Chapter 15
Radiation Protection

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.

Regulatory 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.

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: $[H] = rem = 10^{-2} J/kg$.
- The Q-factor (unitless) value depends on RBE (related to LET) of the radiation.

\begin{align*}
\text{Old unit: } [H] &= \text{rem} = 10^{-2} J/kg \\
\text{New unit: } [H] &= \text{Sv} = \text{rad} = \text{rem} \\
\end{align*}
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.
- The average natural lifetime incidence of cancer in the United States is 42%.

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.

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.
Occupational Dose Limits

- "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.

### Summary of Recommendations

| Source | Radiation Protection Guideline | Energy Limit
|-------|-------------------------------|----------------

**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**

- 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.

**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.

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>Table 16.8</th>
<th>Typical Use Factor for Primary Protection Barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Use Factor</td>
</tr>
<tr>
<td>Film</td>
<td>0.5</td>
</tr>
<tr>
<td>Wait</td>
<td>0.5</td>
</tr>
<tr>
<td>Gowning</td>
<td>0.75, 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.

Primary Radiation Barrier Calculations

• 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>Table 16.7</th>
<th>Typical Occupancy Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full capacity (P = 1)</td>
<td></td>
</tr>
<tr>
<td>Rest areas, other minor stations</td>
<td></td>
</tr>
<tr>
<td>Corridors, entrances, elevators, open spaces</td>
<td></td>
</tr>
<tr>
<td>Entrance, waiting areas, radiation protection rooms, control rooms</td>
<td></td>
</tr>
</tbody>
</table>

Broad-beam Attenuation Curves

• Concrete is cheap, but its density is fairly low 2.35 g/cm³.
• Lead or steel can be used for more compact barriers.
**Secondary Radiation Barrier Calculations: Scatter**

- The transmission factor to reduce scatter $B_s$:
  \[ B_s = \frac{P}{\alpha WT} \cdot d^2 \cdot d'^2 \]
- 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: 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**

- 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 approximately 0.5% of the x-ray dose and falls off to about 0.1% outside the field
- When thermal neutrons are absorbed by the nuclei of atoms within the shielding door, energetic $\gamma$ radiations (called the 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

**Table 16.8**

<table>
<thead>
<tr>
<th>Scattering Angle (from Central Ray)</th>
<th>in-1 %</th>
<th>90°</th>
<th>180°</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>1.0</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>30°</td>
<td>0.8</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>45°</td>
<td>0.0</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>60°</td>
<td>0.0</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>90°</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>

*Scattered radiation measured at 1 m from phantom where field area is 400cm² and the phantom surface incident exposure measured in terms of field half-value thickness. Note: EPRI Guide for the Design and Calculation of Radiation Shielding for Energy up to 35 MV, International Energy Agency, Paris, France, 1989, Appendix D.*
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)

- Geiger-Müller counter (G-M tube) is much more sensitive than ionization chamber due to gas multiplication
  - 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

Radiation Monitoring Instruments

- Neutron detector is typically used independently of x-ray detector to survey outside of the treatment room
  - Detection principles:
    - In hydrogenous materials produce hydrogen recoils or 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

Personnel Monitoring

- Personnel monitoring must be used in controlled areas for occupationally exposed individuals
  - Cumulative radiation monitoring is performed with film, TLD, and OSL (optically stimulated luminescence) dosemeter badges
  - Since the badge is mostly used to monitor the whole body exposure, it should be worn on the chest or abdomen
  - Special badges may also be used to measure exposure to specific parts of the body (e.g., hands) if higher exposures are expected during particular procedures