Nuclear Medicine Shielding and Dosimetry

Bushberg Chapters 23 and 24

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

Review of Units

- Fluence (Photons/Area), Fluence Rate = Flux (Photons/ Area Time)
- Beam of Ionizing Radiation deposits energy in medium through
  1. Photon energy transformed to Kinetic Energy of charged particles (PE, CS)
  2. These particles deposit energy through excitation and ionization.
- Kerma (Kinetic Energy Released in Matter) (1 Gray = J / kg)

Review of Units

- Exposure: amount of electrical charge produced by ionizing electromagnetic radiation per mass of air (coulombs / kg or Roentgen)

$$\mathrm{Exposure} = \frac{\Delta \mathrm{charge}}{\Delta \mathrm{mass\_of\_air}}$$

- Absorbed Dose: energy deposited by ionizing radiation per unit mass of material (1 Gray = J/kg or 1 rad = .01 J/kg, 100 rad = 1Gy)

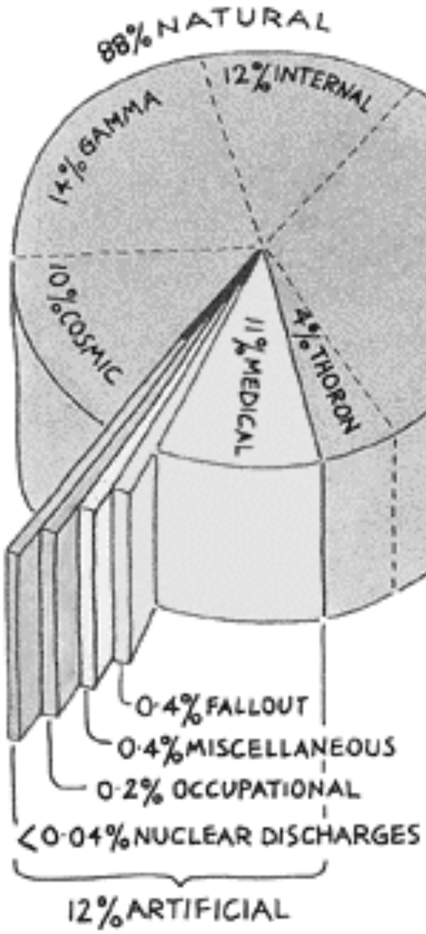
$$Dose = \frac{\Delta Energy}{\Delta mass}$$

- Equivalent Dose: product of absorbed dose and radiation weighting factor (Sievert or rem, 100 rem=1Sv)
  - Dose equivalent: product of absorbed dose and quality factor
  - Radiation weighting factor (and “quality factor”) both equal 1 for diagnostic radiation (so 1 Gray usually equals 1 Sievert)
  - Protons radiation weight factor = 5, neutrons = 5-20.
- Effective Dose: Sum of equivalent dose to each organ and the organ weighting factor (Sievert or rem)

See Bushberg Table 3-6 pg 59 for summary

Reminder: Where Do We Get Our Daily Radiation?

Average total effective dose in USA is 3.6mSv
80% of radiation from natural sources



Average Sources of Exposure
http://www.uic.com.au/ral.htm

Once again, a meeting between management and the Plutonium Truckers' Union grows tense.

Average Dose Equivalent

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

Occupational category	Average annual total effective dose equivalent	
	mSv	mrem
Uranium miners[a]	12.0	1,200
Nuclear power operations[b]	6.0	600
Airline crews	1.7	170
Diagnostic radiology and nuclear medicine techs	1.0	100
Radiologists	0.7	70

Adapted for measurably exposed personnel from National Council on Radiation Protection and Measurements. *Exposure of the U.S. population from occupational radiation.* NCRP report no. 101. Bethesda, MD: National Council on Radiation Protection and Measurements, 1989.
[a]Includes 10 mSv (1 rem) from high LET (α) radiation.
[b]Includes 0.5 mSv (50 mrem) from high LET (α) radiation.
LET, linear energy transfer.

ALARA: As Low As Reasonable Achievable

TABLE 23-18. NUCLEAR REGULATORY COMMISSION (NRC) REGULATORY REQUIREMENTS: MAXIMUM PERMISSIBLE DOSE EQUIVALENT LIMITS[a]

	Maximum permissible annual dose limits	
Limits	**mSv**	**rem**
Occupational limits		
Total effective dose equivalent	50	5
Total dose equivalent to any individual organ (except lens of eye)	500	50
Dose equivalent to the lens of the eye	150	15
Dose equivalent to the skin or any extremity	500	50
Minor (<18 years old)	10% of adult limits	10% of adult limits
Dose to an embryo/fetus[b]	5 in 9 months	0.5 in 9 months
Nonoccupational (public limits)		
Individual members of the public	1.0/yr	0.1/yr
Unrestricted area	0.02 in any 1 hr[c]	0.002 in any 1 hr[c]

[a]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).
[b]Applies only to conceptus of a worker who declares her pregnancy. If the limit exceeds 4.5 mSv (450 mrem) at declaration, conceptus dose for remainder of gestation is not to exceed 0.5 mSv (50 mrem).
[c]This means the dose to an area (irrespective of occupancy) shall not exceed 0.02 mSv (2 mrem) in any 1 hour. This is not a restriction of instantaneous dose rate to 0.02 mSv/hr (2 mrem/hr).

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 (Γ)
  - Used to calculate exposure rate at any distance from particular radionuclide

$$\text{Exposure Rate (R/hr)} = \Gamma A / d^2$$

Γ in $(R \cdot cm^2 / mCi \cdot hr)$

A = 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

Exposure rate constants for photons greater than 20 keV and 30 keV.

TABLE 23-14. EXPOSURE RATE CONSTANTS (Γ_{20} AND Γ_{30})[a] AND HALF VALUE LAYERS (HVL) OF LEAD FOR RADIONUCLIDES OF INTEREST TO NUCLEAR MEDICINE

Radionuclide	Γ_{20} (R·cm²/mCi·hr)[b]	Γ_{30} (R·cm²/mCi·hr)[b]	Half value layer in Pb (cm)[c,d]
Co-57	0.56	0.56	0.02
Co-60	12.87	12.87	1.2
Cr-51	0.18	0.18	0.17
Cs-137/Ba-137m	3.25	3.25	0.55
C-11, N-13, O-15	5.85	5.85	0.39
F-18	5.66	5.66	0.39
Ga-67	0.75	0.75	0.1
I-123	1.63	0.86	0.04
I-125	1.47	0.26	0.002
I-131	2.18	2.15	0.3
In-111	3.20	2.0	0.1
Ir-192	4.61	4.61	0.60
Mo-99/Tc-99m[e]	1.47	1.43	0.7
Tc-99m	0.62	0.60	0.03
Tl-201	0.45	0.45	0.02
Xe-133	0.53	0.53	0.02

[a] Γ_{20} and Γ_{30} calculated from the absorption coefficients of Hubbell and Seltzer (1995) and the decay data table of Kocher (1981):
Hubbell JH, Seltzer SM. Tables of x-ray mass attenuation coefficients and mass energy-absorption coefficients 1 keV to 20 MeV for elements Z = 1 to 92 and 48 additional substances of dosimetric interest. NISTIR 5632, National Institute of Standards and Technology, May 1995.
Kocher DC. Radioactive decay data tables. DOE/TIC-11026, Technical Information Center, U.S. Department of Energy, 1981.
[b] Multiply by 27.03 to obtain μGy·cm²/GBq·hr at 1 m.
[c] The first HVL will be significantly smaller than subsequent HVLs for those radionuclides with multiple photon emissions at significantly different energies (e.g., Ga-67) because the lower energy photons will be preferentially attenuated in the first HVL.
[d] Some values were adapted from Goodwin PN. Radiation safety for patients and personnel. In: Freeman and Johnson's clinical radionuclide imaging, 3rd ed. Philadelphia: WB Saunders, 1984:370. Other values were calculated by the authors.
[e] In equilibrium with Tc-99m.

Bushberg

NM Shielding

Raphex Question:

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

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

Exposure (X) = $[\Gamma \times A \times t]/d^2$.

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

TABLE 23-15. EXPOSURE REDUCTION ACHIEVED BY A 0.5-mm LEAD EQUIVALENT APRON FOR VARIOUS RADIATION SOURCES

Source	Energy (keV)	Exposure reduction with 1 apron	No. of aprons to reduce exposure by 90% (i.e., 1 TVL)	Weight (lbs)
Scattered x-rays	10–30	>90%	~1	~15
Tc-99m	140	~70%	~2	~30
Cs-137	662	~6%	~36	~540

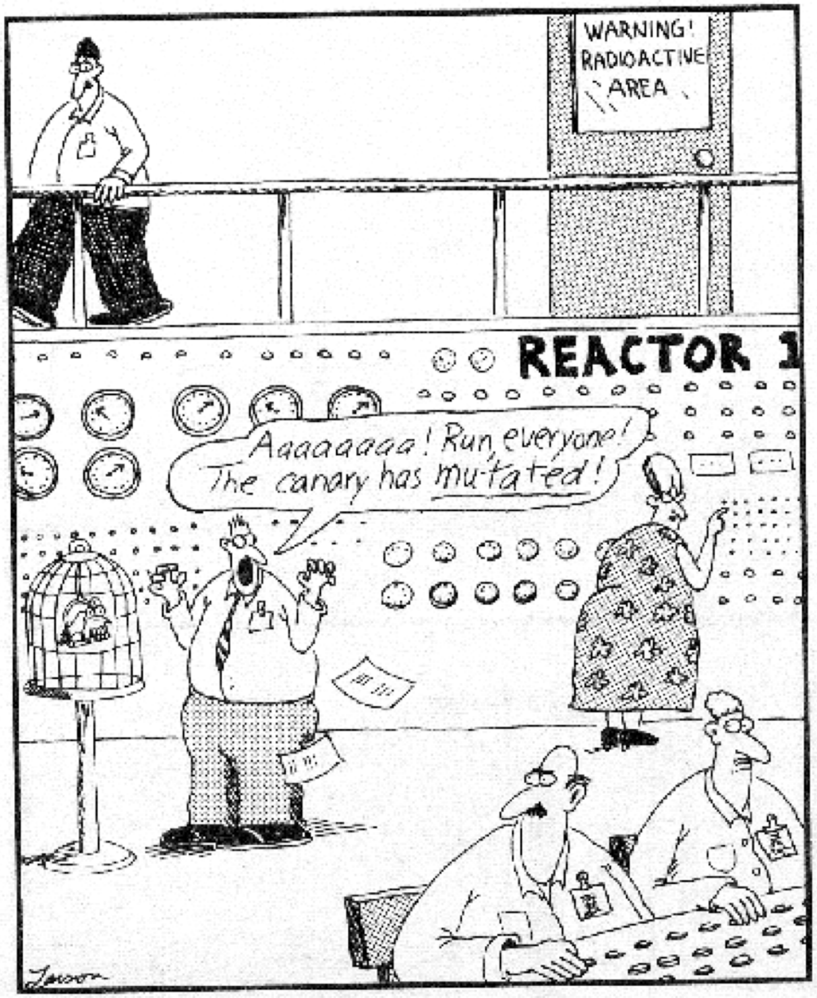
- Also, lead aprons not appropriate for Beta radiation. WHY?

High Z materials will facilitate bremsstrahlung x-ray production
Low Z materials are better shields for Beta's

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)
  6. Report spills or accidents to radiation safety officer! (UW Radiation Safety : 543-0463. www.ehs.washington.edu/RadSaf/)

NM Containment



Inside a nuclear power plant

- 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

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.

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 (not cyclotron produced agents), but many states have their own control programs with connections to the NRC
  - 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) regulated transportation of materials
- Advisory Boards: 1) Congress chartered "National Council on Radiation Protection and Measurements" (NCRP) and 2) "International Commission on Radiological Protection" (ICRP)

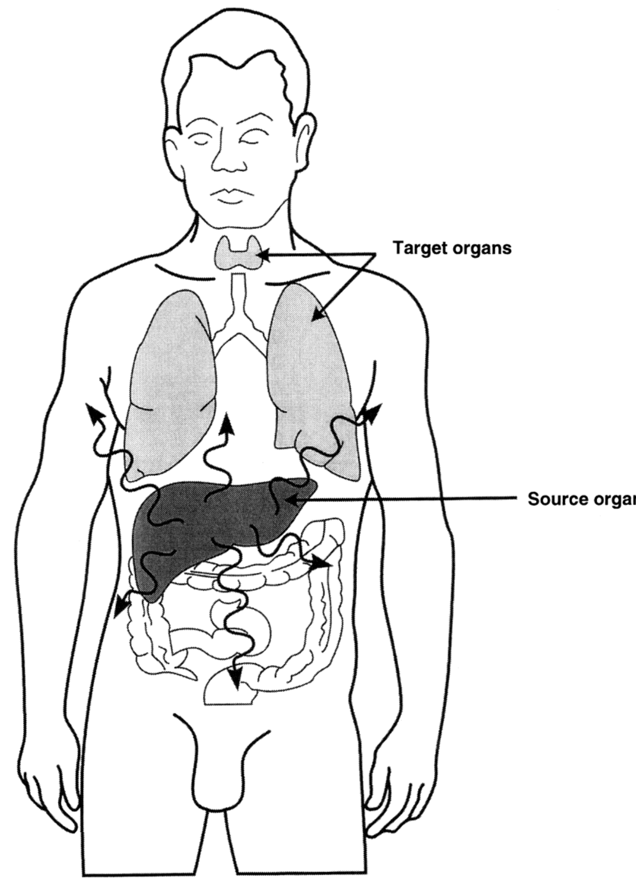
Radionuclide Therapy

- 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 4.8 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 1mR/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



Source Concerns? 1? 2?
Target Concerns? 1? 2?

MIRD Formalism

For a Source Organ (r_h)

and a target organ (r_k)

the Mean Dose (D_{r_k}) to a particular organ is

$$D_{r_k} = \sum_h \tilde{A}_h S(r_k \leftarrow r_h)$$

sum over all sources

where $\tilde{A}_h$ (μCi-hr) is the cumulated activity for each source organ

and S (rad/μCi-hr) is a factor describing absorbed dose in target

for each unit of 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):

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

Activity remaining in organ at time t: $A_t = f A_0 \exp(-\frac{0.693}{T_e} t)$

MIRD

- Cumulated Activity in Source Organ (cont'd.)
  - Now that we have activity at time t, need cumulative activity (Sum activity over all time)

$$\tilde{A}_h = A_0 \cdot f \cdot 1.44 T_e$$

$$(\mu\text{Ci-hr})$$

- S Factor : Dose to target organ per unit of cumulated activity in a specific source organ
  - Specific to each source/target combination and radiation type
- Putting it back together:

$$D_{r_k} = \sum_h \tilde{A}_h S(r_k \leftarrow r_h)$$

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:

$$T_e = \frac{T_p \cdot T_b}{T_p + T_b} = T_p = 6.02\,\text{hr}$$

$$\tilde{A}_h = A_0 \cdot f \cdot 1.44 T_e =$$

$$5{,}000\,\mu\text{Ci} \times 1 \times 1.44 \times 6.02\,\text{hr} = 4.3 \times 10^4\,\mu\text{Ci}\cdot\text{hr}$$

- Step 2: Find S factors and organ doses

Lookup from Table:

[illegible]

[illegible]

$$D_{r_k} = \sum_h \tilde{A}_h S(r_k \leftarrow r_h)$$

$$D_{\text{liver}} = 2.0\ \text{rad}$$

$$D_{\text{kidneys}} = 1.7\ \text{rad}$$

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 to per unit body weight

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