Radiation Injury & Management
Lester Kallus, MD
(adapted from REACTS course)

What is radiation
- Energy released from source
  - Travels to receiving body
- Electromagnetic waves
- High speed subatomic particles

What is ionizing radiation
- Energy that can strip electrons from atoms
  - Causes chemical changes in molecules
- All nuclear radiation is ionizing

Effects of Ionization
- Easy to detect
- May be absorbed by shielding
- Can lead to biological damage

Basic Radiological Physics
- Nucleus
  - Proton (+)
  - Neutron (0)
- Outside nucleus
  - Electron (-)
  - About 1/2000 mass of proton

Types of Ionization Radiation
- Alpha \( \alpha \)
- Beta \( \beta \)
- Gamma \( \gamma \)
- X-ray \( X \)
- Neutron \( \eta \)
Alpha radiation

- High energy helium nucleus
- Very short penetration
  - Few cm in air
  - Few microns in tissue
- (less than external dead cell layer)
- Easily shielded

Alpha source (no longer available)

- "Destroys odors for years"
  (10 billion)

Beta Radiation

- High energy "electron" emitted from nucleus
- Wide range of energies possible
- Moderately penetrating
  - Few meters in air
  - Millimeters in tissue

Gamma Radiation

- Electromagnetic energy emitted from nucleus
  - High frequency photon
  - From keV to MeV
- Specific energies can be used for ID
- Very penetrating (many meters in air)
- Difficult to shield (sometimes with lead)

X-ray Radiation

- Electromagnetic energy from outside nucleus
- May be "machine produced"
  - Bombard high energy electrons on a target (x-ray machine)
- May be emitted from radioactive materials
- Similar shielding & penetrating powers as gamma radiation

Neutron Radiation

- Neutron particle – emitted from nucleus
- Can be very penetrating
- Requires special shielding
- Can induce radioactivity in “stable” elements
  - (N, Na, Al, S, Cl, P, etc.)
Shielding varies with radiation type

Energy Units for Measuring
- Typically keV or MeV
- Each radionuclide emits characteristic energy

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Energy Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-14 beta</td>
<td>157 keV or 0.157 MeV</td>
</tr>
<tr>
<td>Cs-137 gamma</td>
<td>662 keV or 0.662 MeV</td>
</tr>
<tr>
<td>Am-241 alpha</td>
<td>5.485 MeV</td>
</tr>
</tbody>
</table>

What is Exposure
- Physics:
  - Amount of ionization produced
    - X- or γ - standard conditions
- Colloquially:
  - Being in the presence of ionizing radiation
  - Like exposed to measles or exposed to heat

What is dose?
- Uhoh, here we go…

What is dose?
- Absorption of radiation energy per unit mass of absorber
- Conventional unit – rad
- International unit – Gray (Gy)
  - $1 \text{ Gy} = 1 \text{ Joule/Kg}$
  - $1 \text{ Gy} = 100 \text{ rad}$
  - $1 \text{ rad} = 0.01 \text{ Gy}$

What is Dose Equivalent?
- Biological damage & Resulting risk from radiation dose
- Dose equivalent = Dose x Quality Factor
- Conventional unit – “rem”
- SI unit – Sievert (Sv)
  - $1 \text{ Sv} = 100 \text{ rem}$
What does this mean?
- Beta, Gamma, X
- Alpha, Neutron
- Rad = Rem
- Gray = Sievert
- Rad ≠ Rem
- Gray ≠ Sievert
- QF X, γ, β = 1
- QF α = 20 (if internal)
- QF η = 3-20 (depends on energy)

Quality factors?
- Any type of radiation compared to the same absorbed dose γ or X
- QF X, γ, β = 1
- QF α = 20 (if internal)
- QF η = 3-20 (depends on energy)

Radiation Quantities & Units

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Measures</th>
<th>Old Units</th>
<th>SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure</td>
<td>Ionization</td>
<td>Roentgen</td>
<td>Coulomb/kg</td>
</tr>
<tr>
<td>Absorbed Dose</td>
<td>Energy deposition</td>
<td>Rad</td>
<td>Gray Gy</td>
</tr>
<tr>
<td>Dose Equivalent</td>
<td>Biological damage / risk</td>
<td>Rem</td>
<td>Sievert (Sy)</td>
</tr>
</tbody>
</table>

ICCMP
(International Committee to Confuse Medical Personnel)

<table>
<thead>
<tr>
<th>Old term</th>
<th>New term (SI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Curie</td>
<td>Becquerel</td>
</tr>
<tr>
<td>Roentgen</td>
<td>Coulomb / kg</td>
</tr>
<tr>
<td>Rad</td>
<td>Gray</td>
</tr>
<tr>
<td>Rem</td>
<td>Sievert</td>
</tr>
</tbody>
</table>

Note: 20 years from now, what you learn today may not even be taught for historical import.

Just so you know how awful this is:
- Bequerel = 1 nucleus decay per second
- Curie = measurement of decays
- 1 Ci = 3.7 \times 10^{10} \text{ Bq}
- 1 \text{ Bq} = 2.70 \times 10^{-11} \text{ Ci}

Units there are:
- Curie
- Becquerel
- Roentgen
- Coulomb
- Rad
- Gray
- Rem
- Sievert

Units you should know:
- Rad
- Gray
- Rem
- Sievert

Unit to know “somewhat”:
- Curie
Typical Radiation Doses

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Dose (mrem)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural background</td>
<td>360</td>
</tr>
<tr>
<td>Diagnostic CXR</td>
<td>10</td>
</tr>
<tr>
<td>Flight from LA to Paris</td>
<td>4.8</td>
</tr>
<tr>
<td>Barium enema</td>
<td>800</td>
</tr>
<tr>
<td>Smoking 1.5 PPD – 1 yr dose</td>
<td>16,000</td>
</tr>
<tr>
<td>Cardiac cath</td>
<td>45,000</td>
</tr>
<tr>
<td>Mild Acute Radiation Sickness*</td>
<td>200,000</td>
</tr>
<tr>
<td>LD50 for Irradiation</td>
<td>450,000</td>
</tr>
</tbody>
</table>

*acute exposure \( \text{mrem} = \text{millirem} = 1/1000 \text{rem} \)

Annual Regulatory Limits

<table>
<thead>
<tr>
<th>Limit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Members of the public</td>
<td>100 mrem</td>
</tr>
<tr>
<td>Occupational limits</td>
<td>ALP</td>
</tr>
<tr>
<td>Lens of the eye</td>
<td>15 rem</td>
</tr>
<tr>
<td>Single organ dose equivalent</td>
<td>50 rem</td>
</tr>
<tr>
<td>Skin dose equivalent</td>
<td>50 rem</td>
</tr>
<tr>
<td>Extremity dose equivalent</td>
<td>50 rem</td>
</tr>
</tbody>
</table>

What are Radioactive Materials

- Materials that emit ionizing radiation
- Chemically & physically identical to non radioactive counterparts
- Behave the same (e.g. RAI behaves the same as stable Iodine)

Example of half life

- Note, curie = \(3.7 \times 10^{10}\) disintegrations/sec
- 32 microcuries Tc-99m; half-life of 6 hours

<table>
<thead>
<tr>
<th>Time (h)</th>
<th>Activity (microcuries)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>(1/1000) of original activity</td>
</tr>
</tbody>
</table>

Half Life

- Time required for substance to lose ½ of radioactivity
- Every radionuclide has a unique half life
- Range from <1 second to billions of years

So what can happen?

- Irradiation
- Contamination
- Incorporation
Irradiation
- Victim is exposed
- Victim is not radioactive
- Exposure is over and done
- Someone having an x-ray has been irradiated
- Someone flying has been irradiated
- Nevertheless, possible damage to victim

Contamination
- Radionuclide splashed, etc. onto victim
- Victim continuous to be exposed
- Staff can be exposed
- Radionuclide is outside the victim

Incorporation
- Radionuclide has been internalized
- Laceration or other contaminated wound
- Inhaled
- Swallowed
- Punctured
- Continued exposure to victim
- Possible exposure to staff

And the results?
Radiobiology of Man
- Effects determined by:
  - Total dose
  - Dose rate
  - Volume of tissue irradiated
  - Type of radiation
  - Anatomical part irradiated
  - Individual susceptibility
  - Trauma / Illness

Radiation effect

Radiation effect
Damage to DNA
- Delayed division
- Inaccurate division
- Failure to divide

DNA Repair
- Mismatch repair
  - Remove wrong base
  - Insert correct base
- Excision repair
  - Cut out large defect
  - Insert correct bases

Factors effecting repair capacity
- Oxygen content
- Temperature, pH, other factors
- Stage in cell cycle

Mechanism of cell death
- Reproductive death
- Apoptosis

Sensitivity of Cells to Ionizing Radiation
- Highly Sensitive: Mature lymphocytes, Erythroblasts, Certain spermatogonia, Myeloblasts, Intestinal crypt cells, Basal cells, Endothelial cells, Gastric gland cells, Osteoblasts, Spermatzoa, Erythrocytes, Fibrocytes, Chondrocytes, Muscle Cells, Nerve Cells
- Least Sensitive

Acute Radiation Injury Whole Body
- Roughly predictable course
  - Few hours to several weeks
- Subclinical: 0 - 100 cGy
- Hematopoietic: 100 - 800 cGy
- GI: 800 – 3,000 cGy
- Kidneys / Lungs: 1,000 – 2,000 cGy
- CV / CNS: >3,000 cGy

Note: 1 Gy = 100 rads
1 cGy = 1 rad
Acute Radiation Syndrome

- History of exposure
- Symptoms (Time of onset & severity)
- CBC q4-6 hrs (lymphocyte count)
- Chromosome analysis

**Decision Point**

Prodromal signs & symptoms

- Anorexia
- Nausea
- Vomiting
- Diarrhea
- Fever
- Conjunctivitis
- Skin erythema

Management of prodromal period

- Vomiting – zofran or kytril
- Consider anti-viral prophylaxis
- Consider tissue, blood typing
- Treat trauma
- Consult hematology, HP

- Radiation is NOT an extreme emergency
- Treat the trauma first
  (Bring HP in early)

Acute radiation syndrome

- Treatment & supportive care
- Platelet transfusion
- Psychological support
- Infection control
- Stimulation of hematopoietic system

Systemic effects

Hematopoietic Syndrome

- Immunodysfunction
- Increased infections, complications
- Hemorrhage
- Anemia
- Impaired wound healing

**Effects of GI Syndrome**

- Malabsorption
- Ileus – vomiting; GI distension
- GI bleeding
- Sepsis
  - Fluid & electrolyte shifts
  - Dehydration
  - Acute renal failure
  - Cardiovascular collapse
- GI bleeding
- Sepsis
Cerebrovascular / CNS Syndrome
- Vomiting & diarrhea within minutes
- Confusion & disorientation
- Severe hypotension
- Cerebral edema
- Convulsions – coma
- Hyperpyrexia
- Fatal within 24-48 hours

Hospital care – Mild (<2 Gy)
- Triage by prodromal sx
- Biological & physical dosimetry
- Close observation, frequent CBC & diff
- Outpatient management possibly
- Decontaminate

Hospital Care II – Moderate (2-5 Gy)
- Reverse isolation
- Gut sterilization
- Growth factor therapy
- Viral prophylaxis
- Antibiotics for febrile neutropenia

Hospital Care III – Severe (5-10 Gy)
- Reverse isolation
- Gut sterilization & viral prophylaxis
- Growth factor therapy
- Transfusions
  (progenitor cells or cord blood)
- Clinical problems:
  - Severe thrombocytopenia
  - Absolute neutropenia with or without fever
  - Symptomatic anemia

Clinical course

<table>
<thead>
<tr>
<th>Prodromal</th>
<th>Latent</th>
<th>Hrs – 21 days</th>
<th>Hrs – 30 days</th>
<th>Hrs - &gt; 60 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anorexia</td>
<td>Nausea</td>
<td>Vomiting</td>
<td>Diarrhea</td>
<td>Fever</td>
</tr>
<tr>
<td>Conjunctivitis</td>
<td>Erythema</td>
<td>Lymphopenia</td>
<td>Granulocytosis</td>
<td>Prodmata absent or diminished</td>
</tr>
</tbody>
</table>

ARS – Skin manifestations

Chernobyl Victim
Acute Radiation Injury: Local

- Sometimes 1 part of body > rest
- Severe injury to skin / underlying tissue
- Misleading presentation
- Dx difficult
- ARS may or may not be present
- Early lesion can look like brown recluse spider bite

What would you do if there was no hx of known radionuclide exposure?

Common sources inducing radiation injury

- Radiography sources (e.g., $^{192}$Ir)
- Therapy / Irradiation sources (e.g., $^{60}$Co)
- Fission product betas, e.g. Chernobyl
- Medical applicators, (e.g. $^{90}$Sr)
- X-ray machines
- X-ray diffraction units
- X-ray fluorescence units
- Accelerators

Approximate surface dose from common $\gamma$ emitters

<table>
<thead>
<tr>
<th></th>
<th>rad/min/Ci</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}$Co</td>
<td>3100</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>770</td>
</tr>
<tr>
<td>$^{192}$Ir</td>
<td>1200</td>
</tr>
<tr>
<td>$^{226}$Ra</td>
<td>1900</td>
</tr>
</tbody>
</table>

Diagnosis

- History
- Signs & symptoms
- Verify local versus whole body exposure
- Accident mock-up is helpful in dosimetry
- During initial assessment:
  - Take photographs
  - Obtain baseline information
External dose thresholds for skin

<table>
<thead>
<tr>
<th>Dose Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 cGy</td>
<td>Epilation beginning around days 17-21</td>
</tr>
<tr>
<td>600 cGy (threshold)</td>
<td>Erythema, distinguish from thermal burn, minutes to weeks post exposure</td>
</tr>
<tr>
<td>1,000 – 1,500 cGy</td>
<td>Dry desquamation</td>
</tr>
<tr>
<td>2,000 – 5,000 cGy</td>
<td>Wet desquamation, 2-3 weeks post exposure (depending on dose)</td>
</tr>
<tr>
<td>&gt;5,000 cGy</td>
<td>Radionecrosis, deep ulceration</td>
</tr>
</tbody>
</table>

Management of subsequent wounds
- Consult with experts!
- Protect area
- Avoid nicotine
- Assure nutritional requirements
- Prevent / treat infections
- Cover to control pain

Problems in Management
- Wounds evolve slowly
- Healing is very prolonged
- Lesions can be intensely painful
- Dosimetry is frequently imprecise
- Healed epidermis is fragile, easily traumatized

Effects on vascular endothelium
- Endothelial cells swell
- Detach from basement membrane
- Edema – leaks in denuded areas
- Extravasation of fluid & cells
- Platelets fill in areas of denuded basement membrane
- Microthrombi form

Acute local radiation injury: Evaluation & diagnosis
- History
- Laboratory tests
  - CBC, ESR
- Physical exam
- Radiographic studies as needed
- Slit lamp exam
- Serial color photos

Radiation repair process: skin
- Effectiveness depends on:
  - Severity of injury to precursor stem cells
  - Adequacy of microvasculature
  - Structural support of damaged dermis
  - Avoidance of infection & trauma
- Epidermis renewed by:
  - Proliferation of endothelium at edges
  - Epithelium of the hair follicles
New techniques in wound management
- Artificial skin (bi-layered)
- Bioengineered skin (epidermal / dermal constructs)
- New drugs
- Growth factor topically

Internal contamination (Incorporation)
- Inhalation
- Ingestion
- Injection (wound)
- Across abraded skin
- Across intact skin (rare)

Terms:
- **Intake**: Amount that makes its way in
- **Uptake**: Fraction of intake in circulation
- **Deposition**: Fraction of uptake sequestered in a particular organ or tissue

Immediate diagnosis
- Nasal swipes
- Nasal blows
- Sputum
- When all else fails – good history

Diagnosis – Bioassay of limited value
- Slow
- Must have total collection – urine & feces
- May overestimate uptake by 3-5x
- Specimen may get contaminated

Clearance time - nasopharynx

<table>
<thead>
<tr>
<th>Area</th>
<th>Time in minutes to swallowing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior nares</td>
<td>60</td>
</tr>
<tr>
<td>Nasopharynx</td>
<td>10 (10 mm/min)</td>
</tr>
</tbody>
</table>
Clearance Time of Respiratory Tract

<table>
<thead>
<tr>
<th>Structure</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trachea</td>
<td>.1 hrs.</td>
</tr>
<tr>
<td>Bronchi</td>
<td>1.0 hrs.</td>
</tr>
<tr>
<td>Bronchioles</td>
<td>4.0 hrs.</td>
</tr>
<tr>
<td>Terminal Bronchioles</td>
<td>10.0 hrs.</td>
</tr>
<tr>
<td>Alveoli</td>
<td>100.0 Days +</td>
</tr>
</tbody>
</table>

Clearance time of GI Tract

Where is the radionuclide from time of ingestion?
(in hours)

<table>
<thead>
<tr>
<th>Structure</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stomach</td>
<td>1</td>
</tr>
<tr>
<td>Small intestine</td>
<td>4</td>
</tr>
<tr>
<td>Upper colon</td>
<td>13</td>
</tr>
<tr>
<td>Lower colon</td>
<td>24</td>
</tr>
</tbody>
</table>

Treatment methods

- Block absorption
- Block deposition
- Dilute
- Displace
- Remove (chelate)

Absorption of radionuclides

<table>
<thead>
<tr>
<th>Group</th>
<th>Elements</th>
<th>% Absorbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkali Metals</td>
<td></td>
<td>High ~90</td>
</tr>
<tr>
<td>24Na</td>
<td></td>
<td></td>
</tr>
<tr>
<td>42K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>85Rb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>137Cs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group VIII Metals</td>
<td></td>
<td></td>
</tr>
<tr>
<td>54Fe</td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>60Co</td>
<td></td>
<td>30-90</td>
</tr>
<tr>
<td>109Ru</td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>

Absorption of ingested radionuclides

<table>
<thead>
<tr>
<th>Group</th>
<th>Elements</th>
<th>% Absorbed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lanthanides</td>
<td>144Ce</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td>159Eu</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td>147Pm</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td>169Tb</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Actinides</td>
<td>232Th</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td></td>
<td>233U</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Transuranics</td>
<td>237Np</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>239Pu</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td></td>
<td>241Am</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Reduction of GI absorption

- Antacid
- Precipitation into insoluble salt
- Catharsis
Protecting vital organs:
- Prevent thyroid uptake of radioisotopes
- KI

Chelating agents
- DTPA – Diethylenetriaminepentacetic acid
- EDTA – Versene
- BAL – Dimercaprol
- DFOA – Deferoxamine
- PCA – Penicillamine

Common medications with Chelating Effects
- Anti-inflammatories
  - Salicylates
  - Indocin
  - Aminopyrine
  - Tylenol
  - Butazolidin Group
- Steroids
- Psychotropic drugs
  - Chlorpromazine
- Dilantin

Common medications with Chelating Effects (cont)

<table>
<thead>
<tr>
<th>Antibiotic</th>
<th>Radionuclide</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-aminosalicylic acid</td>
<td>Fe, Cu</td>
</tr>
<tr>
<td>Bacitracin</td>
<td>Zn</td>
</tr>
<tr>
<td>Isoniazid</td>
<td>Fe, Cu, Mn, Co</td>
</tr>
<tr>
<td>Kanamycin</td>
<td>Ca</td>
</tr>
<tr>
<td>Neomycin</td>
<td>Fe, Al</td>
</tr>
<tr>
<td>Novobiocin</td>
<td>Mg</td>
</tr>
<tr>
<td>Penicillin</td>
<td>Co</td>
</tr>
<tr>
<td>Polymyxin</td>
<td>Mg, Mn, Ca, Fe</td>
</tr>
<tr>
<td>Streptomycin</td>
<td>Mn</td>
</tr>
<tr>
<td>Tetracyclin</td>
<td>Fe, Mg, Mn, Mo, Al, Ca</td>
</tr>
</tbody>
</table>

Special problems - Uranium
- Problem – nephrotoxic
- Treatment –
  - Alkalinize urine – Sodium bicarb
  - Consider temporary dialysis

Food as a cure

<table>
<thead>
<tr>
<th>Chelaters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabbage</td>
</tr>
<tr>
<td>Eggs</td>
</tr>
<tr>
<td>Soybean flour</td>
</tr>
<tr>
<td>Stop vitamin C*</td>
</tr>
</tbody>
</table>

(*Vitamin C noted to increase Fe absorption)
Potential events:
- Industrial accidents
- Dirty bombs

Industrial Accident, Yanango, Peru
- Construction workers, hydroelectric power plant
- Welding being checked with $^{192}$Ir source
- Welders not done, checking equipment left at scene
- That night, film proved to be unexposed
- Iridium was missing

Case story, Yanango, Peru
- 1 AM, recovered source at home of welder
- Welder had found the source in the pipe
- Put it in his back pocket
- Felt a sting
- Dropped his pants, went to doctor
- Wife sat on pants and nursed baby
- Doc reported an insect bite

Images scanned from “The Medical Basis for Radiation Accident Preparedness”, Ricks & Berger, 2001

Yanango Peru
Welder day 3

Yanango Peru
Welder, Day 10

Yanango, Peru
- Welder, Day 73
What if terrorists deployed a contaminated explosion?

Potential effect on NYC of a dirty bomb with prevailing wind from the SW.

Billions of dollars for any cleanup.
Order of people to protect in disasters

- First – protect yourself
- Next – protect the rest of your institution
- Last – protect the individual patient

First – protect yourself

- PPE before treating potentially contaminated patients
- Otherwise, that may be your last patient ever

Second – protect your institution

- Contaminated patient does not enter
- Don’t make institution uninhabitable

Last

- Protect the patient
- The patient is important BUT
- You and the institution’s ability to care for others takes a priority

Steps:

- Get information
- Don PPE
- Treat life-threatening emergencies
- Decontaminate
- Patient may enter when HP says “OK”
- Get advice for treating ARS

Who you gonna call?

- HP – Ed O’Connell
- EHS – Environmental Health & Safety
- REACTS – 1-865-576-1005
- If BNL event, BNL HP will help