Chapter 15
Radiation Protection

Radiation Dosimetry I

F.M. Khan, The Physics of Radiation Therapy, 4th ed., Chapter 16
http://www.utoledo.edu/med/depts/radther

Introduction

• Radiation exposure standards were introduced as early as the start of the 20th century when the potential hazards of radiation were realized
• Limits on radiation exposure to public and radiation workers
• Radiation presents a risk to workers that is similar to other industrial hazards
• Radiation dose recommendations for occupational exposures have evolved as more information is gathered on the effects of radiation on humans

Main Principles of Radiation Protection

• **Time** – exposure is proportional to duration
• **Distance** – governed by the inverse square law
• **Shielding** – presence of protective barrier

  • Minimize time and maximize distance and shielding

Advisory bodies

• The International Commission on Radiological Protection (ICRP) issues reports which form the basis for many national protection guidelines
• In the United States, the National Council on Radiation Protection and Measurements (NCRP) functions as a primary standard-setting body through its separate publications
• Both are advisory bodies: collect and analyze data, and put forward recommendations on radiation protection
• Recommendations are utilized by regulatory groups to develop regulations

Regulatory bodies

• The Nuclear Regulatory Commission (NRC) has regulatory powers in US, having control over the use of all reactor-produced materials (e.g., ^{60}Co and ^{192}Ir)
• The naturally occurring radioactive materials (e.g., radium and radon) and x-ray machines are regulated by individual states
• US NRC has agreement with states (called ‘agreement states’) that allows these states to enforce NRC regulations
• Many other federal agencies regulate different aspects of radiation protection pertaining to their specific program area (FDA, FEMA, OSHA, DOT, EPA, USPS)

Regulations in individual states

• Oversight of naturally occurring radioactive materials and x-ray machines
• "Non-agreement states" are partially or fully regulated by the NRC
• "Agreement states" are self-regulating

http://www.utoledo.edu/med/depts/radther
Example: DOT label

Transport Index (TI) – reading in mR/h at 1 m must be indicated on DOT label
See 49 CFR 172.403 (CFR – Code of Federal Regulations)

<table>
<thead>
<tr>
<th>Label</th>
<th>Surface (mR/h)</th>
<th>At 1 m (mR/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White I</td>
<td>&gt; 0.5</td>
<td>N/A</td>
</tr>
<tr>
<td>Yellow II</td>
<td>0.5 – 50</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>Yellow III</td>
<td>50 – 200</td>
<td>1 – 10</td>
</tr>
</tbody>
</table>

7 – hazard class for radioactive materials in DOT designation

Dose Equivalent

- The biologic effects of radiation depend not only on dose, but also on the type of radiation, the dosimetric quantity relevant to radiation protection is the dose equivalent H, defined as:

\[ H = D \cdot Q \]

Old unit: \[ H = \text{rem} = 10^{-2} J / kg \]

- The Q-factor (unitless) value depends on RBE (related to LET) of the radiation

Effective Dose Equivalent

- For a given uniform exposure
  - Received dose may differ markedly for various tissues
  - Tissues vary in sensitivity to radiation-induced effects
- The concept of effective dose equivalent has been adopted by the ICRP and the NCRP as “the sum of the weighted dose equivalents for irradiated tissues or organs”

\[ H_E = \sum W_T H_T \]

Based on risk estimates

Risk Estimates

- The excess risk is estimated in terms of the probability to develop a fatal cancer in various organs of the body
  - Stochastic (no threshold) quantity
  - The severity of the effect does not depend on the dose
  - Risks of tumor induction are higher (e.g., since ~50% of breast cancers are curable the risk of induction is 2x)
- Estimates are based on effects at high doses (no data for dose equivalent < 100mSv)
- The average natural lifetime incidence of cancer in the United States is 42% +39.5% based on 2015–2017 data

Background Radiation

- The background radiation is contributed mainly by 3 sources: terrestrial radiation, cosmic radiation, and radiation from radioactive elements in our bodies
  - Terrestrial radiation varies based on surrounding materials, including buildings (granite rocks contain small amount of Uranium-238 producing radon)
  - Cosmic radiation levels change with elevation and latitude (~20% in going from equator to 50° latitude)
  - The internal irradiation arises mainly from 40K in our body, which emits γ and β rays and decays with a half-life of 1.3x10^9 years
Background Radiation

Table 16.2: Estimated Total Effective Dose Equivalent Rate for a Member of the Population in the United States and Canada from Various Sources of Natural Background Radiation

<table>
<thead>
<tr>
<th>Source</th>
<th>Lung</th>
<th>Gastrointestinal</th>
<th>Bone</th>
<th>Skin</th>
<th>Eyes</th>
<th>Brain</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>0.12</td>
<td>0.25</td>
<td>0.09</td>
<td>0.12</td>
<td>0.06</td>
<td>0.01</td>
<td>0.49</td>
</tr>
<tr>
<td>Cosmic</td>
<td>0.03</td>
<td>0.17</td>
<td>0.06</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.27</td>
</tr>
<tr>
<td>Elevations</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>Latitude</td>
<td>0.09</td>
<td>0.28</td>
<td>0.09</td>
<td>0.10</td>
<td>0.09</td>
<td>0.09</td>
<td>0.49</td>
</tr>
<tr>
<td>Solar events</td>
<td>0.04</td>
<td>0.08</td>
<td>0.08</td>
<td>0.11</td>
<td>0.11</td>
<td>0.11</td>
<td>0.49</td>
</tr>
<tr>
<td>Measured levels</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*The effective dose equivalent rate for a member of the population in the US from various sources of natural background radiation is ~3.0 mSv/year (300 mrem/year).

- The total effective dose equivalent rate for a member of the population in the US from various sources of natural background radiation is ~3.0 mSv/year (300 mrem/year).
- Actually 6.2 mSv/year from [epa.gov](http://epa.gov).

Background Radiation: Cosmic

- Elevation and latitude: the Earth’s atmosphere and magnetic shield (strongest at the equator and weakest near the poles) protect us from cosmic radiation.
  - People in Denver, Colorado, are exposed to slightly more cosmic radiation than those in Miami, Florida.
  - A one-way flight across the country (New York to Los Angeles), we likely receive 2-5 mrem (0.02-0.05 mSv) of radiation. The radiation from two cross-country flights is about equal to that from a single chest x-ray.
  - Solar events can raise radiation levels.

From https://www.epa.gov/radtown/cosmic-radiation

Occupational Dose Limits

- NCRP recommendations on exposure limits of radiation workers are based on the following criteria:
  - at low radiation levels the nonstochastic effects are essentially avoided
  - the predicted risk for stochastic effects should not be greater than the average risk of accidental death among workers in “safe” industries
  - the ALARA principle should be followed, for which the risks are kept “as low as reasonably achievable”, taking into account social and economic factors
  - Negligible Individual Risk Level (NIRL) - a threshold below which efforts to reduce the risk further is not warranted

- “Safe” industries are defined as “having an associated annual fatality accident rate of 1 or less per 10,000 workers, or an average annual risk of $10^{-4}$.
- The radiation industries show an average fatal accident rate of $<0.3 \times 10^{-4}$, therefore the radiation industries compare favorably with the “safe” industries.

Occupational Dose Limits

- Harmful effects of radiation are classified into two general categories:
  - Stochastic effects, with the severity of the effect independent of the dose
  - Nonstochastic: increases in severity with increasing absorbed dose, due to damage to increasing number of cells and tissues. Examples: radiation-induced degenerative changes such as organ atrophy, fibrosis, lens opacification, blood changes, etc.
  - Assumed linear-no threshold (LNT) model may overestimate the effect at low doses

![Models for the Health Risks from Exposure to Low Levels of Ionizing Radiation](image-url)
Occupational Dose Limits

- Radiation workers are limited to an annual effective dose of 50 mSv (5 rem)
- The pregnant woman who is a radiation worker can be considered as an occupationally exposed individual, but the fetus cannot. The total dose-equivalent limit to an embryo-fetus is 5 mSv (0.5 rem), with the added recommendation that exposure to the fetus should not exceed 0.5 mSv (0.05 rem) in any 1 month
- Once a pregnancy is made known, the dose-equivalent limit of 0.5 mSv (0.05 rem) in any 1 month should be the guiding principle

Effective Dose-Equivalent Limits

<table>
<thead>
<tr>
<th>Summary of Recommendations</th>
<th>Effective Dose-Equivalent Limits</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary barriers to radiation</td>
<td>Maximum dose equivalent</td>
<td>mSv</td>
<td>mSv</td>
</tr>
<tr>
<td>- Isotopic source barriers to radiation</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>- Gamma-ray source barriers to radiation</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>- Neutron source barriers to radiation</td>
<td>20</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Secondary barriers to radiation</td>
<td>Maximum dose equivalent</td>
<td>mSv</td>
<td>mSv</td>
</tr>
<tr>
<td>- Isotopic source barriers to radiation</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>- Gamma-ray source barriers to radiation</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>- Neutron source barriers to radiation</td>
<td>20</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

Structural Shielding Design

- NCRP provides radiation protection guidelines for the design of structural shielding for radiation installations (new and remodeled facilities):

Structural Shielding Design

- Protective barriers are designed to ensure that the dose equivalent received by any individual does not exceed the applicable maximum permissible value
- The areas surrounding the room are designated as controlled or noncontrolled, depending on whether or not the exposure of persons in the area is under the supervision of a radiation protection supervisor
  - For the controlled areas the dose-equivalent limit is assumed to be 1 mSv/week or 50 mSv/year
  - For the noncontrolled areas the limit is 0.02 mSv/week or 1 mSv/year annual limit

Structural Shielding Design

- Protection is required against three types of radiation: the primary radiation, the scattered radiation, and the leakage radiation through the source housing
  - A barrier sufficient to attenuate the useful beam to the required degree is called the primary barrier
  - The required barrier against stray radiation (leakage and scatter) is called the secondary barrier
Primary Radiation Barrier Calculations

- Workload (W) expressed in rad/week at 1 m
  - For x-ray equipment operating below 500 kVp usually expressed in mA-minutes per week of beam “on” time
  - For MV machines usually stated as weekly dose delivered at 1 m from the source; can be estimated by multiplying the number of patients treated per week with the dose delivered per patient at 1 m
- Use Factor (U) - fraction of the operating time during which the radiation under consideration is directed toward a particular barrier

<table>
<thead>
<tr>
<th>Location</th>
<th>Use Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td>1</td>
</tr>
<tr>
<td>Wall</td>
<td>1/2</td>
</tr>
<tr>
<td>Ceiling</td>
<td>1/10, depending on equipment and techniques</td>
</tr>
</tbody>
</table>

Primary Radiation Barrier Calculations

- For the maximum permissible dose equivalent for the area to be protected $P$ (NCRP#151: 0.1 mSv/week for controlled and 0.02 mSv/week for noncontrolled area) the required transmission factor $B$ is given by

$$ B = \frac{P \cdot d^2}{WUT} $$

- Using broad-beam attenuation curves for the given energy beam, one can determine the barrier thickness required

Secondary Radiation Barrier Calculations: Scatter

- The transmission factor to reduce scatter $B_S$:

$$ B_S = \frac{P}{\alpha W T F} \cdot \frac{400}{d^2} \cdot d'^2 $$

- Here $\alpha$ is the ratio of scattered dose to incident dose, $F$ is the area of the beam incident at the scatter, $d'$ is the distance from the scatterer to the area of interest
- $U=1$ for secondary barriers

Secondary Radiation Barrier Calculations: Scatter

- Occupancy Factor (T) - fraction of the operating time during which the area of interest is occupied by the individual
- Distance (d) in meters from the radiation source to the area to be protected. Inverse square law is assumed for both the primary and stray radiation

<table>
<thead>
<tr>
<th>Location</th>
<th>Use Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-room (P = 1)</td>
<td>Work areas, other, non-room</td>
</tr>
<tr>
<td>Partial-room (P = 0.5)</td>
<td>Personnel operating with rotating equipment</td>
</tr>
<tr>
<td>Occasional (P = 0.1)</td>
<td>Waiting areas, cranes, docks, nonclassified barrier, easily accessible for personnel or vehicular traffic</td>
</tr>
</tbody>
</table>

Concrete is cheap, but its density is fairly low 2.35 g/cm$^3$

Lead or steel can be used for more compact barriers
Secondary Radiation Barrier Calculations: Leakage

- The transmission factor for the leakage barrier for therapy units, above 500kVp, $B_L$:
  \[ B_L = \frac{P \cdot d^2}{0.001WT} \]
- The quality of leakage radiation is approximately the same as that of the primary beam
- For MV installations the leakage barrier usually far exceeds that required for scatter radiation

Door Shielding

- Unless a maze entranceway is provided, the door must provide shielding equivalent to the wall surrounding the door
- For MV installations, a door that provides direct access to the treatment room will have to be extremely heavy
- The function of the maze is to prevent direct incidence of radiation at the door. With a proper maze design, the door is exposed mainly to the multiply scattered radiation of significantly reduced intensity and energy

Door Shielding

- The door shielding can be calculated by tracing the path of the scattered radiation from the patient to the door and repeatedly applying equation for $B_S$
- In a properly designed maze the required shielding turns out to be less than 6 mm of lead

Shielding Against Neutrons

- For x-ray beams with energy >10MV, photonuclear interactions ($\gamma,n$) result in neutron contamination
- In the 16- to 25-MV x-ray therapy mode the neutron dose equivalent along CA is ~0.5% of the x-ray dose and falls off to ~0.1% outside the field
- When thermal neutrons are absorbed by the nuclei of atoms within the shielding door, energetic $\gamma$ radiations (neutron-capture $\gamma$ rays) are produced, their energy is up to 8MV
- In general, a longer maze (>5 m) is desirable in reducing the neutron fluence at the door
- A few inches of a hydrogenous material such as polyethylene can be added to the door to thermalize the neutrons and reduce the neutron dose

Protection Against Brachytherapy Sources

- Governed by NCRP report 40
- Storage: lead-lined safes with adequate shielding, ventilation for radium source storage
- Source preparation: usage of lead L-block for handling applicators
- Source transportation in lead containers or leaded carts
- Leak testing of sealed sources (e.g., check radium source for radon leaks); periodicity is specified by NRC or state regulations

Radiation Protection Surveys

- After the installation of radiation equipment, a qualified expert must carry out a radiation protection survey of the installation
- The survey includes
  - Equipment survey to check equipment specifications and inter-locks related to radiation safety
  - Area survey as evaluation of potential radiation exposure to individuals in the surrounding environment
- Since low levels of radiation are measured, the instrument must be sensitive enough to measure such low levels
Radiation Monitoring Instruments

- The detectors most often used for surveys are ionization chambers and Geiger counters
  - Ion chamber survey meter: large volume (~600 cc), sensitivity ~mR/hr
  - Usually calibrated with γ-ray beam of brachytherapy sources (Cs or Ra)
  - For linac installations additional calibration corrections may be required (energy response, linearity, T-P, angular dependence)

A Cutie Pie survey meter, Victoreen

- Geiger-Müller counter (G-M tube) is much more sensitive than ionization chamber due to gas multiplication
  - Can detect individual particles
    - Not a dose-measuring device; useful for preliminary surveys to detect the presence of radiation, ionization chambers are recommended for quantitative measurement
    - Because of their inherently slow recovery time they can never record more than 1 count/machine pulse, significantly underestimating radiation levels for linacs

A portable neutron rem counter 'Rascal' (Eberline)

- Neutron detector is typically used independently of x-ray detector to survey outside of the treatment room
  - Detection principles:
    - In hydrogenous materials neutrons produce hydrogen recoils (protons) that can be detected by ionization measurements, proportional counters, scintillation counters, cloud chambers, or photographic emulsions.
    - Activation detectors: detected by their induced nuclear reactions in certain materials
  - Neutron count rate in mrem/hr

- Radiation Monitoring Instruments

- Personnel Monitoring

- Acute Radiation Effects

- Summary

- Basic principles: time-distance-shielding
- Regulated by NRC, states, DOT, etc.
- Effective dose equivalent and risk estimates
- Structural shielding design
  - Primary, scatter, leakage
  - Controlled vs. noncontrolled areas
- Radiation protection monitoring