

Radiation Protection

RT4220 - LECTURE #9

KEDREE PROFFITT

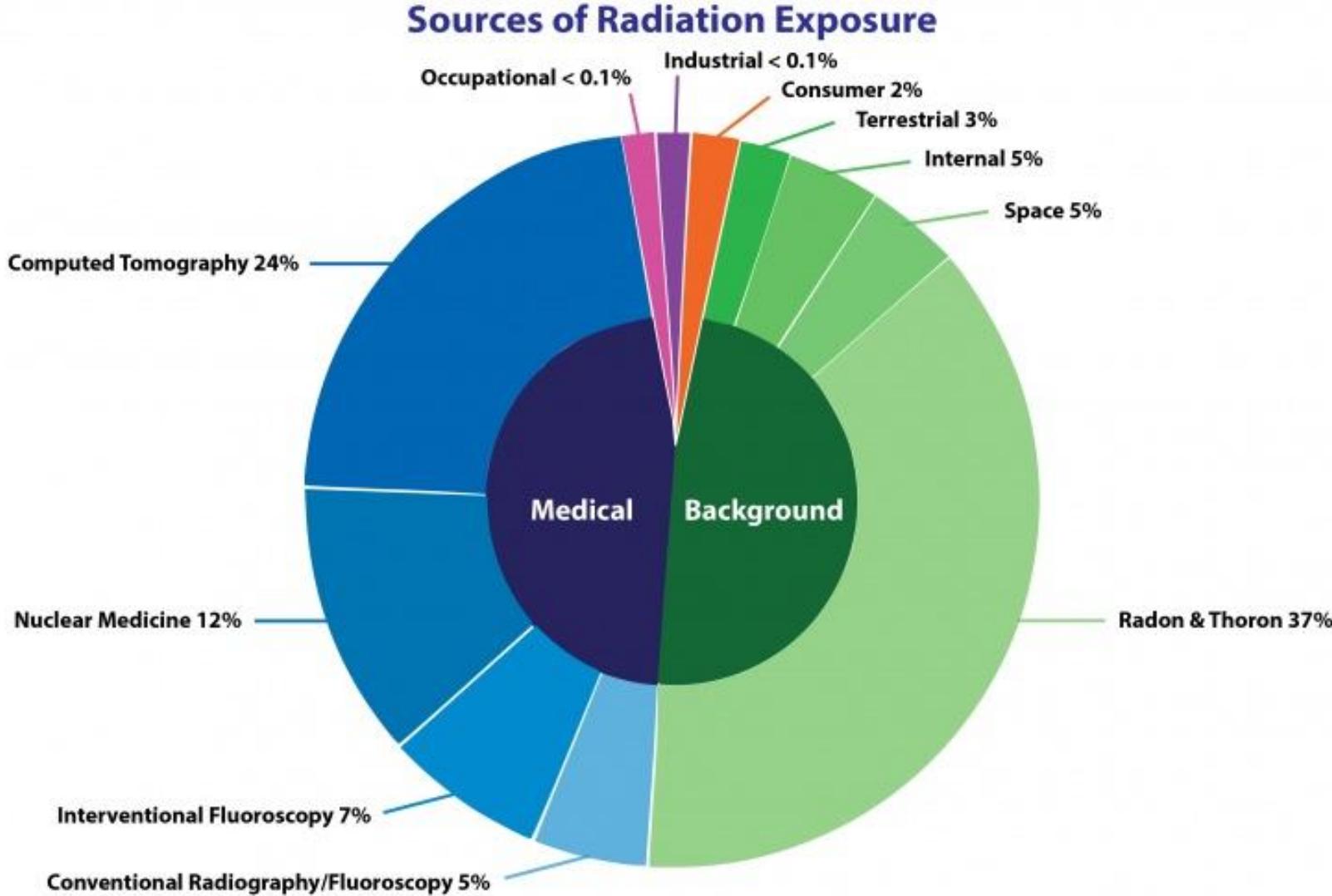
WSU

10/09/2025



Background Radiation Context

- For the **average** individual ~50% of their annual dose is medical, and ~50% natural
- For the Amish and *poor* its probably ~100%
- Average annual dose for an American is quoted to be about 6.4 mSv (3.2 mSv natural, 3.2 mSv man-made)
- Plurality of man-made is CTs (medically necessary and fruitful!)
- Majority of Natural is Radon/Thoron (probably not as bad as we think)
- Every hour of flying at cruising height adds 0.004 mSv
- Flight from Detroit to Shanghai is then ~ 2% of *your* **annual dose** (0.06 mSv)



| Average Annual Radiation Dose | | | | | | | | | | | |
|-------------------------------|----------------|---------------------|------------------|----------------------------|----------|--------------------------------------|----------|-------------|----------|--------------|------------|
| Sources | Radon & Thoron | Computed Tomography | Nuclear Medicine | Interventional Fluoroscopy | Space | Conventional Radiography/Fluoroscopy | Internal | Terrestrial | Consumer | Occupational | Industrial |
| Units | | | | | | | | | | | |
| mrem (United States) | 228 mrem | 147 mrem | 77 mrem | 43 mrem | 33 mrem | 33 mrem | 29 mrem | 21 mrem | 13 mrem | 0.5 mrem | 0.3 mrem |
| mSv (International) | 2.28 mSv | 1.47 mSv | 0.77 mSv | 0.43 mSv | 0.33 mSv | 0.33 mSv | 0.29 mSv | 0.21 mSv | 0.13 mSv | 0.005 mSv | 0.003 mSv |

(Source: National Council on Radiation Protection & Measurements, Report No. 160)

Radiation Doses from Medical Diagnosis

| Type of examination | Diagnostic reference levels ^{*1} | Actual exposure dose ^{*2} | |
|--------------------------------------|--|--|--|
| | | Dose | Type of dose |
| General imaging: Front chest | 0.3mGy | 0.06mSv | Effective dose |
| Mammography (mean glandular dose) | 2.4mGy | Around 2 mGy | Equivalent dose (Mean glandular dose) |
| Fluoroscopy | IVR (InterVentional Radiology): Fluoroscopic dose rate 20 mGy/sec | Gastric fluoroscopy Around 4.2-32 mSv ^{*3} (varies depending on operators and subjects) | Effective dose |
| Dental imaging | From 1.1 mGy at the frontal teeth of the mandible to 2.3 mGy at the molar teeth of the maxilla | Around 2-10 μ Sv | Effective dose |
| X-ray CT scan | Adult head simple routine: 85 mGy Child (age 6-10), head: 60mGy | Around 5-30mSv | Effective dose |
| Nuclear scanning | Value for each radioactive medicine | Around 0.5-15mSv | Effective dose |
| PET scan | Value for each radioactive medicine | Around 2-20mSv | Effective dose |

* 1 : "Diagnostic Reference Levels based on the Latest Survey within Japan," J-RIME, etc., June 7, 2015 (partially updated on August 11, 2015) (<http://www.radher.jp/J-RIME/>)

* 2 : "Q&A on Medical Exposure Risks and Protection Regarding Medical Exposure from CT Scans, etc.," National Institutes for Quantum and Radiological Science and Technology (<http://www.nirs.qst.go.jp/rd/faq/medical.html>)

* 3 : Prepared based on "Gastric Fluoroscopy" in "X-ray Medical Checkup" in "Basic Knowledge on Medical Radiation," (<http://www.khp.kitasato-u.ac.jp/hoshasen/iryo/>), Kitazato University Hospital, Radiology Department

Prepared based on materials *1, *2 and *3 above

Radiation Safety: Quantities and Units

- Cumulative Activity
- Effective Half-life
- Exposure (X)
- Absorbed Dose (D)
- Dose Equivalent (H)
- Relative Biological Effectiveness

Cumulative Activity

- Cumulated Activity (\tilde{A})
- Total amount of radioactivity absorbed
- The SI unit for cumulated activity is Bq*sec or just “disintegrations” (Ci*s is also acceptable)
- If the source is left in place permanently then:

$$\text{Cumulated activity } (\tilde{A}) \approx A_0 * \tau$$

A_0 = Initial activity

τ = Mean life

$\tilde{A} = A_0 * t_{1/2} * 1.44$

$$\tau = \frac{1}{\lambda} = \frac{t_{1/2}}{\ln 2} = 1.44 * t_{1/2}$$

Cumulative Activity: Effective Mean Life

- If the source is left in place (permanently) and the body is biologically ridding itself of the radionuclide at the same time then:

$$\text{Cumulated activity } (\tilde{A}) \approx A_0 * \tau_{\text{eff}}$$

A_0 = Initial activity

τ_{eff} = Effective Mean Life

$$\tau_{\text{eff}} = 1.44 * t_{1/2 \text{ eff}}$$

$$\tilde{A} = A_0 * t_{1/2 \text{ eff}} * 1.44$$

Effective Half-life

$$\frac{1}{(t_{1/2})_{eff}} = \frac{1}{(t_{1/2})_{phy}} + \frac{1}{(t_{1/2})_{bio}}$$

- The effective half-life $(t_{1/2})_{eff}$ is a combination of physical and biological half-life
 - $(t_{1/2})_{phy}$ = Physical Half-life: time required to decay to one half of radioactive nuclide
 - $(t_{1/2})_{bio}$ = Biological Half-life: time required for the body to clear one half of the drug from the body/system
- The effective half-life determines the what radioactivity will be observed while the body is ridding itself of the radionuclide over time by urine, feces, sweat, etc

Exposure

- It is the amount of ionization produced in air
- Only defined for air
- Unit of Roentgen or Coulomb / kg
- $1 \text{ R} = 2.58 \times 10^{-4} \text{ C / kg}$

Absorbed Dose

- Absorbed dose is the energy absorbed per unit mass
- Units: rad or Gray (1 Gy = 1 J/kg)
 - $100 \text{ rad} = 1 \text{ Gy} = 100 \text{ cGy}$
 - $1 \text{ rad} = 1 \text{ cGy}$

Dose Equivalent

- Dose equivalent (H)
 - Product of absorbed dose (D) and radiation weighting factor (W_R), formerly the quality factor (QF)
- W_R accounts for the type of radiation deposited (neutrons, photons, etc)
- Unit: Sievert (Sv) or rem
- $100 \text{ rem} = 1 \text{ Sv}$
- $1 \text{ rem} = 10 \text{ mSv}$

Dose Equivalent

Absorbed Dose Equiv. (H) =

Absorbed dose (D) x Weighting Factor (W_R)

Sievert = Gray * W_R (SI units)

rem = rad * W_R

(100 rem = 1 Sievert)

(1 rem = 0.01 Sievert)

(100 rad = 1 Gray)

(1 rad = 0.01 Gray)

Radiation Weighting Factor

Radiation weighting factor (w_R)

The radiation weighting factor is a dimensionless factor to derive the equivalent dose from the absorbed dose averaged over a tissue or organ, and is based on the quality of the radiation.

| Radiation weighting factors* | |
|--|-------|
| Type and energy range | w_R |
| Photons, all energies | 1 |
| Electrons and muons, all energies | 1 |
| Neutrons, energy <10 keV | 5 |
| 10 keV–100 keV | 10 |
| >100 keV–2 MeV | 20 |
| >2 MeV–20 MeV | 10 |
| >20 MeV | 5 |
| Protons, other than recoil, energy >2 MeV | 5 |
| Alpha particles, fission fragments, heavy nuclei | 20 |

* See Table 1 of *Publication 60* for further details (ICRP, 1991).

Principles of Radiation Safety

- Reduce dose as much as is reasonably possible (ALARA)
- Dose reduction via three methods:
 - **Distance** (Inverse Square Law)
 - **Time** (Duh)
 - **Shielding** (idk what to put here)
- Keep in mind **what** we are shielding from!

Exposure Limits

- NRC and NCRP define **Maximum Permissible Doses** for civilians and rad. workers alike (you!)
- Only include exposure from work activities! (No background rad.)
- Any personnel expected to receive >10% of the limit **must** use a Radiation Monitoring Device.

§ 20.1502 Conditions requiring individual monitoring of external and internal occupational dose.

Each licensee shall monitor exposures to radiation and radioactive material at levels sufficient to demonstrate compliance with the occupational dose limits of this part. As a minimum—

- (a) Each licensee shall monitor occupational exposure to radiation from licensed and unlicensed radiation sources under the control of the licensee and shall supply and require the use of individual monitoring devices by—
 - (1) Adults likely to receive, in 1 year from sources external to the body, a dose in excess of 10 percent of the limits in § 20.1201(a),

Maximum Permissible Dose Limits

| Occupational Exposure | Whole Body (mSv) | Extremities (mSv) | Lens of the Eye (msV) | Embryo-Fetus (mSv) |
|-----------------------|------------------|-------------------|-----------------------|--------------------|
| Monthly | | | | 0.5 |
| Annual | 50 | 500 | 150 | 5 |
| Cumulative | 10 x Age | | | |
| Civilian Exposure | Infrequent (mSv) | Frequent (mSv) | | |
| Annual | 1 | 5 | | |

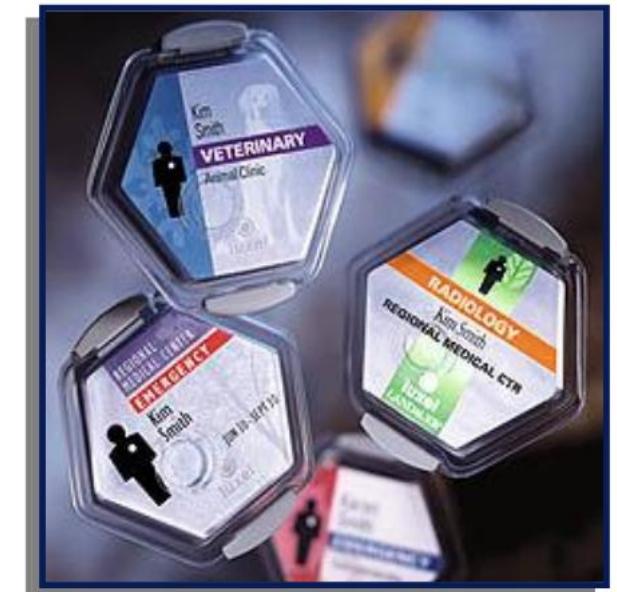
* The rule for minors is always 10% of the above

Pregnancy Declaration

- Pregnant workers should declare pregnancy ASAP **in writing**
- The rules only apply to you after that declaration!
- Most workers find that their job is barely affected, they become more cognizant of unnecessary dose
- Multiple methods of staying aware:
 - Begin consultation with RSO on how to reduce dose
 - Constant use of an “always-on” pocket dosimeter with an alarm

Personal Dosimeters

- No reason to not wear them!
- Front of the badge faces away, should be placed below the neck, but above the waist
- If they are damaged or lost, contact your RSO, they don't bite!



Keep personal dosimeters away from heat, sources of radiation.

Do not take them home!

Protective Devices

Leaded Glasses

Lead Thyroid Collar

Lead Apron
(≥ 0.5 mm lead)

Over-Apron Badge

(head/thyroid/eyes)
[Red Icon] or
[Black Icon]

Under-Apron Badge
(whole body)
[Yellow Icon]

Finger Ring Dosimeter

Dosimeters

Ring badges worn on hand during radionuclide assay

ALARA

- AS LOW AS REASONABLY ACHEIVABLE
- This concept is ever-present, every radiation worker in every step of the process keeps this principle in mind
- Keep dose low, keep people safe, keep expectations reasonable so that people actually follow the rules!
- Vast majority of rad. workers' dose is <10% of the limit, we do a great job!

Dose Reduction Techniques



Minimize Time

Slow is steady, steady is fast.
Practice and become confident,
but not complacent

Do not dilly-dally!



Maximize Distance

Probably the easiest one to do,
especially for radiopharm
procedures, easiest to forget too!

Stay as far away as is reasonable,
without freaking the patient out



Maximize Shielding

Often overlooked, and personal
shielding can be strenuous

Fluoroscopic Excessive Dose Example



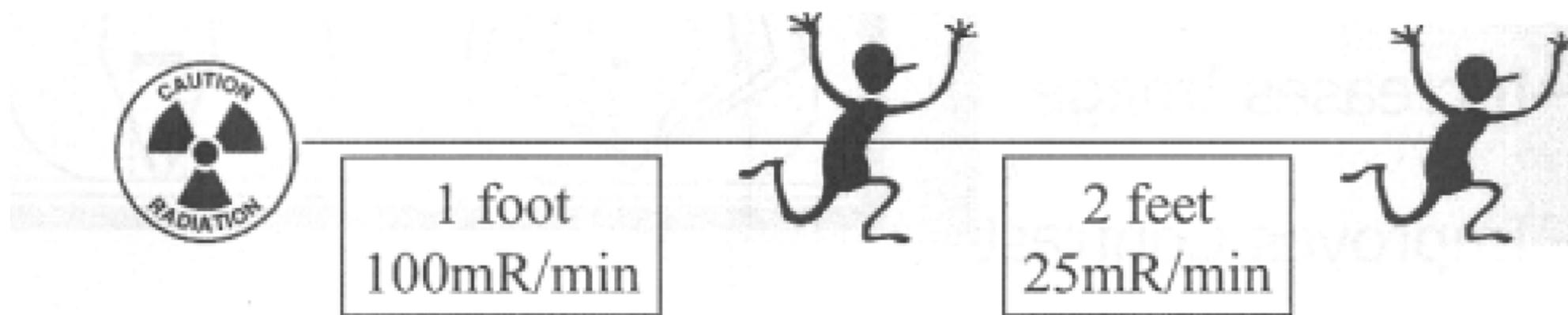
The image shows the area of injury 6 to 8 weeks following the procedures.



18 to 21 months following procedures, demonstrating tissue necrosis

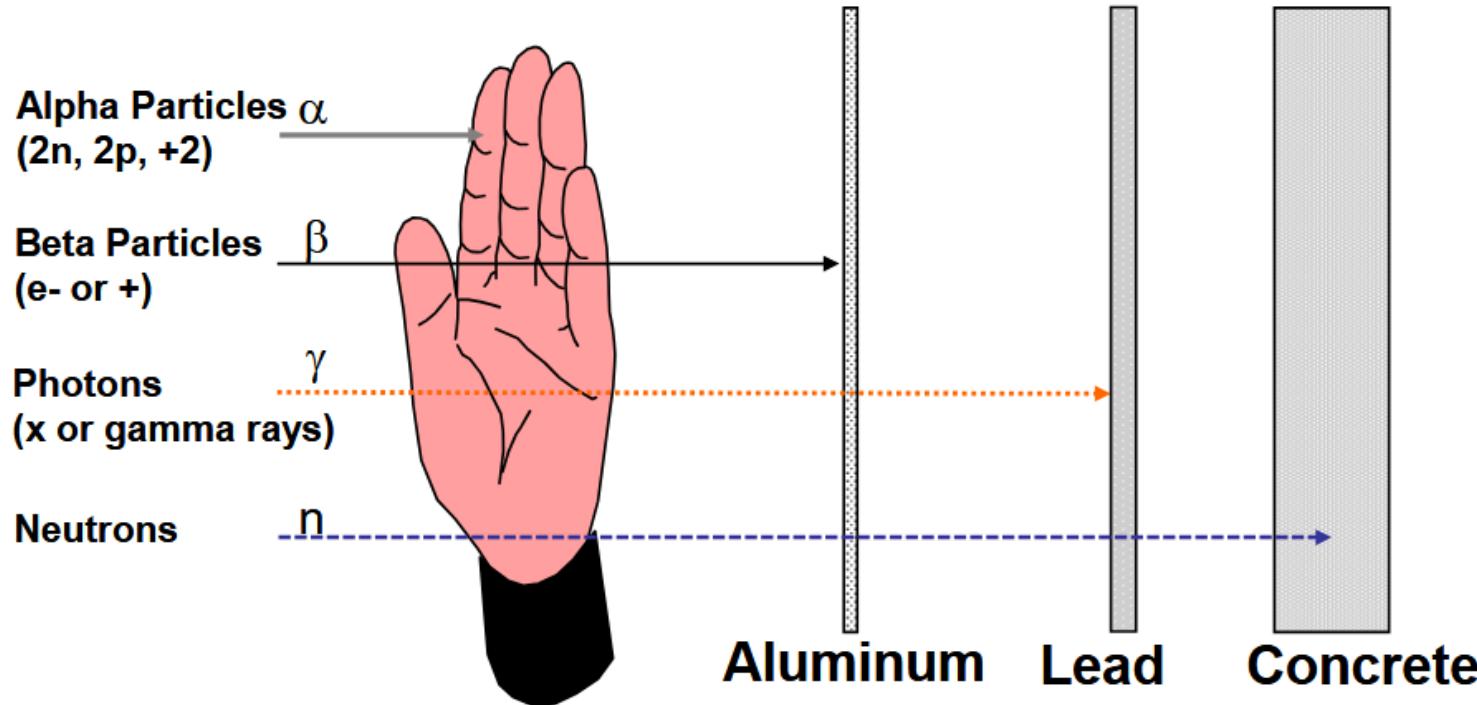
Importance of Distance as Radiation Protection

- Extremely effective and more importantly cheap!
- Just one step back can “reduce exposure by a factor of 4”



Exposure Rates are Example only - running from Radiation not a good idea.

Alpha, Beta, X-ray/Gamma and Neutron Shielding



- High Z materials (lead) are usually used to attenuate photons
- Neutrons require high hydrogen content (borated polyethylene or the water content found in concrete)

Shielding as a Protective Method

- Types of personal shields:
 - Lead Aprons
 - Thyroid Shields
 - Leaded Eye Wear
 - Leaded Gloves
- Leaded materials have a “lead equivalent” (0.5 mm is standard)
- Lead is awesome for betas and low energy (scatter/diagnostic) photons
- Lead is nearly useless for high-energy photons:
 - 100 keV Transmission = 4.3%
 - 511 keV Transmission = 91%

When Lead Aprons are Less Useful

- Medium to high energy photons are barely protected against
 - Tc-99m
 - I-131
 - Positron Emitters like F-18
- Those aprons are **heavy!** It really takes a toll on your body

X-Ray Shielding Guidelines (NCRP)

- NCRP Report No. 147: Structural Shielding Design for Medical X-Ray Imaging Facilities
- NCRP Report No. 151: Structural Shielding Design and Evaluation for Megavoltage X and Gamma ray Radiotherapy Facilities
- Physicists use the above to calculate how much shielding we need to keep everyone within spec. (limits and ALARA guidelines too!)

X-Ray Shielding

- We protect against the following three sources of radiation (descending importance):
 - Primary Radiation (the beam)
 - Scattered Radiation (mostly the patient)
 - Leakage (from the tube and housing)
- Shielding is done **in context** with surrounding rooms, even the outdoors!
 - Toilets require less shielding than offices
 - Is there a car park nearby?
 - Do not put your linac above the maternity ward...

Primary Beam Shielding

- For radiography AND Linacs we need to know the following:
 - **Workload (W)**: Average use per week in mA minutes for X-Ray
 - Average beam-on time per week, accounting for kVp and mAs
 - **Use Factor (U)**: Fraction of the time that the beam is pointed at this barrier
 - **Occupancy Factor (T)**: Fraction of the time where people are in the area to be protected when the beam is on
 - **Maximum Permissible Exposure (P)**: 10% of the regulation limits for ALARA in mSv/wk
 - Occupational: 0.1 mSv/wk ($50 \text{ mSv/yr} * 10\% = 5 \text{ mSv/yr} * 1 \text{ yr}/50 \text{ wk} = 0.1 \text{ mSv/wk}$)
 - General Public: 0.02 mSv/wk ($1 \text{ mSv/yr} * 1 \text{ yr}/50 \text{ wk} = 0.02 \text{ mSv/wk}$)

Controlled Area Classification

- Controlled Area:
 - Area in which exposure of persons to radiation is under the **supervision of the RSO** (control of access, occupancy, and working conditions)
 - Used for **Occupational Limits**
- Uncontrolled Area:
 - Areas not directly related to the use of radioactive sources (**no control of access to area**; general public and other department personnel allowed)
 - Use the “Grandma Test”
 - Used for **General Public Limits**

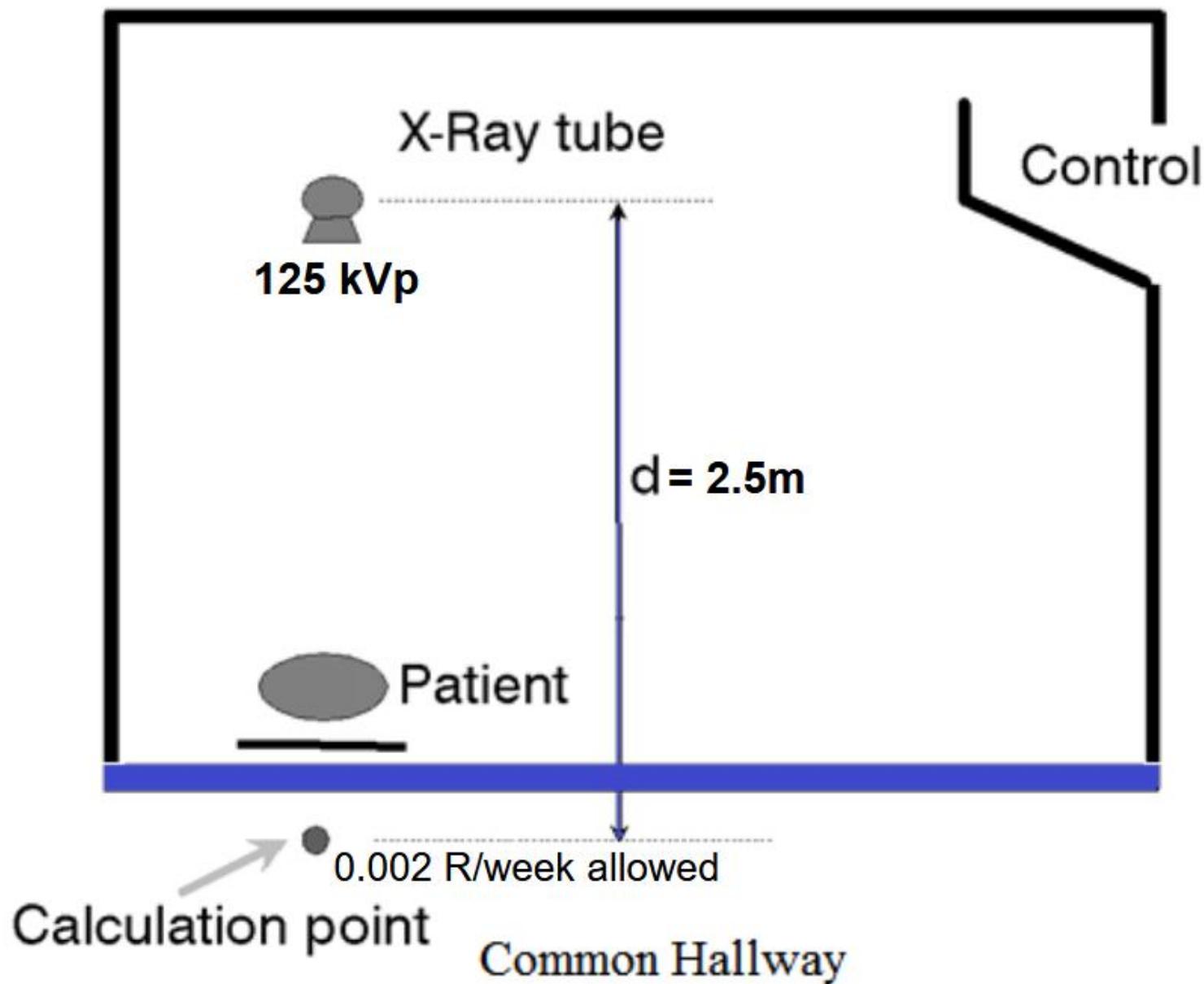
X-Ray Shielding Calculations: Primary Barrier

$$K = d^2 P / WUT$$

where:

- K = transmission factor in units of R-m²/mA-min
- d = distance from source to person being protected
- P = maximum permissible exposure rate (R/week)
- W = weekly workload (in mA-min)
- U = use factor
- T = occupancy factor

How much shielding is needed for the blue wall?



Typical Assumptions: Workload (W)

| Diagnostic | Daily Pa-tient Load | Weekly workload (W) mA min | | |
|--|---------------------|-----------------------------|---------------------|---------------------|
| | | 100 kV ^a or less | 125 kV ^a | 150 kV ^a |
| Admission Chest: (Miniature, with photo-timing grid) | 100 | 100 | - | - |
| Chest: (14 × 17: 3 films per patient, no grid) | 60 | 150 | - | - |
| Cystoscopy | 8 | 600 | - | - |
| Fluoroscopy including spot filming | 24 | 1,500 | 600 | 300 |
| Fluoroscopy without spot filming | 24 | 1,000 | 400 | 200 |
| Fluoroscopy with image intensification in- cluding spot filming | 24 | 750 | 300 | 150 |
| General Radiography | 24 | 1,000 | <u>400</u> | 200 |
| Special Procedures | 8 | 700 | 280 | 140 |

Typical Assumptions: Use Factor (U)

- Use 1 if the beam is stationary and pointed at the barrier
- If the beam rotates or is used in different orientations then estimate the fraction of time the beam is pointed at the barrier you are calculating for
- If you are doing leakage or scatter calculations, always use 1 (we are only covering primary here)

Typical Assumptions: Occupancy Factor (T)

- 1 for work areas, labs, shops, nurses' stations, living quarters, children's' play areas
- $\frac{1}{4}$ - $\frac{1}{5}$ for corridors, rest rooms, elevators using an operator, unattended parking lots
- $\frac{1}{16}$ - $\frac{1}{40}$ for waiting rooms, toilets, stairways, unattended elevators, outside pedestrian areas

X-Ray Shielding Calculations: Primary Barrier Example

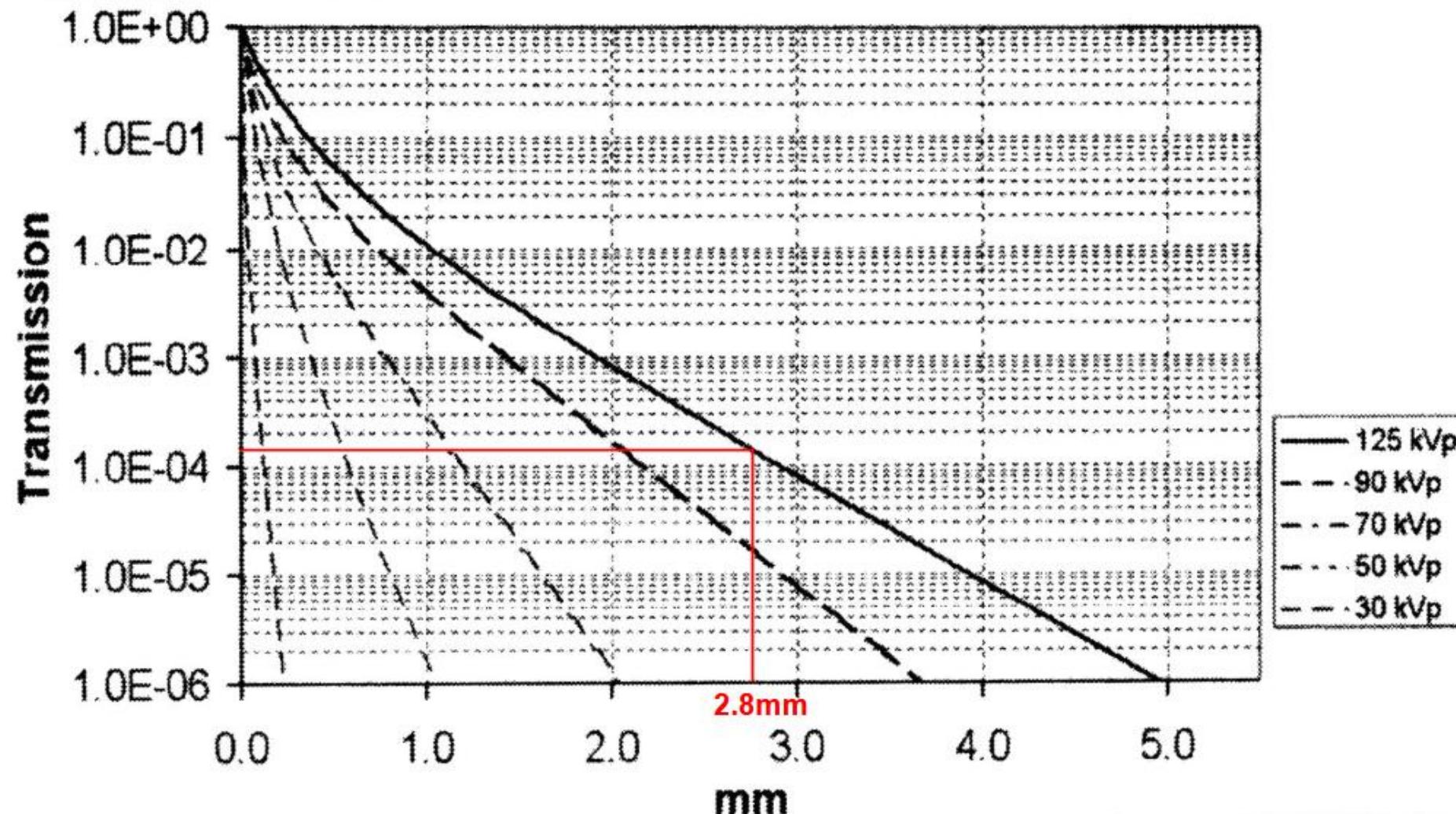
$$K = d^2 P / WUT$$

- $d = 2.5$ meters
- $P = 0.002$ R/week
- $W = 400$ mA min/week
- $U = 1$
- $T = 1/5$

$$K = 1.6 \times 10^{-4} \text{ R-m}^2/\text{mA-min}$$

Now what? – Let's check the graph in NCRP 147...

Primary Barrier Example: Transmission in Lead (Pb)



Head Leakage

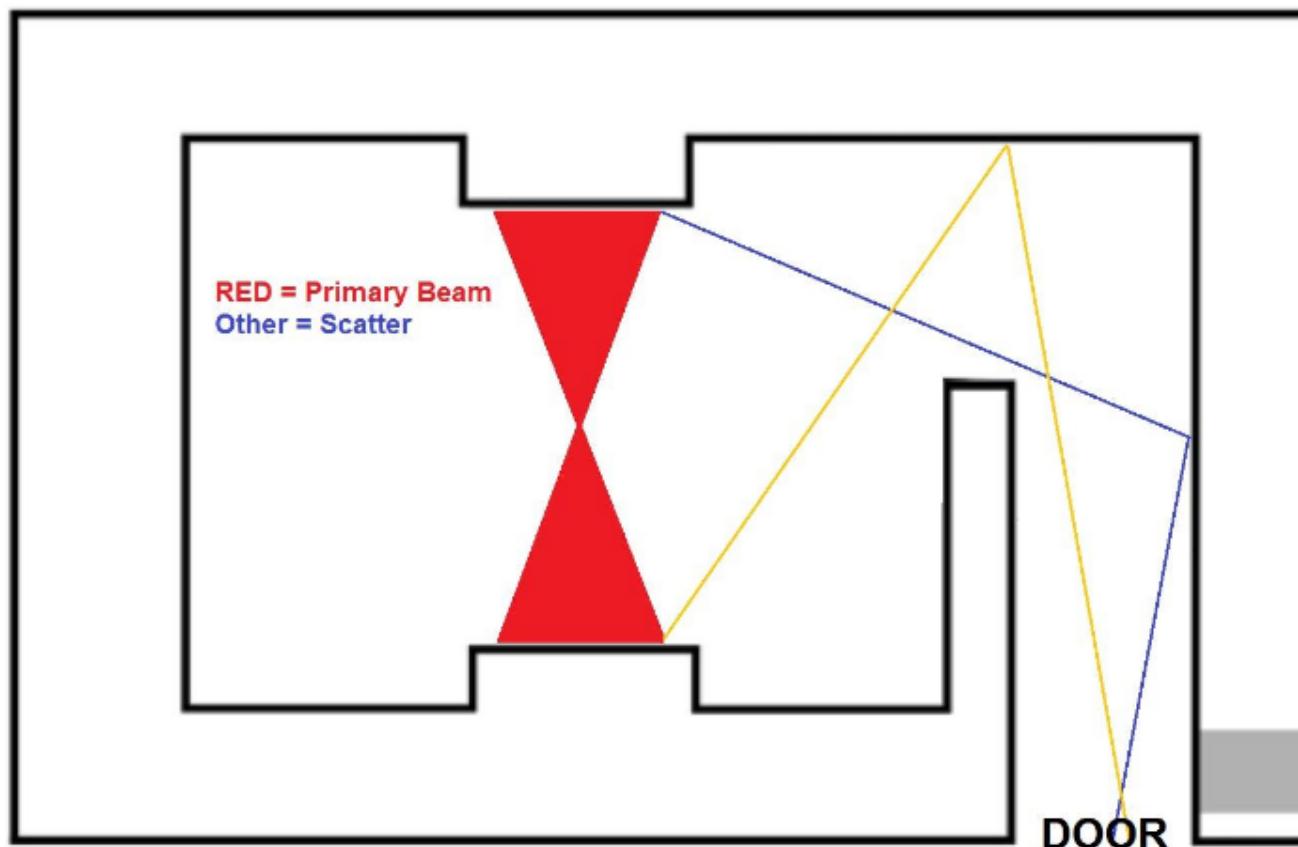
NCRP Exposure Limits (at 1m from the target)

| Type | Exposure Limit |
|-------------------|-------------------------|
| Diagnostic unit | 0.1 R/h |
| Therapy (<500keV) | 1.0 R/h |
| Therapy (>500keV) | 0.1% of the useful beam |

Usually head leakage can be ignored. However, if it contributes a significant amount of dose at a calculation point then it should be added to the transmission calculation. The same applies for scattered or secondary radiation.

Typical LINAC Vault Design

- The following image is a typical LINAC vault design
 - Typically, primary radiation must be scattered at least twice before reaching the vault door
 - Can you imagine any other characteristics that might be important?



The 2.0mR/hr in controlled areas is derived from the NCRP guidelines:

$$2\text{mR/Hr} \times 2080 \text{ work hours/year}$$

$$= 4160\text{mrem/year}$$

$$\approx 5 \text{ rem/year}$$

$$\approx 50 \text{ mSv/year}$$

(the occupational radiation exposure limit for 1 year)

Note that for photons: 1 rem \approx 1 R

Photon Attenuation Calculation

look familiar?

$$I = I_o e^{-\mu x}$$

I = Radiation intensity after barrier

I_o = Radiation intensity without barrier

e = base for the natural logarithm

μ = Linear attenuation coefficient, cm^{-1}

x = Thickness of shielding, cm

Find I_o from the given quantities

$$I = I_o e^{-\mu x}$$

$$I = 2.0 \text{mR/hr} \quad \mu = 3.164 \text{cm}^{-1} \quad x = 0.125 \text{ cm}$$

$$\frac{I}{e^{-\mu x}} = I_o$$

$$2 \text{mR/Hr} / e^{-(3.164 \text{ cm}^{-1} * 0.125\text{cm})} = I_o$$

$$\underline{2.97 \text{mR/Hr}} = I_o$$

Controlled areas should be kept below an exposure rate of 2.0mR/hr

Half & Tenth Value Layer

- Half value Layer (HVL)
 - Thickness of material required to reduce intensity of radiation to one half of its original intensity

$$I/I_o = 1/2$$

- Tenth value layer (TVL)
 - Thickness required to reduce the intensity to one tenth its original intensity

$$I/I_o = 1/10$$

Security of Sources

- Critical homeland security mandate
 - Remember this radioactivity can be used as a weapon in the wrong hands
- Never leave radioactive materials unattended
- Doors must be locked when sources are not under the staff control
 - *don't leave the key in the lock*
 - *do not give out combinations*
- Any unauthorized individual must be escorted from controlled areas

Written Directive

- Written Directive: an authorized user's written order for the administration of byproduct material or radiation from byproduct material to a specific patient
- Patient Identification verified
- Must be issued prior to ordering dose from pharmacy
 - quantities greater than 30 µCi of either I-125 or I-131
 - any therapeutic administration of a radipharmaceutical, other than I-125 or I-131

Radionuclide Therapy Instruction

- Provide radiation safety instruction for all personnel caring for the patient receiving Tx:
 - 1) Patient or human research subject control
 - 2) Visitor control
 - 3) Contamination control
 - 4) Waste control
 - 5) Notification of the RSO in case of the patient's death or medical emergency

Radionuclide Safety Precautions

- Provide a private room with a private sanitary facility
- Post the patient's door with a "Radioactive Materials" sign
- Note on the door or in the patient's chart where and how long visitors may stay in the patient's room

Breast-feeding Instructions

- If the dose to a breast-feeding infant or child could exceed 1 mSv assuming there were no interruption of breastfeeding, provide instructions
 - 1) Guidance on the interruption or discontinuation of breast-feeding
 - 2) Information on the consequences of failure to follow the guidance.

Prevention of Unintentional Fetal Exposure

- Good History (includes asking direct question "Are you pregnant?")
- Common-sense Assessment of Risk of Pregnancy (age, prior surgery, contraception)
- Pregnancy test - Beta HCG
- Report to NRC any fetal exposure over 5 Rem

10CFR35 Patient Release Rules

- A patient may be released from licensee control when the highest dose to a member of the public due to exposure to the released patient is less than 5 mSv
- A patient must be given written radiation safety instructions describing methods to reduce the radiation exposure to others when the dose to another individual may exceed 1 mSv

Release of Individuals Containing Radiopharmaceuticals

- Maintain a record of the dose calculation for authorizing the release of an individual
 - 1) *Using the “retained” activity rather than the activity administered,*
 - 2) *Using an occupancy factor less than 0.25 at 1 meter (must instruct patient & care givers),*
 - 3) *Using effective half-life, and*
 - 4) *May consider the shielding done in tissues*