An Introduction To The Health Effects of Radiation and Radioactive Materials

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Historical Awareness

- 1895 - Wilhem Conrad Roentgen discovered X-rays and in 1901 he received the first Nobel Prize for physics.
- 1903 - Marie Curie and Pierre Curie, along with Henri Becquerel were awarded the Nobel Prize in physics for their contributions to understanding radioactivity, including the properties of uranium.
- 1942 - Enrico Fermi and others started the first sustained nuclear chain reaction in a laboratory beneath the University of Chicago football stadium.
- 1945 – Nuclear bombs dropped on Japan.
Radiation

Non-ionizing

Ionizing
Non-ionizing Radiation

**Sources**
- Ultraviolet light
- Visible light
- Infrared radiation
- Microwaves
- Radio & TV
- Power transmission
Non-ionizing Examples

- Ultraviolet – Black light – induce fluorescence in some materials
- Vision – very small portion that animals use to process visual information
- Heat – infrared – a little beyond the red spectrum
- Radio waves – beyond infrared
- Micro waves
- Electrical power transmission – 60 cycles per second with a wave length of 1 to 2 million meters.
Ultraviolet - Sources

- Sun light
- Most harmful UV is absorbed by the atmosphere – depends on altitude
- Fluorescent lamps
- Electric arc welding
  Can damage the eye (cornea)
- Germicidal lamps
- Eye damage from sun light
- Skin cancer
Ultraviolet - Effects

- High ultraviolet – kills bacterial and other infectious agents
- High dose causes - sun burn – increased risk of skin cancer
- Pigmentation that results in suntan
- Suntan lotions contain chemicals that absorb UV radiation
- Reaction in the skin to produce Vitamin D that prevents rickets
- Strongly absorbed by air – thus the danger of hole in the atmosphere
Visible Energy

- Energy between 400 and 750 nm
- Standards are set for the intensity of light in the workplace (measured in candles or lumens)
Infrared Radiation

- Energy between 750 nm to 0.3 cm
- The energy of heat – Heat is the transfer of energy
- Can damage – cornea, iris, retina and lens of the eye (glass workers – “glass blower’s cataract”)
Microwaves & Radio Waves

• Energy between 0.1 cm to 1 kilometer
• Variety of industrial and home uses for heating and information transfer (radio, TV, mobile phones)
• Produced by molecular vibration in solid bodies or crystals
• Health effects – heating, cataracts
• Long-term effects being studied
Electrical Power

- Standard in homes and businesses
- Highest level of exposure from electric-power generation and distribution system (high voltage power lines)
- Medical system – Magnetic imaging
- Acute health effects – shock
- Long-term health effects?
Ionizing Radiation
Ionizing Radiation

Ionization Defined

Radiation capable for producing ions when interacting with matter – in other words enough energy to remove an electron from an atom.

Sources – x-rays, radioactive material produce alpha, beta, and gamma radiation, cosmic rays from the sun and space.
Stable vs. Radioactive Isotopes

• Atoms “prefer” a particular neutron/proton ratio in the nucleus

• If “too many” neutrons or protons
  – Nuclei will decay
  – Give off ionizing radiation (particles)
  – Stable ratio
Stable vs. Radioactive Isotopes

• In the process unstable $\rightarrow$ stable
  – Nuclei give off particles (atom decay)
  – The process liberates particles or radiation
Types of Ionization Radiation

- Alpha $\alpha$
- Beta $\beta$
- Gamma $\gamma$
- X-ray $X$
- Neutron $\eta$
Alpha particles (decay)

- Alpha - a - He++ - Very short range

Large, unstable nucleus → Smaller, more stable nucleus + Alpha particle
Alpha particles (decay)

- Primary hazard from internal exposure
- Alpha emitters can accumulate in tissue (bone, kidney, liver, lung, spleen) causing local damage
Beta particles (decay)

- Beta - $\beta^-$ or $e^-$ - Medium Range
- Positron - $\beta^+$ - Medium Range
Beta-minus Decay

Carbon-14 → $\beta^-$ → Nitrogen-14 + Antineutrino + Electron
6 protons + 8 neutrons → 7 protons + 7 neutrons + $\bar{\nu}$ + $\nu$

Beta-plus Decay

Carbon-10 → $\beta^+$ → Boron-10 + Neutrino + Positron
6 protons + 4 neutrons → 5 protons + 5 neutrons + $\nu$ + $\bar{\nu}$
Beta Particles

• Can cause skin burns or be an internal hazard of ingested
Gamma Radiation

- Gamma radiation - penetrating

Gamma decay

$^{240}_{94}\text{Pu}^*$ → $^{240}_{94}\text{Pu}$

γ-radiation: high-energy electromagnetic waves
Gamma Radiation

• Emitted from nucleus of radioactive atoms – spontaneous emission
• Emitted with kinetic energy related to radioactive source
• Highly penetrating – extensive shielding required
• Serious external radiation hazard
X-Rays

X-Ray Production (Bremsstrahlung)

Electron

Target Nucleus Tungsten

X-Ray

Cathode (-)

Anode (+)

X-Rays
X-Rays

• Produced from orbiting electrons or free electrons – usually machine produced
• Produced when electrons strike a target material inside and x-ray tube
• Emitted with various energies & wavelengths
• Highly penetrating – extensive shielding required
• External radiation hazard
• Discovered in 1895 by Roentgen
Neutron particles

- Uncharged
- Able to penetrate deeply
- Hazard inside nuclear reactors
Radiation Source

Alpha Particles
Stopped by a sheet of paper

Beta Particles
Stopped by a layer of clothing or by a few millimeters of a substance such as aluminium.

Gamma Rays
Stopped by several feet of concrete or a few inches of lead.
Radiation or Radioactive material?
• Radiation is energy or particles that are given off when something decays to reach a stable proton to neutron ratio.
• The radioactive material contains the unstable nuclei which are decaying.
• These often get confused.
What cause a material to become radioactive?

• In order to induce radioactivity it is necessary to change the proton to neutron ratio in a nucleus

• Radiation from a radioactive material does not cause its surroundings to become radioactive
What cause a material to become radioactive?

• If the radiation from a radioactive material is placed on a table or next to a person, this radiation does not cause the table or person to become radioactive.
What cause a material to become radioactive?

• Only if a material is exposed to neutrons from a nuclear reactor or a high energy charged particle accelerator can a non-radioactive material become radioactive.
Radioactive Material

- Either natural or created in nuclear reactor or accelerator
- Radioactive material is unstable and emits energy in order to return to a more stable state (particles or gamma-rays)
- Half-life – time for radioactive material to decay by one-half
WHAT IS DOSE?

• Absorption of radiation energy per unit mass of absorber
  – Conventional unit – rad  International unit – Gray (Gy)
  1 Gy = 1 Joule/Kg
  – 1 Gy = 100 rad
  – 1 rad = .01 Gy
WHAT IS DOSE EQUIVALENT?

- Biological damage & resulting risk from radiation dose
- Dose equivalent = Dose x Quality Factor
  - Quality factor: Any type of radiation compared to same absorbed dose γ or X
    - QF X, γ, β = 1
    - QF α = 20 (if internal)
    - QF η = 3-20 (depends on energy)
- Conventional unit – “rem”
- SI unit – Sievert (Sv)
- 1 Sv = 100 rem
## Radiation Units

<table>
<thead>
<tr>
<th>Measure of</th>
<th>Quantity</th>
<th>Unit/SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of radioactive material</td>
<td>Activity (measurement of decay)</td>
<td>curie (Ci)/Becquerel</td>
</tr>
<tr>
<td>Ionization in air</td>
<td>Exposure</td>
<td>roentgen (R)/Coulomb/Kg</td>
</tr>
<tr>
<td>Absorbed energy per mass (energy deposition)</td>
<td>Absorbed Dose</td>
<td>Rad/gray</td>
</tr>
<tr>
<td>Biological Damage</td>
<td>Dose Equivalent</td>
<td>100 rad = 1Gy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rem/Sievert</td>
</tr>
</tbody>
</table>
### Radiation Doses and Dose Limits

<table>
<thead>
<tr>
<th>Activity</th>
<th>Dose (mrem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flight from Los Angeles to London</td>
<td>5</td>
</tr>
<tr>
<td>Annual public dose limit</td>
<td>100</td>
</tr>
<tr>
<td>Annual natural background</td>
<td>300</td>
</tr>
<tr>
<td>Fetal dose limit</td>
<td>500</td>
</tr>
<tr>
<td>Barium enema</td>
<td>870</td>
</tr>
<tr>
<td>Annual radiation worker dose limit</td>
<td>5,000</td>
</tr>
<tr>
<td>Heart catheterization</td>
<td>45,000</td>
</tr>
<tr>
<td>Life saving actions guidance (NCRP-116)</td>
<td>50,000</td>
</tr>
<tr>
<td>Mild acute radiation syndrome</td>
<td>200,000</td>
</tr>
<tr>
<td>LD50/60 for humans (bone marrow dose)</td>
<td>350,000</td>
</tr>
<tr>
<td>Radiation therapy (localized &amp; fractionated)</td>
<td>6,000,000</td>
</tr>
</tbody>
</table>
Half-Life (HL)

• **Physical Half-Life**
  Time (in minutes, hours, days or years) required for the activity of a radioactive material to decrease by one half due to radioactive decay

• **Biological Half-Life**
  Time required for the body to eliminate half of the radioactive material (depends on the chemical form)

• **Effective Half-Life**
  The net effect of the combination of the physical & biological half-lives in removing the radioactive material from the body

• Half-lives range from fractions of seconds to millions of years
<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Physical Half-Life</th>
<th>Activity</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cesium-137</td>
<td>30 yrs</td>
<td>1.5x10^6 Ci</td>
<td>Food Irradiator</td>
</tr>
<tr>
<td>Cobalt-60</td>
<td>5 yrs</td>
<td>15,000 Ci</td>
<td>Cancer Therapy</td>
</tr>
<tr>
<td>Plutonium-239</td>
<td>24,000 yrs</td>
<td>600 Ci</td>
<td>Nuclear Weapon</td>
</tr>
<tr>
<td>Iridium-192</td>
<td>74 days</td>
<td>100 Ci</td>
<td>Industrial Radiography</td>
</tr>
<tr>
<td>Hydrogen-3</td>
<td>12 yrs</td>
<td>12 Ci</td>
<td>Exit Signs</td>
</tr>
<tr>
<td>Strontium-90 Device</td>
<td>29 yrs</td>
<td>0.1 Ci</td>
<td>Eye Therapy</td>
</tr>
<tr>
<td>Iodine-131 Therapy</td>
<td>8 days</td>
<td>0.015 Ci</td>
<td>Nuclear Medicine</td>
</tr>
<tr>
<td>Technetium-99m Imaging</td>
<td>6 hrs</td>
<td>0.025 Ci</td>
<td>Diagnostic</td>
</tr>
<tr>
<td>Americium-241</td>
<td>432 yrs</td>
<td>0.0000005 Ci</td>
<td>Smoke Detectors</td>
</tr>
<tr>
<td>Radon-222 Level</td>
<td>4 days</td>
<td>1 pCi/l</td>
<td>Environmental</td>
</tr>
</tbody>
</table>
32 microcuries Tc-99m; half-life of 6 hours
After 1 half-life (6h)
16 mCi
After 2 half-lives (12 h)
8 mCi
After 3 half-lives (18 h)
4 mCi
After 4 half-lives (24 h)
2 mCi
After 10 half-lives (16h)
1/1024 of original activity
Types of Radiation Hazards

- **Exposure** -
  Whole body or partial body absorbs penetrating ionizing radiation from an external source.
  Exposure also occurs from internal contamination.
  Acute radiation syndrome (high dose)

- **Contamination** -
  Contamination results when a radioisotope (as gas, liquid, or solid) is released into the environment and then ingested, inhaled, or deposited on the body surface.
If the patient is externally contaminated with radionuclides, you can Decontaminate.
If radionuclides have gotten inside the body, consider chelation therapy
Causes of Radiation Exposure/Contamination

• Accidents
  – Nuclear reactor
  – Medical radiation therapy
  – Industrial irradiator
  – Lost/stolen medical or industrial radioactive sources
  – Transportation

• Terrorist Event
  – Radiological dispersal device (dirty bomb)
  – Low yield nuclear weapon
Effects of Radiation

• Effects determined by:
  – Total dose
  – Dose rate
  – Volume of tissue irradiated
  – Type of radiation
  – Anatomical part irradiated
  – Individual susceptibility
  – Trauma / Illness
Radiation Effect

radiolysis
Radiation effects: UV damage
# Cell Sensitivity to Irradiation

<table>
<thead>
<tr>
<th>Radiosensitivity</th>
<th>Cell Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Nerve cells</td>
</tr>
<tr>
<td></td>
<td>Muscle cells</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Osteoblast</td>
</tr>
<tr>
<td></td>
<td>Endothelial cells</td>
</tr>
<tr>
<td></td>
<td>Fibroblast</td>
</tr>
<tr>
<td></td>
<td>Spermatids</td>
</tr>
<tr>
<td>High</td>
<td>Spermatogonia</td>
</tr>
<tr>
<td></td>
<td>Lymphocytes</td>
</tr>
<tr>
<td></td>
<td>Stem Cells</td>
</tr>
<tr>
<td></td>
<td>Intestinal mucosa cells</td>
</tr>
<tr>
<td></td>
<td>Erythroblast</td>
</tr>
</tbody>
</table>
Ionizing radiation

Seconds
Radiation damage
- DNA strand breaks
- Oxidative damage

Minutes
Cellular response
- Gene expression changes: mRNA, protein
- Protein modification

Hours
Cell function/fate
- Cell death
- Genomic instability

One day

Weeks
Acute syndromes
- Organ failure
- Cancer
- Birth defects
- Gene pool

Years
Drives medical consequences
Factors Determining Radiation Exposure

- Time
- Distance
- Shielding
Injuries Associated with Radiological Incidents

- Acute Radiation Syndrome (ARS)
- Localized radiation injuries/cutaneous radiation syndrome
- Internal or external contamination
- Combined radiation injuries with
  - Trauma
  - Burns
- Fetal effects
Acute Radiation Syndrome

- The required conditions for Acute Radiation Syndrome (ARS) are:
  - The radiation dose must be large (>0.7 Gy)
  - The dose usually must be external
  - The radiation must be penetrating
  - The entire body (able to reach the internal organs)
  - The dose must have been delivered in a short time (usually a matter of minutes).
Acute Radiation Syndrome
A Spectrum of Disease
Phases of Acute Radiation Syndrome

Exposure

Prodromal Stage | Latent Stage | Manifest Illness | Recovery

Time (days to years)

University of Colorado Hospital

Anschutz Medical Campus
Phases of Acute Radiation Syndrome

- Prodromal Period: >100 rad, hours to days
- Latent Period: 100-5,000+ rad, hours to weeks
- Manifest Illness:
  - Hematologic Syndrome (200-1000 rad)
  - Gastrointestinal Syndrome (1000-5000 rad)
  - Central Nervous Syndrome (>5000 rad)
- Recovery or Death
<table>
<thead>
<tr>
<th>Syndrome</th>
<th>Dose*</th>
<th>Prodromal Stage</th>
<th>Latent Stage</th>
<th>Manifest Illness Stage</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hematopoietic (Bone marrow)</td>
<td>&gt; 0.7 Gy (&gt; 70 rads) (mild symptoms may occur as low as 0.3 Gy or 30 rads)</td>
<td>• Symptoms are anorexia, nausea and vomiting. Onset occurs 1 hour to 2 days after exposure. Stage lasts for minutes to days.</td>
<td>• Stem cells in bone marrow are dying, although patient may appear and feel well. Stage lasts 1 to 6 weeks.</td>
<td>• Symptoms are anorexia, fever, and malaise. Drop in all blood cell counts occurs for several weeks. Primary cause of death is infection and hemorrhage. Survival decreases with increasing dose. Most deaths occur within a few months after exposure.</td>
<td>• In most cases, bone marrow cells will begin to repopulate the marrow. There should be full recovery for a large percentage of individuals from a few weeks up to two years after exposure. Death may occur in some individuals at 1.2 Gy (120 rads). The LD$_{50/60}^{+}$ is about 2.5 to 5 Gy (250 to 500 rads).</td>
</tr>
<tr>
<td>Gastrointestinal (GI)</td>
<td>&gt; 10 Gy (&gt; 1000 rads) (some symptoms may occur as low as 6 Gy or 600 rads)</td>
<td>• Symptoms are anorexia, severe nausea, vomiting, cramps, and diarrhea. Onset occurs within a few hours after exposure. Stage lasts about 2 days.</td>
<td>• Stem cells in bone marrow and cells lining GI tract are dying, although patient may appear and feel well. Stage lasts less than 1 week.</td>
<td>• Symptoms are malaise, anorexia, severe diarrhea, fever, dehydration, and electrolyte imbalance. Death is due to infection, dehydration, and electrolyte imbalance. Death occurs within 2 weeks of exposure.</td>
<td>• The LD$_{100}^{+}$ is about 10 Gy (1000 rads).</td>
</tr>
<tr>
<td>Cardiovascular (CV)/ Central Nervous System (CNS)</td>
<td>&gt; 50 Gy (5000 rads) (some symptoms may occur as low as 20 Gy or 2000 rads)</td>
<td>• Symptoms are extreme nervousness and confusion; severe nausea, vomiting, and watery diarrhea; loss of consciousness; and burning sensations of the skin. Onset occurs within minutes of exposure. Stage lasts for minutes to hours.</td>
<td>• Patient may return to partial functionality. Stage may last for hours but often is less.</td>
<td>• Symptoms are return of watery diarrhea, convulsions, and coma. Onset occurs 5 to 6 hours after exposure. Death occurs within 3 days of exposure.</td>
<td>• No recovery is expected.</td>
</tr>
</tbody>
</table>
Cutaneous Radiation Syndrome (CRS)

- Syndrome that results from acute radiation exposure to skin
- ARS usually comes with some skin damage
- CRS without ARS (e.g. X-rays, beta radiation)
• Inflammation
• Erythema
• Desquamation
• Epilation
• Blistering and ulceration
Examples of Radiation Skin Burns
Management

• Triage
  – ABC
  – Treat major trauma, burns, respiratory injury
  – Blood samples: CBC
  – Treat contamination as needed
  – Assess lymphocyte depletion
Management

• Diagnosis
  – History
  – Clinical presentation (prodromal syndrome)
  – Dose reconstruction
  – Laboratory data
Absolute Lymphocyte Count

• Measure every 4 - 6 hours initial 48 hours
• Normal: approx 2500 cells/ml
• > 1200: probably non-lethal
• 300 to 1200 cells/ml: significant (hospitalize)
• < 300 cells/ml: critical
Estimate Dose from Exposure

- Lymphocyte depletion kinetics
- Chromosome analysis (dicentrics)
Lymphocyte Depletion Kinetics: Andrews Curve

1: 1 Gy
2: 4 Gy
3: 6 Gy
4: 7.1 Gy
Dicentric chromosomes

- Chromosome with 2 centromeres
- Dicentrics are considered the most sensitive and most specific for assessing radiation dose.
Management

• Treatment
  – Supportive care
  – Growth factors (for WBC, platelets, RBC)
  – Chelators/antidotes
  – Stem cell transplants
  – Psychological support
Treatment of Internal Contamination

- Radionuclide-specific
- Most effective when administered early
- May need to act on preliminary information
- NCRP Report No. 65, Management of Persons Accidentally Contaminated with Radionuclides

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Route</th>
<th>Treatment</th>
<th>Route</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cesium-137</td>
<td>Prussian blue</td>
<td>Oral</td>
<td>Oral</td>
</tr>
<tr>
<td>Iodine-125/131</td>
<td>Potassium iodide</td>
<td>Oral</td>
<td>Oral</td>
</tr>
<tr>
<td>Strontium-90</td>
<td>Aluminum phosphate</td>
<td>Oral</td>
<td>Oral</td>
</tr>
<tr>
<td>Americium-241/</td>
<td>Ca- and Zn-DTPA</td>
<td>IV</td>
<td>IV</td>
</tr>
<tr>
<td>Plutonium-239/</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cobalt-60</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Chronic Health Effects from Radiation

- Ionizing radiation in high doses is a proven carcinogen (atomic bomb survivors, Chernobyl)
- Unclear whether it is a carcinogen at low doses (< 20 rem)
- Natural incidence of cancer ~ 40%; mortality ~ 25%
- Risk of fatal cancer is estimated as ~ 4% per 100 rem
- A dose of 5 rem increases the risk of fatal cancer by ~ 0.2%
- A dose of 25 rem increases the risk of fatal cancer by ~ 1%
What are the Risks to Future Children? Hereditary Effects

- Magnitude of hereditary risk per rem is 10% that of fatal cancer risk
- Risk to caregivers who would likely receive low doses is very small - 5 rem increases the risk of severe hereditary effects by ~ 0.02%
- Risk of severe hereditary effects to a patient population receiving high doses is estimated as ~ 0.4% per 100 rem
Fetal Irradiation- No significant risk of adverse developmental effects below 10 rem

<table>
<thead>
<tr>
<th>Disorder due to Fetal Irradiation</th>
<th>Days gestation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st 2 weeks of gestation</td>
<td></td>
</tr>
<tr>
<td>&gt;10 rad</td>
<td></td>
</tr>
<tr>
<td>Prenatal death 0.1% increase in the spontaneous abortion rate</td>
<td></td>
</tr>
<tr>
<td>Weeks 2-9 Organogenesis</td>
<td></td>
</tr>
<tr>
<td>&gt;10 rad</td>
<td></td>
</tr>
<tr>
<td>Congenital defects: skeletal, CNS, and organ systems</td>
<td></td>
</tr>
<tr>
<td>&gt;6 weeks to partition (fetal stage)</td>
<td></td>
</tr>
<tr>
<td>&gt; 10 rad</td>
<td></td>
</tr>
<tr>
<td>Microcephly Leukemia</td>
<td></td>
</tr>
<tr>
<td>Anomaly</td>
<td></td>
</tr>
<tr>
<td>• Cataracts</td>
<td>0-6</td>
</tr>
<tr>
<td>• Spontaneous abortion</td>
<td>0-35</td>
</tr>
<tr>
<td>• Cleft palate</td>
<td>20-30</td>
</tr>
<tr>
<td>• Skeletal disorders</td>
<td>25 and greater</td>
</tr>
<tr>
<td>• Growth disorders</td>
<td>&gt;54 days</td>
</tr>
</tbody>
</table>
Radioiodines and Thyroid Cancer

Radioiodines concentrate in the thyroid gland and can increase the risk of thyroid cancer.
You can reduce the radioiodine thyroid dose by giving potassium iodide

• Potassium Iodide (KI) considerations
  • Who should get KI?
  • Useful at the beginning of an exposure
  • Only protects against thyroid cancer
Key Points

- Ionizing radiation includes:
  - Electromagnetic radiation: X and gamma
  - Particulate radiation: alpha, beta, neutrons
Key Points

• Patient can be:
  – Irradiated externally
  – Contaminated with radionuclides

• Which patients are radioactive?
  – Those contaminated with radionuclides
  – These patients need to be decontaminated
  – Some internally deposited radionuclides can be removed with chelation therapy
Key Points

• Protect yourself from radiation:
  – Reduce the time of exposure
  – Increase the distance from the radiation source
  – Apply shielding between yourself and the radiation source
Key Points

• Acute Radiation Syndrome:
  – Stages progress from hematopoietic to gastrointestinal to central nervous system with increasing dose
  – The absolute lymphocyte count is the best predictor of dose

• Long-term consequences
  – Increase in cancer, especially thyroid cancer
  – With radiiodine exposure, thyroid dose can be reduced by using KI
Thank you!