Review from Last Week:
Intro to Emission Tomography - From R. Miyaoka

**SPECT** - Single Photon Emission Computed Tomography
- Detector orbits - 180, 360 degree, auto-contour

**PET** - Positron Emission Tomography
- Detection of two photons in coincidence - electronic collimation
- Types of events - trues, randoms, scatter
- Modes of acquisition - 2D and 3D

Data corrections for quantitative imaging:
- Attenuation - easier in PET than SPECT; both moving toward using CT for attenuation map
- Scatter - PET (model based); SPECT (energy based)
- Randoms - PET only
- Normalization - SPECT requires longer normalization than planar gamma camera

Image reconstruction:
- Filtered Back Projection versus Backprojection
- OSEM - iterative image reconstruction

Dosimetry Descriptors - From Ionizing Radiation

**Exposure:**
- Charge per mass, Coulomb/kg = 3876 roentgens
- Can be measured directly
- Does not account for biological effects

**Absorbed Dose:**
- Energy per mass, Joules/kg = gray (Gy) = 100 rads
- Usually calculated from exposure measurement
- Does not account for biological effects

**Equivalent Dose:**
- \( \text{Equivalent Dose} = \text{Absorbed Dose} \times w_R \) or \( Q \) factor
- Also energy/mass, but units are sieverts (Sv) = 100 rem
- Biological effects of absorbed dose depend on the type of radiation

**Effective Dose:**
- Sum Over All Tissues(\( \text{Equivalent Dose,}_T \) \) \times w_T)
- Also measured in Sv

The risk of cancer from a dose equivalent depends on the organ receiving the dose. The quantity “effective dose” is used to compare the risks when different organs are irradiated.

**Dosimetry and Shielding**

Adam Alessio, Ph.D.
alessio@u.washington.edu
Division of Nuclear Medicine
Dept of Radiology

Lectures at: http://depts.washington.edu/uwmip/

Sources of Radiation Exposure in U.S.

This figure is based on data from “DOCOM93: Sources of Exposure to Ionizing Radiation Exposure of the Population of the United States,” National Council on Radiation Protection and Measurements, No.93, 1987.
Estimating Effective Dose

To go from absorbed dose (Gy) to equivalent dose (Sv), need:

<table>
<thead>
<tr>
<th>Radiation type</th>
<th>wR</th>
<th>Tissue weighting factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>1</td>
<td>Corresponding wT values</td>
</tr>
<tr>
<td>Electrons (β), muons</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Neutrons (varies)</td>
<td>5-20</td>
<td></td>
</tr>
<tr>
<td>Protons</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

For CT and PET, 1Gy = 1Sv

To go from Equivalent Dose (Sv) to Effective Dose (Sv), need:

<table>
<thead>
<tr>
<th>Type</th>
<th>wE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>1</td>
</tr>
<tr>
<td>Electrons (β), muons</td>
<td>1</td>
</tr>
<tr>
<td>Neutrons</td>
<td>5-20</td>
</tr>
<tr>
<td>Protons</td>
<td>20</td>
</tr>
</tbody>
</table>

To go from absorbed dose (Gy) to equivalent dose (Sv), need:

\[ D_{eq}(P) = \text{absorbed dose to the whole body that has probability } P \text{ of causing cancer} \]

\[ D_{eq}(P) = \text{absorbed dose in a single organ, } T, \text{ that has probability } P \text{ of causing cancer in that organ} \]

International Commission on Radiological Protection, ICRP, Publ. 60, 1990

www.icrp.org, Annals of the ICRP

Average Dose Equivalent

TABLE 23-3. AVERAGE ANNUAL OCCUPATIONAL EFFECTIVE DOSE EQUIVALENT IN THE UNITED STATES

<table>
<thead>
<tr>
<th>Occupational category</th>
<th>Average annual total effective dose equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mSv</td>
</tr>
<tr>
<td>Nuclear power operations</td>
<td>12.0</td>
</tr>
<tr>
<td>Airline crew</td>
<td>0.7</td>
</tr>
<tr>
<td>Diagnostic radiology and nuclear medicine techs</td>
<td>1.0</td>
</tr>
<tr>
<td>Radiologists</td>
<td>0.7</td>
</tr>
</tbody>
</table>


ALARA: As Low As Reasonable Achievable

TABLE 23-15. NUCLEAR REGULATORY COMMISSION (NRC) REGULATORY REQUIREMENTS: MAXIMUM PERMISSIBLE DOSAGE EQUIVALENT LIMITS

<table>
<thead>
<tr>
<th>Limits</th>
<th>Maximum permissible annual dose limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupational limits</td>
<td>mSv</td>
</tr>
<tr>
<td>Total effective dose equivalent</td>
<td>50</td>
</tr>
<tr>
<td>Total dose equivalent to any individual organ</td>
<td>500</td>
</tr>
<tr>
<td>(except lens of eye)</td>
<td>150</td>
</tr>
<tr>
<td>Dose equivalent to the skin or any extremity</td>
<td>300</td>
</tr>
<tr>
<td>Minor (&lt;18 years old)</td>
<td>10% of adult limits</td>
</tr>
<tr>
<td>Dose outside of extremity</td>
<td>3 in 9 months</td>
</tr>
<tr>
<td>Nonoccupational (public limits)</td>
<td>1.25</td>
</tr>
<tr>
<td>Individual members of the public</td>
<td>0.02 in any 1 hr</td>
</tr>
<tr>
<td>Unrestricted area</td>
<td>0.02 in any 1 hr</td>
</tr>
</tbody>
</table>

*These limits are exclusive of natural background and any dose the individual has received for medical purposes, inclusive of internal committed dose equivalent and external effective dose equivalent (i.e., total effective dose equivalent).

**Applies only to pregnant and workers who have not declared pregnancy. If the limit exceeds 4.5 mSv (450 rem), an individual may be allowed to exceed this limit if deemed necessary for the protection of the public interest.

**This means that the dose to an area (irrespective of occupation) shall not exceed 9.02 mSv (900 rem) in any 1 hour. This is not a restriction of instantaneous dose rate to 632 mSv (63.2 rem) in 5 minutes.

Radiation Safety

4 Principals to minimize exposure

1. Time
   - For NM, Decay considerations
2. Distance (inverse square law)
   - If exposure rate at 1 cm from a source is 100 mR/hr, what is the exposure rate at 5 cm?
3. Shielding...
4. Containment...
NM Shielding

• Specific Exposure Rate Constant \( \Gamma \)
  – Exposure rate in R/hr at 1 cm from 1 mCi of specific radionuclide
  – Used to calculate exposure rate at any distance from particular radionuclide

\[
\text{Exposure Rate (R/hr)} = \frac{\Gamma}{d^2}
\]

\( \Gamma \) in [R/hr/mCi]
\( d \) – activity in mCi
\( d \) – Distance in cm from source of activity

• Types of Shielding: Tungsten, Lead, or leaded glass.
• Examples: Syringes, Vials, Pigs (for transporting vials)

NM Shielding: Lead Aprons?

• Lead aprons work fairly well for low-energy scattered x-rays (less than 60 keV), but not for medium-energy photons

Raphex Question:

A radiation worker standing for 3 hours at 1 meter from a 5 mCi radioactive source, for which \( \Gamma = 2.0 \, \text{R cm}^2/\text{mCi-hr} \), will be exposed to about _____ mR.

A. 0.6
B. 1
C. 3
D. 30
E. 300

Exposure = (Exposure Rate) x (time) = \[\Gamma \times A \times t/d^2\].

Diagnostic Radiology Imaging Physics Course
6/26/08
Adam Alessio, UW Radiology, alessio@u.washington.edu
NM Containment

• Contamination: uncontained radioactive material located where it is not wanted
• Controlled areas are locations where workers are under supervision of Radiation Safety Officers (RSO)
• Keep in mind:
  – Plastic-backed absorbent paper should be used on all work surfaces
  – If skin is contaminated, wash with soap and warm water
  – External contamination is bad, internal contamination is very bad
• Reduce Risk of Contamination:
  1. Label all radioactive materials
  2. Do not eat, drink, or smoke in radioactive work areas
  3. Do not pipette radioactive material by mouth
  4. Discard all radioactive materials and disposable work materials in Radioactive Waste receptacles
  5. Use caution with ventilation studies (Xe-133) (negative pressure with respect to hallway pressure)

NM Containment

• Contamination control is monitored by
  – periodic Geiger-Mueller (GM) meter surveys (fairly easy to detect contamination unlike other hazardous substances)
  – Wipe tests are also performed: small pieces of filter paper (“swipes”) are placed in NaI gamma well counter
  – Areas that have twice the background radiation levels are considered contaminated
  – Each institution has guidelines for surveying
• Radioactive Material Spills
  – First Aid takes priority over personal decontamination over facility decontamination
  – Spill should be contained with absorbent material and area isolated and warning signs posted
  – Decontamination performed from perimeter of spill toward the center.

NM Containment

• Protection of Patient: Appropriate labeling, confirm patient identity
  – special care for pregnant or nursing women (unique guidelines)
    • Example: Use of I-131 greater than 30 microCi requires rule out of pregnancy with test
    • Example: After administration of just 5 microCi of I-131 requires 68 days of cessation of breast feeding
• Radionuclide Therapy
  – NRC regulations require that patients receiving radioimmunotherapy be hospitalized until the total effective dose to others will not exceed 5 mSv.
  – I-131 (used to treat thyroid cancer) has an 8 day half-life emitting high-energy beta’s and gamma rays (and Excreted in all bodily fluids)
• Some Thoughts on Precautions for Home care following radioiodine therapy:
  • Majority of activity eliminated through urine (double-flush)
  • Wash all dishes and utensils immediately after use, sleep in separate bed, wash clothing separately from others
  • keep distance from others.

Summary of Dose Levels

Raphex Question:
Match the following exposure conditions with the appropriate dose.

A. 1 mSv
B. 0.1 mSv
C. 2 mSv
D. 2 μGy
E. 50 mSv

14. The maximum organ dose for patients undergoing nuclear medicine procedures
15. The regulatory weekly dose limit in controlled areas
16. The annual effective dose limit for a nuclear medicine technologist

14. E. 50 mSv = 5 rem
15. A. 1 mSv = .5 rem
16. E. 50 mSv = 5 rem
Summary of Dose Levels

Regulations limit the radiation dose equivalent to patients undergoing radiological procedures to ____ mSv/year.

A. 500
B. 50
C. 5
D. 1
E. None of the above

Radioactive Waste Disposal

• General Rule: radioactive material is held for 10 half-lives and surveyed prior to discarding in regular trash

• Liquid Waste: At UW, we are allowed to dispose of material that is soluble into the sanitary sewer. A portion of the total UW allowance is allocated to each RAM (radioactive materials) lab where a sink is designated for liquid radioactive waste (about 200 microCi per quarter for common radiology isotopes)

• Dry Waste: At UW, Low activity material (those with long half-lifes) must be places in Low Specific Activity (LSA) boxes lined with plastic bags. Radiation safety staff disposes of this.

• Other guidelines for Infectious Wastes (some biological agent like blood), Mixed Wastes (radioactive and hazardous)

Raphex Question

12. The basic consideration in setting limits for disposal of radioactive materials into the sewer system is:

A. Contamination of the sewer.
B. Risk to swimmers.
C. Fish death.
D. Entrance into the food and fresh water chains.
E. Evaporation into the air.

D. Very low concentrations of radioactive materials, when ingested, can produce high, localized radiation doses to internal organs.

Raphex Question

Which of the following is true for low-level radioactive wastes, such as tubing and swabs contaminated with 99mTc?

A. They can never be thrown away since some activity always remains.
B. They can be thrown away immediately since the amount of activity is generally harmless.
C. They can only be disposed of by a commercial rad-waste service.
D. They can be stored until reaching background levels and then disposed of with other medical trash.
Regulatory Fun!

General Rule: “Cradle to Grave” for all radiation sources

- U.S. Nuclear Regulatory Commission (NRC) regulates all material produced directly or indirectly from nuclear fission (many states have their own control programs with connections to the NRC)
  - Does not regulate cyclotron produced agents (F-18, Ti-201, I-123, etc.)
  - Regulate activities such as: Employee rights and responsibilities, survey requirements, warning signs, disposal procedures, storage, etc.
- FDA regulates radiopharmaceutical development and manufacturing and often times installations (not directly involved in end user work except mammography)
  - Is involved in regulatory aspects of human research and education
- U.S. Department of Transportation (DOT) regulates transportation of materials
- Advisory Boards which suggest “Standards of Good Practice”: 1) Congress chartered “National Council on Radiation Protection and Measurements” (NCRP) and 2) “International Commission on Radiological Protection” (ICRP)

Radionuclide Therapy

- Thyroid cancer and hyperthyroidism often treated with NaI-131 (8-day half life)
- Patient allowed to leave hospital when activity in patient below 1.2 GBq (33mCi)
- We know exposure rate is proportional to administered activity…
- If we know the Total Amount of Administered activity and the Initial Exposure rate, we can measure exposure rate at any time and estimate the activity in the patient.
- Ex: Patient is injected with 4.4 GBq of I-131.  At time of injection exposure rate at 1m is 40 mR/h.  2 days later, the exposure rate at 1m is 10mR/h.  Can the patient go home?

NM Dosimetry

- MIRD (Medical Internal Radiation Dosimetry) Committee of the Society of Nuclear Medicine
  - Developed methodology for calculating radiation dose to selected organs and whole body from internally administered radionuclides
  - Two Elements: 1) Estimation of quantity of radiopharmaceutical in various SOURCE organs 2) Estimation of radiation absorbed in selected TARGET organs

MIRD Formalism

\[
\sum_{i=0}^{n} \left( D_i L_i \right) \left( J_i \right) = \text{Total Dose}
\]

where \( D_i \) is the total dose absorbed in each organ and \( J_i \) is the radiation absorbed dose in target for each administered activity in the source organ
MIRD

- **Cumulated Activity in Source Organ:**
  - Total number of disintegrations from radionuclide located in particular source organ.
    - Depends on:
      1) Portion of injected dose taken up by source organ
      2) Rate of elimination from source organ
  - Assume fraction (f) of injected activity is localized in source organ
  - Assume exponential physical decay of radionuclide (Half Life: $T_p$)
  - Assume exponential biological excretion from source organ (Half Life: $T_b$)
  - Total exponential Effective Half Life ($T_e$):

$$T_e = \frac{T_p}{2} + \frac{T_b}{2}$$

- Activity remaining in organ at time $t$:

$$N_a = N_{inj} \times f \times \frac{1}{2} \left(1 - e^{-\frac{t}{T_e}}\right)$$

MIRD simple example

- Patient is injected with 5mCi of Tc-99m-sulfur colloid. What is the absorbed dose to the a) liver and b) kidneys?
  - Source Organ: Liver (assume all activity in liver, uptake in liver is instantaneous, and no biologic removal)
  - Step 1: Find Accumulated Activity:

$$\sum \sum \sum \sum \sum$$

- Step 2: Find S factors and organ doses

Lookup from Table:

$$\sum \sum \sum \sum$$

Another MIRD example

- Dose calculation for a time-varying activity input:
  - Intravenous injection of human albumin microspheres labeled with 10mCi Tc-99m are taken immediately in the lung and then released to other organs. What is the total absorbed dose in the liver? Kidneys?
  - Same Steps as before, Need understanding of Accumulated dose in all source organs. Need to find total contribution of all source organs to target organs.
MIRD Discussion

Raphex:
In I-131 therapy for thyroid cancer, the whole body clearance curve is commonly plotted versus time. The radiation absorbed dose to the patient is proportional to the _____.
   A. Administered activity of I-131
   B. Administered activity per unit body surface area
   C. Administered activity per unit body weight
   D. Peak counts in the clearance curve
   E. Area under the clearance curve normalized per unit body weight

E. The absorbed dose depends on the patient specific clearance kinetics. The same activity administered to two different patients of the same weight could result in different absorbed doses, if they metabolized and cleared the I-131 at different rates.

MIRD Limitations

- MIRD provides reasonable estimates of organ doses (but could be off by as much as 50%)
- Limitations:
  1. Radioactivity assumed to be uniformly distributed in each source organ
  2. Organ sizes and geometries idealized into simple shapes to aid mathematics
  3. Each organ assumed to be homogenous in density and composition
  4. Reference phantoms for "adult", "adolescent", and "child" not matched to dimensions of specific individual
  5. Energy deposited is averaged over entire mass of organ when in reality effect occurs on molecular/cellular level
  6. Dose contributions from bremsstrahlung and other minor radiation sources ignored
  7. With few exceptions, low-energy photons and particulate radiation assumed to be absorbed locally (don’t penetrate)

Review with Raphex

Match the following units with the quantities below:

A) Bq
B) Sv
C) C kg\(^{-1}\)
D) Gy
E) J

5. Absorbed dose
6. Activity
7. Exposure
8. Dose equivalent

Some Discussion Questions

If a 5 year old girl (Suzy) is injected with 7mCi of F18 FDG and a 25 year old girl (Franny) is injected with 7mCi of F18 FDG for PET Exams…

1. Who received more activity?
2. Who received more absorbed dose?
3. Who received more equivalent dose?
4. Who received more effective dose?
5. Who has a greater radiation induced risk?
Some Discussion Questions
If a 5 year old girl (Suzy) stands 10 meters from a F-18 source and a 25 year old girl (Franny) stands 10 meters from an I-131 source...
1. Who received more absorbed dose?
2. Who received more effective dose?
3. Franny walks away and Suzy stands near source for 3x as long as Franny... Who received more effective dose?

Certainty of Single Measurements
Detected 10 counts, how certain are we about that measurement?
- We know true number of counts is distributed as a Poisson (assume has a mean of 10... best we can do...(if mean =10, variance = 10, standard deviation = 3.2)
- Looks a lot like a Gaussian (mean=variance=10, See below)

\[ \mu \pm \sigma = 10 \pm 3 \Rightarrow 68.3\% \text{ of events} \]
\[ \mu \pm 2\sigma = 10 \pm 6 \Rightarrow 95.3\% \text{ of events} \]

Loose Ends...Counting Error
Distributions of interest:
1. Binomial - For binary process (success/failure), (photon detection/no-detection)
2. Poisson - Binomial process basically Poisson when success is rare and have a lot of tries (large N) - !! Nuclear Decay and Detection Behaves Like Poisson !!
3. Gaussian - Poisson process is basically Gaussian when N>20

When estimating uncertainty in single measurement, best we can do is assume measurement is the mean of the distribution...

Key Item to remember:
For Poisson Distribution, the mean = variance

How accurate is a single measurement?
- Take a single measurement of radioactive source and detect 100 events.
  - Estimate that the real number of detectable events is 100 (variance = mean with Poisson, so var =100, so sd =10.
  - How close is this to the truth?
    68% Probability: 90 < truth < 110 est +/− sd
    95% Probability: 80 < truth < 120 est +/− 2sd
    99% Probability: 70 < truth < 130 est +/− 3sd
- Take a single measurement of radioactive source and detect 10,000 events.
  - Estimate that the real number of detectable events is 10,000.
  - How close is this to the truth?
    68% Probability: 9900 < truth < 10,100
    95% Probability: 9800 < truth < 10,200
    99% Probability: 9700 < truth < 10,300
Raphex Question

A series of measurements has a mean of 100 counts. There is 68% confidence that the true measurement is in the range...

A. 95-105
B. 90-110
C. 88-137
D. 50-150
E. 33-167

Raphex Question

• If the background is 100 counts and the sample is 900 counts, the net standard deviation is:

A. 50.0
B. 28.3
C. 24.1
D. 40.0
E. 31.6

Raphex Question

• How many counts must be collected in an instrument with zero background to obtain an error limit of 1% with a confidence interval of 95%?

A. 1000
B. 3162
C. 10,000
D. 40,000
E. 100,000

Loose Ends…Statistics

Items of Particular Importance:
1. We use statistics to describe random phenomena
2. To describe central tendency of phenomena often use mean
3. To measure dispersion, often use variance (dispersion around mean) and standard deviation (square root of variance, has same units as mean!)
4. Error Propagation - When adding or subtracting random numbers, the variance adds together (standard deviation adds in quadrature)

\[
\begin{align*}
\mu_1 - \mu_2 &= \mu_3 \\
\sigma_1^2 + \sigma_2^2 &= \sigma_3^2 \\
\sqrt{\sigma_1^2 + \sigma_2^2} &= \sqrt{\sigma_3^2}
\end{align*}
\]

If you subtract 2 random numbers, the mean is the subtraction of the 2 means. The variance of the new number is sum of two variances (new number is more noisy than first two numbers) Identical to the standard deviations add in quadrature