 53 | 5 – 10 |
| 53 – 175 | 10 - 20 |

# Example 1

- The total dose of alpha particles to an individual is three rad. Calculate the dose equivalent in rem using the appropriate Quality Factor (QF).

$$Dose = 3 \cdot rad$$

$$QF\left(\alpha\right) = 10$$

$$DE = Dose \times QF$$

$$DE = \left(3\right)\left(10\right)$$

$$DE = 30\ rem$$

| RADIATION | QUALITY FACTOR |
|---|---|
| GAMMA | 1 |
| X | 1 |
| BETA, ELECTRON>0.03 MeV | 1 |
| BETA, ELECTRON < 0.03 MeV | 1.7 |
| THERMAL NEUTRONS | 3 |
| FAST NEUTRONS | 10 |
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| ALPHA | 10 |
| HEAVY IONS | 20 |

# Example 2

- As measured by instruments, an individual was exposed to radiation field consisting of 5 mrad gamma, 2 mrad beta, and 5 mrad fast neutrons. Calculate the dose equivalent in rem.

$$DE\,(rem) = Dose\,(rad)\,x\,QF$$

$$QF\,(\gamma) = 1$$
$$QF\,(\beta) = 1$$
$$QF\,(FN) = 10$$

$$DE = (5)(1) + 2(1) + 5(10)$$
$$= 57\ mrem$$

| RADIATION | QF |
|---|---|
| GAMMA | 1 |
| X | 1 |
| BETA, ELECTRON>0.03 MeV | 1 |
| BETA, ELECTRON < 0.03 MeV | 1.7 |
| THERMAL NEUTRONS | 3 |
| FAST NEUTRONS | 10 |
| PROTONS | 10 |
| ALPHA | 10 |
| HEAVY IONS | 20 |

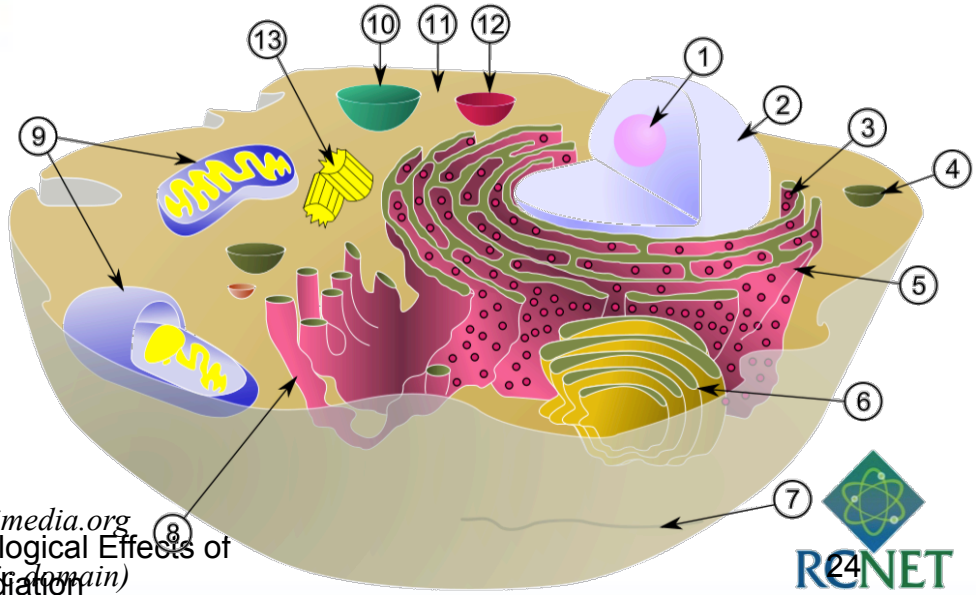
# Biological Organization

- Cell – basic unit of the human body
- Tissue - cells with similar structure performing same function
- Organ – cells with different structure (different tissues) performing similar overall function
- System – group of organs performing common function
- Organism

# Biological Organization: Cell

- Cell membrane
  - protects cell from external influences, such as toxins
  - "gatekeeper"
- Cytoplasm
  - 80% water
  - Helps convert nutrients into energy
  - Location of biochemical reactions for bodily functions

1. nucleolus
2. nucleus
3. ribosome
4. vesicle
5. rough endoplasmic reticulum (ER)
6. Golgi apparatus
7. cytoskeleton
8. smooth endoplasmic reticulum
9. mitochondria
10. vacuole
11. cytoplasm
12. lysosome
13. centrioles within centrosome

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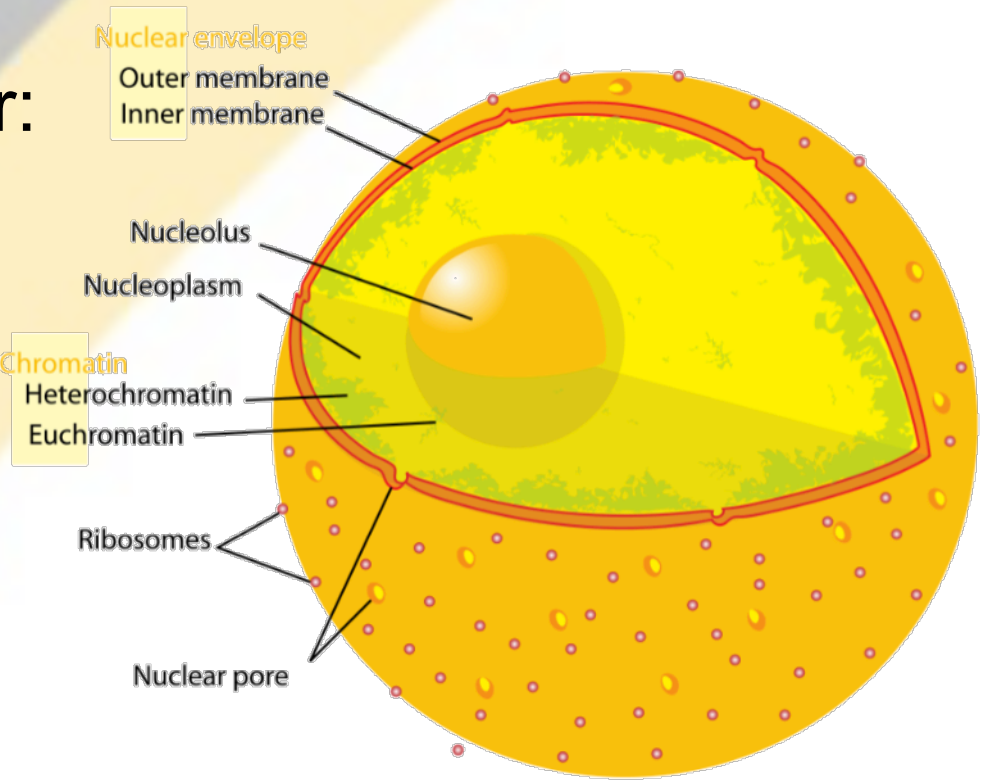
# Biological Organization: Cell

- Nucleus
  - Contains instructions for:
    - Cellular reproduction
    - Cellular function

    Contained within chromosomes
- Chromosomes
  - Strands of amino acids (deoxyribonucleic acids – DNA)
  - Abnormal bodily function if damaged or malformed

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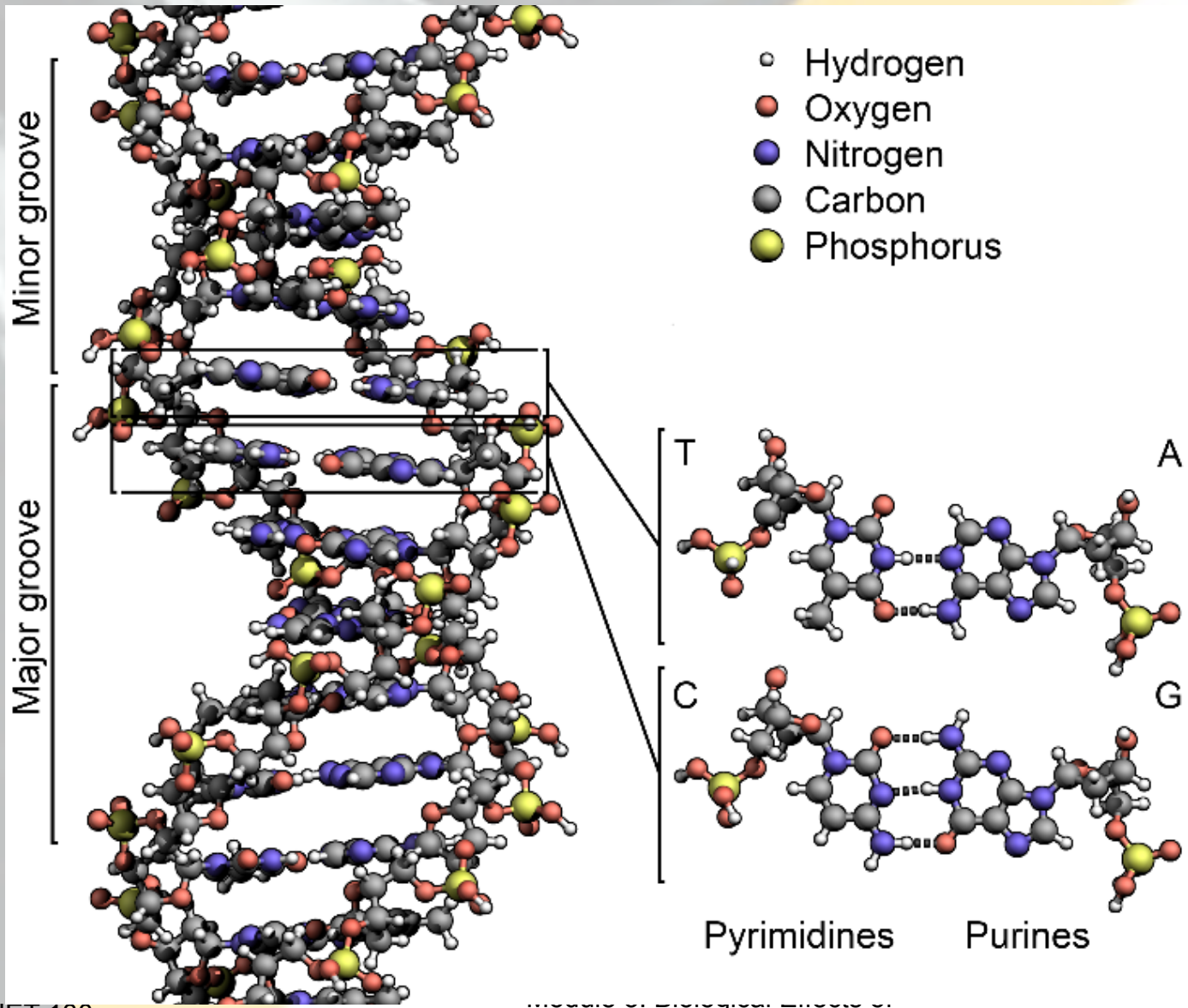
# Segment of DNA Strand

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# Cellular Effects of Radiation

- Free radical formation
- Direct radiation damage

# Cellular Effects of Radiation: Free Radical Formation

- Radical
  - An atom (either neutral or charged) with unpaired electrons that wants to join with another atom to stabilize itself
- Free radicals
  - Radicals that have not yet bonded with other atoms
  - Highly reactive atoms or chemical compounds that can alter existing state of cells
- Changes in cellular chemistry are the root causes of all the harmful effects of radiation.

# Cellular Effects of Radiation: Free Radical Formation

- Direct Effect of Radiation on Cells
  - Ionization and excitation of intracellular water molecules produces free radicals

- Indirect Effect of Radiation on Cells
  - Subsequent interference of free radicals with cells not direct affected by radiation

# Cellular Effects of Radiation: Free Radical Formation

- Radiolysis: production of free radicals in water
- Radiolysis by Ionization: Hydrogen Radical ($H^{\cdot}$)
  - Electron absorbed
  - Hydrogen radical and hydroxyl ion formed

$$H_2O + e^- \rightarrow H^{\cdot} + OH^-$$

$^{\cdot}$ = radical

# Cellular Effects of Radiation: Free Radical Formation

- Radiolysis by Ionization:
  Hydroxyl Radical ($OH^{\cdot}$)
  - Electron removed from water molecule
  - Positively ionized water removes hydrogen from neutral water to form hydroxyl radical

$$H_2O - e^- \rightarrow H_2O^+$$

$$H_2O^+ + H_2O \rightarrow OH^{\cdot} + H_3O^+$$

# Cellular Effects of Radiation: Free Radical Formation

- Radiolysis by Excitation:

  Hydrogen and Hydroxyl Radicals
  - Incident electron excites water molecule, but is not absorbed
  - Excited water molecule splits into hydrogen and hydroxyl radicals

$$H_2O + e^- \rightarrow H_2O^* + e^-$$

$$H_2O^* \rightarrow H^\cdot + OH^\cdot$$

* = excited

# Cellular Effects of Radiation: Free Radical Formation

- Most of these radicals immediately react with each other to produce harmless compounds

$$H^{\cdot} + H^{\cdot} \rightarrow H_2$$ **Hydrogen Gas**

$$OH^{\cdot} + OH^{\cdot} \rightarrow H_2O_2$$ **Hydrogen Peroxide**

$$H^{\cdot} + OH^{\cdot} \rightarrow H_2O$$ **Water**

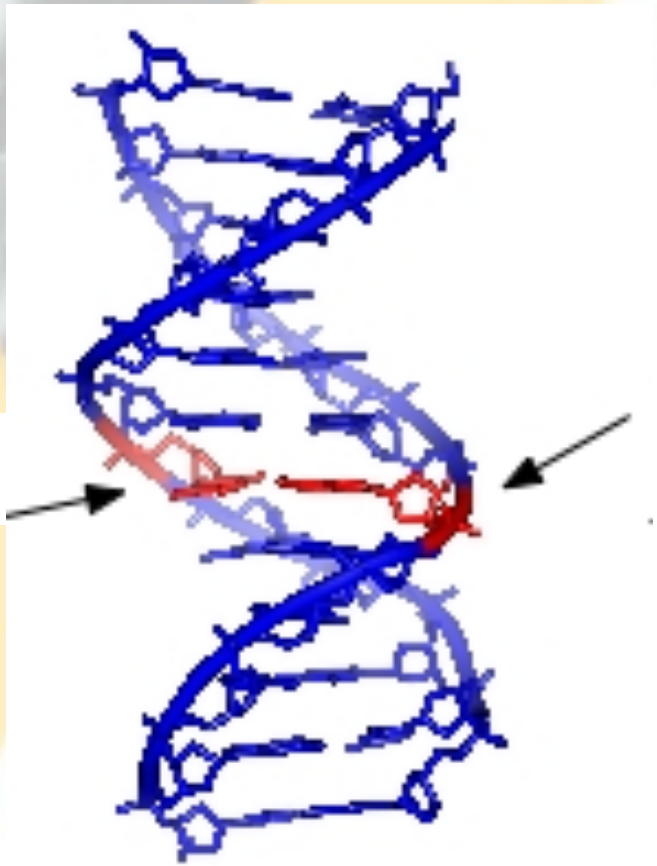
- However, they might react with other molecules in the cell, causing damage

# Cellular Effects of Radiation

- Cell may die
- Cell may reproduce but new cells may die
- Cell may reproduce producing abnormal cells
- Cell may repair itself and function normally

# Cellular Effects of Radiation

- DNA radiation damage



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# Effects of Radiation by Biological Organization

- Molecular
  - Damage to enzymes, DNA etc. and interference with biological pathways
- Subcellular
  - Damage to cell membranes, nucleus, chromosomes etc.
- Cellular Inhibition of cell division, cell death, transformation to a malignant state

# Effects of Radiation by Biological Organization

- Tissue, Organ
  - Disruption to central nervous system, bone marrow, intestinal tract
  - Induction of cancer
- Whole Animal
  - Death
  - Life shortening
- Populations
  - Changes in the genetic characteristics of individual members

# Radiosensitivity

- Different cells within the body have different structures and functions

- Vary in their **radiosensitivity**
  - Susceptibility to radiation-induced damage

# 4 Factors Affecting Radiosensitivity

1. Cellular division rate
   - Rapidly dividing cells are more sensitivity to radiation damage
2. Cellular metabolism rate
   - Cells with high metabolism rate are more susceptible to radiation damage
3. Developmental stage
   - Cells in division stage are more susceptible to radiation damage
4. Blood / nourishment to cell
   - Normally undernourished cells reproduce less
   - Faster reproduction = more mutations

# Organ / Tissue Radiation Effects

- Organ / tissue radiosensitivity influenced by 2 factors
  - Radiosensitivity of the tissue/organ cells
  - Importance to overall organism

- Most radiosensitive organs and tissues
  - Blood (tissue)
  - Blood-forming organs
  - Gonads (reproductive organs)
  - Lens of the eye
  - Skin
- Least radiosensitive organ
  - Brain (cells do not reproduce)

# Organ / Tissue Radiation Effects

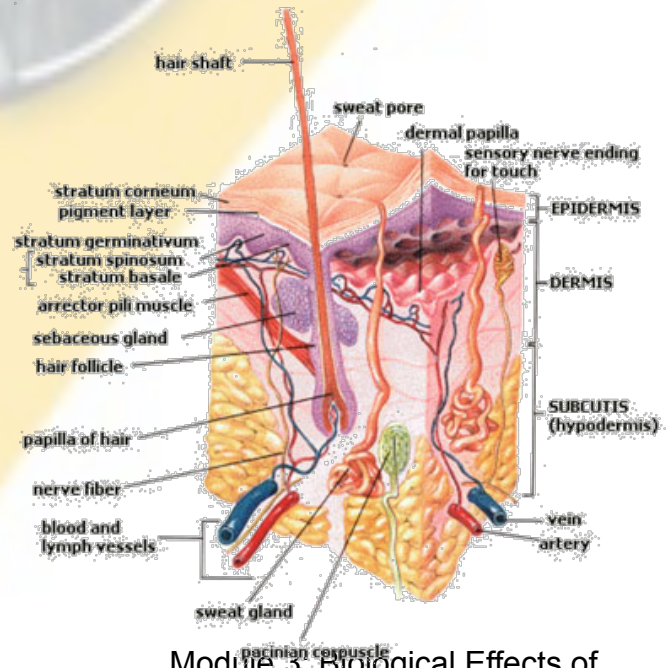
- Blood
  - One of the most radiosensitive tissues in the human body
  - Normal blood cells have an already short lifespan and high metabolic rate
    - Take in toxins quickly
- Gonads (reproductive organs)
  - Mutations occurring in egg or sperm cells could result in a mutation in the offspring
  - 100 rads: temporary depletion of sperm count
  - 300 to 400 rad: function of ovaries impaired

# Organ / Tissue Radiation Effects: Blood

| BLOOD CELL TYPE | FUNCTION | PRODUCTION SITE | LIFETIME OF CELL | EFFECT OF SINGLE RADIATION EXPOSURE OF > 100 RADS |
|---|---|---|---|---|
| Red (Erythrocytes) | Carry oxygen and nutrients to body | Bone marrow | 100 days | Slight decrease in number |
| Lymphocyte (type of white blood cell) | Fight infection | Lymph nodes and spleen | 1 day | Highly radiosensitive; decrease in number increases with dose; decrease within 2 days after exposure; large decrease in number can result in infection |
| Euthrophils (type of white blood cells) | Fight infection | Bone marrow | 7 days | Highly radiosensitive; decrease in number proportional to dose; depletion results in infection and fever |
| Platelets | Blood clotting | Bone marrow | 7 – 10 days | Highly radiosensitive; decrease in number increases with dose; decrease in number can result in hemorrhaging |

# Organ / Tissue Radiation Effects: Skin

- First tissue to exhibit noticeable radiation injury
- High radiosensitivity due to the high rate of cell division and degree of exposure
- 400 to 500 rad: Erythema (reddening)
- Higher dose: blistering and ulceration may occur
- Long term complications: scarring and skin cancer

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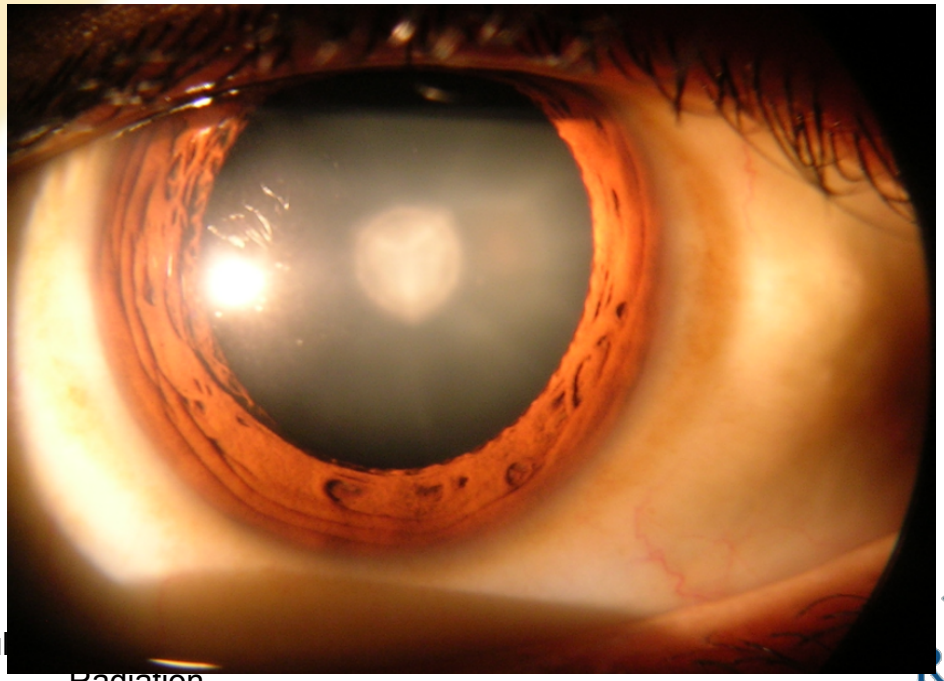
# Organ / Tissue Radiation Effects: Lens of the Eye

- May result in cataract formation (cloudiness)
- Single dose of 200-500 rad
- Cumulative (spread over several months) dose of 1000 rad



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# Radiation Effects on Humans

- Four factors:
  - Radiation type
  - Area exposed
  - Total dose
  - Dose rate

# Radiation Effects on Humans: Radiation Type

- For radiation of same type, range in tissue increases with increasing energy
- Depth of penetration is function of type of radiation
- Charged particles and neutrons will not penetrate as far as electromagnetic radiation
- Linear Energy Transfer (LET)
  - LET depends on charge, mass, and energy
  - Higher LET = higher QF = more biological damage

# Radiation Effects on Humans: Portion of Body Exposed

- Whole Body Exposure
  - Irradiation of all cells, organs, and tissues
  - Symptoms depends on which organ is sensitive at the given dose level

- Partial Body Exposure
  - Damage limited to tissues and organs within exposed area
  - Very high localized doses of radiation are used to treat certain cancers without significant damage to the rest of the body

# Radiation Effects on Humans: Rate of Exposure

- Biological damage decreases with decreasing dose rate
- Acute Exposure
  - High dose
  - Short exposure time
- Chronic Exposure
  - Low dose
  - Long exposure time
  - Occupational radiation exposure
  - Exposure from natural background radiation

# Acute Radiation Effects: Whole Body Exposure

- Subclinical Range (0 to 100 rem)
  - No sickness occurs which requires medical attention
  - Some changes occur in the blood for doses near 100 rem
- Therapeutic Range (100 to 200 rem)
  - Nausea, vomiting, loss of appetite, and fatigue
  - Blood damage more severe
  - Redness of the skin
- Lethal Range (>200 rem)
  - Nausea and vomiting become more severe
  - Internal hemorrhaging may occur
  - Hair loss at 300 rem
  - 200 - 600 rem: small percentage of people will die within 30 days
  - 600 - 1000 rem: higher chance of death
  - >1000 rem: Certain death

# Acute Radiation Effects: Whole Body Exposure

| Dose (Rads*) | Effects |
|---|---|
| 25-50 | First sign of physical effects (drop in white blood cell count) |
| 100 | Threshold for vomiting (within a few hours of exposure) |
| 320 - 360 | ~ 50% die within 30 days (with minimal supportive care) |
| 480 - 540 | ~50 % die within 30 days (with supportive medical care) |
| 1,000 | ~ 100% die within 30 days |

| RANGE | 0 TO 100 REMS SUBCLINICAL RANGE | 100 TO 1,000 REMS THERAPEUTIC RANGE | | | OVER 1,000 REMS LETHAL RANGE | |
|---|---|---|---|---|---|---|
| | | 100 TO 200 REMS | 200 TO 600 REMS | 600 TO 1,000 REMS | 1,000 TO 5,000 REMS | OVER 5,000 REMS |
| | | CLINICAL SURVEILLANCE | THERAPY EFFECTIVE | THERAPY PROMISING | THERAPY PALLIATIVE | |
| Incidence of vomiting | None | 100 rems: 5%<br>200 rems: 50% | 300 rems = 100% | 100% | 100% | |
| Delay time | - | 3 hours | 2 hours | 1 hour | | |
| | | | | | | |
| Leading organ | None | Hematopoietic tissue | | | Gastrointestinal tract | Central nervous system |
| Characteristic signs | None | Moderate Leukopenia | Severe leucopenia; purpose; hemorrhage; infection. Hair loss above 300 rems. | | Diarrhea; fever, disturbance of electrolyte balance | Convulsions; tremor; ataxia; lethargy |
| | | | | | | |
| Critical period post exposure | - | - | 4 to 6 weeks | | 5 to 14 days | 1 to 48 hours |
| Therapy | Reassurance | Reassurance; hematological surveillance | Blood transfusion; antibiotics | Consider bone marrow transplantation | Maintenance of electrolyte balance | Sedatives |
| Prognosis | Excellent | Excellent | Good | Guarded | Hopeless | |
| | | | | | | |
| Convalescent period | None | Several weeks | 1 to 12 months | Long | 90 to 100% | |
| Incidence of death | None | None | 0 to 100% (variable) | 80 to 100% (variable) | | |
| Death occurs within | - | - | 2 months | | 2 weeks | 2 days |
| Cause of death | - | - | Hemorrhage; infection | | Circulatory collapse | Respiratory failure |

# Acute Radiation Effects: Localized Exposure

# Acute Radiation Effects: Localized Exposure


# Acute Radiation Effects: Localized Exposure


# Acute Radiation Effects: Localized Exposure

- Telangiectasia
  - Dilation (expansion) of the blood vessels in the skin
  - Some areas receive excessive blood flow, diverting blood away from other areas
  - The cells that LOSE blood flow suffer from oxygen deprivation
- Erythema
  - Early Transient: Slight inflammation of skin due to inflamed blood vessels
  - Main: more severe inflammation
  - Late: Severe inflammation of skin due to damaged blood vessels

# Acute Radiation Effects: Localized Exposure

- Erythema
  - Early Transient: Slight inflammation of skin due to inflamed blood vessels
  - Main: more severe inflammation
  - Late: Severe inflammation of skin due to damaged blood vessels

# Acute Radiation Effects: Localized Exposure

- Acute Ulceration
  - Early loss of outer skin cells (peeling)
- Dermal Atrophy
  - Thinning of the skin tissues
- Epilation (hair loss)
- Dry Desquamation
  - Keratinization (hardening) of the skin
- Moist Desquamation
  - Skin loss due to inability of damaged skin cells to reproduce
- Secondary Ulceration
  - Skin damage due to dehydration and infection resulting from severe moist desquamation

# Acute Radiation Effects: Localized Exposure

- Dermal Necrosis
  - Cell/tissue death due to insufficient blood flow
- Acute Epidermal Necrosis
  - Severe tissue loss
  - High-dose, low-energy beta irradiation

# Chronic Radiation Effects: Whole Body Exposure

- Human body tolerates small doses of radiation exposure better over a long period of time.
- Human body –
  - Repairs radiation damage
  - Eliminates radiation-induced byproducts
- ….As long as the repair or elimination rate is larger than the production rate.
- 500 rem acute dose
  - Severe radiation sickness
- 500 rem delivered at 10 rem per week
  - Little noticeable effect

# Chronic Radiation Effects: Threshold Effect

- No permanent biological damage occurs unless total dose exceeds some value (threshold)

- Limit long term chronic exposures to less than threshold values to protect against permanent damage

# Chronic Radiation Effects: Tissue Damage and Repair

- Body continuously attempts to repair damage as it occurs
- If damage too severe
  - Repair mechanisms become strained
  - Aging effects are increased
- Continued exposure shortens average life span
- May result in cancer
  - Genetic mutation of cells
  - Leukemia: Inability to produce white blood cells normally

# Genetic Effects of Radiation

- Only seen in offspring of exposed workers
- Changes to genetic information in reproductive cells due to damaged DNA structure
- May be spontaneous changes due to background radiation

# Somatic Effects of Radiation

- Occur in the exposed person
  - Blood changes
  - Skin reddening (erythema)
- Depends on:
  - Total Dose
  - Dose Rate
  - Region Exposed
  - Body % Exposed

# Internal Radiation Exposure

- 4 ways radionuclides can enter the body:
  - Inhalation
  - Swallowing
  - Absorption
  - Through Cuts

# Critical or Target Organ Concept: Swallowing and Inhalation of Radionuclides

- When swallowed, radionuclides pass through normal digestion processes.
- When inhaled, radionuclides enter the lungs.
- If soluble, transmitted through blood stream
- In the blood stream, it travels through out the body.
- Some organs have an affinity to specific elements – radioactive or not.

# Critical or Target Organ Concept

- Example:
  - Dial painters contract bone cancer after years of "pointing" the radium dipped brush with their tongues.
  - Radium falls in same periodic table grouping as Calcium
    - Replaces Calcium in bone.
  - The target organ for Radium is bone.


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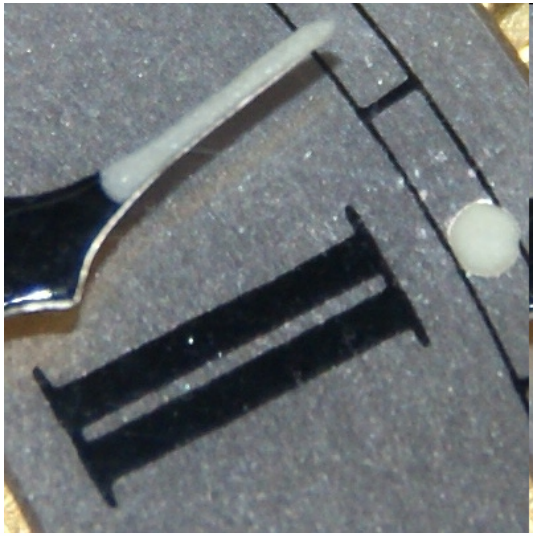

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# Critical or Target Organ Concept

- Radium – Bone
- Strontium – Bone
- Cobalt – whole body
- Cesium – large intestine
- Iodine - Thyroid

# Body Burden

- Amount of internally-deposited radioactivity causing maximum permissible dose to any organ.

# Protection from External Radioactivity

- Time – minimize time exposed
- Distance – Increase distance from source
- Shielding – Increase shielding

# Protection from Internal Radioactivity

- Administratively controlled: PREVENTION
  - Respirators
  - No eating / drinking in contaminated areas
  - No open wounds