ASTRO’s 2007 Core Physics Curriculum for Radiation Oncology Residents

Learning Objectives

1. General concept of shielding, including exposures that are “as low as reasonably achievable” (ALARA), and federal regulations.

2. Units of personnel exposure, sources of radiation, (man-made and natural), and means of calculating and measuring exposure for compliance with regulations.

3. Components of a safety program, including NRC definitions and the role of a radiation safety committee.

A. Radiation safety - Concepts and units

Radiation protection standards
Definitions for radiation protection
Quality factors [Dose equivalent]
Effective dose equivalent

Types of radiation exposure
Natural background radiation
Man-made radiation

(NCRP) #91 Recommendations on Exposure Limits
Protection regulations

ASTRO’s 2007 Core Physics Curriculum for Radiation Oncology Residents (cont’d, p.3)

NRC definitions
  Medical event
  Authorized user
  NRC administrative requirements

Radiation safety program
  Radiation safety officer
  Radiation safety committee
  NRC regulatory requirements (including security)

Personnel monitoring

B. Radiation shielding

Treatment Room Design
- Controlled/uncontrolled areas
- Types of barriers
- Factors in shielding calculations
  - Workload (W)
  - Use factor (U)
  - Occupancy factor (T)
  - Distance

Shielding calculations (including IMRT)
- Primary radiation barrier
- Scatter radiation barrier
- Leakage radiation barrier
- Neutron shielding for high-energy photon beams
Sealed source storage (Brachytherapy)
Protection equipment and surveys

Operating principles of gas-filled detectors as radiation monitoring equipment
Ionization chambers (Cutie Pie), Geiger–Mueller counters, Neutron detectors

Additional shielding design issues
- Shielding requirements for conventional simulators, CT simulators
- High dose-rate (HDR) unit shielding (linac vault vs. dedicated bunker)
- Special procedure shielding (total body irradiation [TBI])
High-Level Radiation Effects

![Graph showing the effects of radiation dose on different physiological systems. The x-axis represents days, and the y-axis represents dose in rads. Key outcomes include cerebral death, gastrointestinal death, hematopoietic death, and therapy.](image-url)
Low-Level Radiation Effects (e.g. less than 10 cGy)

- Genetic Effects – radiation-induced gene mutations, chromosome breaks, and anomalies
- Neoplastic Diseases – leukemia, thyroid tumors, skin lesions
- Effect on Growth and Development – fetus and young children
- Effect on Life span – diminishing life span or premature aging
- Cataracts – opacification of lens
High-LET vs. Low-LET

Not all dose is biologically equivalent, e.g., densely-ionizing (high-LET) $\alpha$ particles deposit dose that is more biologically effective than dose from X-rays or electron beams (low-LET)
**Equivalent Dose** $H$

Special unit used in radiation protection

Sievert (Sv)

Equivalent Dose: \( H[\text{Sv}] = D[\text{Gy}] \cdot W_R \)

\( W_R \) is Quality Factor (formerly Q)

- X-rays, electrons \( W_R = 1 \)
- Protons \( W_R = 2 \)
- Thermal neutrons \( W_R = 5 \)
- Fast neutrons \( W_R = 20 \)
- Alpha, pions \( W_R = 20 \)

Older Unit: \( H[\text{rem}] = D[\text{rad}] \cdot Q \)
Question

10 μSv is equal to _______ mrem.

A. 100
B. 10
C. 1
D. 0.1
E. 0.01
Effective Dose (E)

When irradiation is from radionuclides deposited in various tissues and organs, nonuniform or partial body exposures usually occurs.

Effective dose (E) is associated with the same probability of the occurrence of cancer and/or genetic effects as received by the whole body.
Quantities and Units for Radiation Measurement and Radiation Protection

- Exposure $X$
  - Absorbed Dose $D$
  - Equivalent Dose $H_T$
  - Effective Dose $H_E$
Effective Dose Equivalent

In addition, biological response to radiation varies based on tissue type. Therefore, dose equivalent is modified to effective dose equivalent, as defined by

\[ E = \sum W_T H_T \]

Equivalent dose equivalent

<table>
<thead>
<tr>
<th>$W_T$ = 0.01</th>
<th>$W_T$ = 0.05</th>
<th>$W_T$ = 0.12</th>
<th>$W_T$ = 0.20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone surface</td>
<td>Bladder</td>
<td>Bone marrow</td>
<td>Gonads</td>
</tr>
<tr>
<td>Skin</td>
<td>Breast</td>
<td>Colon</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Liver</td>
<td>Lung</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Esophagus</td>
<td>Stomach</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thyroid</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$W_T$ values from NCRP 116 – quoted from ICRP Publication 60 (1990)
Stochastic vs. non-stochastic

• **Stochastic effect**: probability increases with dose, but severity does not depend on magnitude of dose (“all or none” effect)

• **Non-stochastic effect**: somatic effect that increases in severity with increasing dose in an individual, owing to damage to increasing numbers of cells and tissues; also called deterministic effect.

Adapted from NCRP 91
Low-Level Radiation Effects

Stochastic effects

- Carcinogenesis
- Genetic effects
- Birth defects
  
  *Example*: leukaemogenesis

Non-stochastic, or deterministic effects

Increases in severity with increasing absorbed dose

- Fibrosis
- Organ atrophy
- Lens opacification
- Blood changes
- Decrease in sperm count
  
  *Examples*: epilation, radiation sickness, erythema
Stochastic radiation risks
BEIR VII data on A-bomb survivors

Excess relative risk of solid cancer per Sv

Radiation dose, Sv
Objectives of Radiation Protection

- **Stochastic effects**: To limit risk to a reasonable level in comparison with non-radiation risks* by adhering to dose limits below apparent practical thresholds.

- **Non-stochastic effects**: To prevent, to the extent practicable, occurrence of severe radiation-induced deterministic effect.

* ~ $10^{-4}$/y occupational

Adapted from NCRP 91
Effective Dose Equivalent Limits should conform to the “ALARA Principle”:

Ensure that total societal detriment of radiation exposures from justified activities is...

*As Low As Reasonably Achievable*

...taking into account economic and social factors

Justifications and ALARA radiation exposure limits must also ensure that individuals or groups of individuals are not subjected to levels exceeding acceptable risk.
Principles of Radiation Protection

1. Any activity involving radiation exposure must be justified on the basis that expected benefits exceed predicted cost (i.e., risk)

2. Need to reduce total radiation detriment to as low as reasonably achievable (ALARA)

3. Need to apply individual dose limits to ensure that justification and ALARA do not result in exceeding levels of acceptable risk

Adapted from NCRP 91
Radiation Protection Standards

Proposed by national and international councils and agencies

- National Council on Radiation Protection and Measurements (NCRP)
- International Commission on Radiological Protection (ICRP)
- International Atomic Energy Agency (IAEA)

None of these agencies has regulatory authority, even though IAEA is a United Nations Commission.
Regulatory Agencies

- Nuclear Regulatory Commission (NRC)
- State Department of Health
- Department of Transportation (U.S. DOT)
- FDA (radiopharmaceuticals)
Background Radiation

- **Natural**: 82%
- **Man-Made**: 18%

**Contributions**: 
- Terrestrial: 8%
- Cosmic: 8%
- Internal: 11%
- Medical X-rays: 11%
- Nuclear Medicine: 4%
- Consumer Products: 3%
- Other (<1%): 
  - Occupational: 0.3%
  - Fallout: <0.3%
  - Nuclear Fuel Cycle: 0.1%
  - Miscellaneous: 0.1%
- Radon: 54%
Background Radiation – Effective Dose

• **Natural Background**
  Excluding radon: 100 mrem/year
  Including radon: 330 mrem/year

• **Medical**
  30 mrem (chest film)
  300 mrem (abdominal)
Question

The largest contribution to the radiation exposure of the U.S. population as a whole is from:

A. Radon in the home.
B. Medical x-rays.
C. Nuclear medicine procedures.
D. The nuclear power industry.
The annual average natural background radiation dose to members of the public in the United States, excluding radon, is approximately _____ mrem

A. 10
B. 50
C. 100
D. 200
E. 400
# Effective Dose Equivalent Risk Estimates

Nominal lifetime probability coefficients for stochastic effects

<table>
<thead>
<tr>
<th>Exposed Population</th>
<th>Fatal Cancer</th>
<th>Nonfatal Cancer</th>
<th>Severe genetic Effects</th>
<th>Total Detriment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adult Workers</td>
<td>$10^{-2}\text{ Sv}^{-1}$</td>
<td>$10^{-2}\text{ Sv}^{-1}$</td>
<td>$10^{-2}\text{ Sv}^{-1}$</td>
<td>5.6</td>
</tr>
<tr>
<td>Whole Population</td>
<td>5.0</td>
<td>1.0</td>
<td>1.3</td>
<td>7.3</td>
</tr>
</tbody>
</table>

Effective Dose Equivalent Limits

Summary of Annual Occupational and Public Dose Limits

A. Occupational exposures

1. Effective dose limits
   a) Annual 50 mSv (5 rem)
   b) Cumulative 10 mSv x age

2. Equivalent dose annual limits for tissues and organs
   a) lens of eye 150 mSv (15 rem)
   b) skin, hands and feet 500 mSv (50 rem)

B. Public exposures (annual)

1. Continuous or frequent 1 mSv (100 mrem)
2. Infrequent 5 mSv (500 mrem)
3. For tissues and organs
   a) lens of eye 15 mSv (1.5 rem)
   b) skin, hands and feet 50 mSv (5 rem)

C. Embryo-fetus (monthly)

0.5 mSv (50 mrem)

Dose Limits - Patient’s Relatives/Visitors

• The dose limits for members of the public do not apply. However,
  – the dose must be constrained so that it is unlikely that an effective dose of 5 mSv will be exceeded during the diagnostic procedure or treatment
  – for children, the constraint should be 1 mSv
Effective Dose Equivalent Limits

Dose Limits for Pregnant Women

Annual Maximum Permissible Dose

50 mSv          5 rem          Radiation Worker
5 mSv *     0.5 rem          Pregnant Radiation Worker
1 mSv          0.1 rem        General Public

Effective Dose Equivalent Limits

Negligible Individual Risk Level [NIRL] (NCRP 91)

Negligible Individual Dose [NID] (NCRP 116)

“a level of average annual excess risk of fatal health effects attributable to irradiation, below which further effort to reduce radiation exposure to the individual is unwarranted”

NID is 0.01 mSv = 1mrem

Current estimate of lifetime risk detriment from NID is $7 \times 10^{-7}$
Structural Shielding Design

Three Principles of Radiation Protection

• Distance
• Time
• Shielding
Hazard Reduction Methods

- Time
- Shielding
- Distance
Shielding

- Use of high atomic number and high density materials e.g., lead, concrete, steel

- Normal building materials e.g., brick, mortar, wallboard, can be either very poor shielding materials, or have quite variable and very unpredictable properties
**Distance**

*Inverse square law*

– radiation from a point source decreases by the square of the distance

*Dose is proportional to $1/((\text{distance})^2)$*

i.e., twice the distance gives 1/4 the dose, but half the distance gives 4 times the dose
Structural Shielding Design

NCRP Reports 49 & 51, NCRP 151 update, Guidelines:

*Controlled* (Radiation Workers - Area supervised by RSO)

Permissible Limit: \( P = 100 \text{ mrem (1 mSv)} / \text{wk} \)

*Noncontrolled Areas* (General Public)

Permissible Limit: \( P = 10 \text{ mrem (0.1 mSv)} / \text{wk} \)

frequent exposure \( P = 2 \text{ mrem (0.02 mSv)} / \text{wk} \)
Structural Shielding Design

Exposure Rate

“WUT” factor:

\[ X = \frac{W \cdot U \cdot T}{(d/d_{ref})^2} \cdot B \]

Workload (W):

10,000 to 100,000 MU/wk

Use Factor (U):

.25 for isocentric units

Occupancy Factor (T):

1, 1/4, 1/8, 1/16

Distance factor:

\[ \frac{d_{ref}^2}{d^2} = \]

\( d \) is distance from radiation source to shielded area.
Radiation Shielding Requirements

**Controlled areas** (supervised by Radiation Safety Office)
- Maximum dose equivalent: 1.0 mSv/week
- 50.0 mSv/year

**Noncontrolled areas** (general public)
- Maximum dose equivalent: 0.1 mSv/week
- 5.0 mSv/year

Radiation shielding must be designed to reduce doses to these limits

- Primary radiation, scattered radiation, leakage radiation
Primary Radiation Barrier

Maximum dose

Distance to protected area

\[ B_x = \frac{Pd_{pri}^2}{WUT} \]

Effective dose with no shielding at \( d_{ref} \)

Required transmission factor
Broad-beam transmission

Broad-beam transmission, NCRP 51

Broad-beam transmission, MV range NCRP 51
Leakage Radiation Barrier

\[ B_L = \frac{Pd_L^2}{0.001WT} \]

0.1% leakage limit through source housing for megavoltage units

Bigger concern than scattered radiation (higher energy)
Door Shielding

Use maze room layout. 
Repeatedly apply:

\[ B_s = \frac{P}{\alpha WT} \cdot \frac{400}{F} \cdot \frac{d_{sca}^2}{d_{sec}^2} \]

\( (d_m) \quad (L) \)

to trace photons from source to the door over multiple scattering interactions.

NCRP 151. Khan, Eq. (16.6)

\( F: \) Area of the beam in the plane of the scatterer (cm\(^2\))
\( \alpha: \) Scatter fraction; \((\theta, E)\)
# Scattered radiation

Ratio, $\alpha$, of Scattered to Incident Exposure\(^a\), NCRP 151

<table>
<thead>
<tr>
<th>Scattering Angle (From Central Ray)</th>
<th>6 MV</th>
<th>10 MV</th>
<th>18 MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>$1.0 \times 10^{-2}$</td>
<td>$1.7 \times 10^{-2}$</td>
<td>$1.4 \times 10^{-2}$</td>
</tr>
<tr>
<td>30°</td>
<td>$2.8 \times 10^{-3}$</td>
<td>$3.2 \times 10^{-3}$</td>
<td>$2.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>45°</td>
<td>$1.4 \times 10^{-3}$</td>
<td>$1.3 \times 10^{-3}$</td>
<td>$8.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>60°</td>
<td>$8.2 \times 10^{-4}$</td>
<td>$7.6 \times 10^{-4}$</td>
<td>$4.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>90°</td>
<td>$4.2 \times 10^{-4}$</td>
<td>$3.8 \times 10^{-4}$</td>
<td>$1.9 \times 10^{-4}$</td>
</tr>
<tr>
<td>135°</td>
<td>$3.0 \times 10^{-4}$</td>
<td>$3.0 \times 10^{-4}$</td>
<td>$1.2 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

\(^a\)Scattered radiation measured at 1 m from phantom when field area is 400 cm\(^2\) at the phantom surface; incident exposure measured at center of field but without phantom.
Neutron Shielding

1. 10 MV and higher energy X-ray beams are contaminated with neutrons produced by photon/electron interactions within the accelerator head and/or shielding. These neutrons contribute dose as well as producing $\gamma$-rays by neutron capture when interacting with matter.

2. Primary and secondary wall shielding are sufficient to reduce neutron dose. Depending on the maze configuration, additional door shielding is sometimes required.

3. A few inches of a hydrogenous material (polyethylene) can be used to capture neutrons. In general however it is preferable to reduce scattered neutron flux than to shield against neutrons and capture-produced $\gamma$-rays.
Radiation Surveys

State requires qualified expert to perform survey before operation of a linear accelerator may begin.

**Equipment**

- Use film to locate radiation leaks through source housing
- Use ionization chamber to measure dose at 1 m from source in various directions of possible leakage.

**Area**

- Use ionization chamber to measure dose outside treatment room with phantom in treatment position.
- Incorporate estimates of W, U, T
Radiation Monitoring Instruments

Ionization Chambers

Used for low-level X-ray measurements. A photo appears in Fig. 16.4 of Khan

Large ionization chamber volume (~ 500 ml.). Called a “Cutie Pie”. Accurate even at low exposure rates (~0.1 mR/h = 1.0 µSv/h)

Calibrated using a γ-ray source of known activity.
Radiation Monitoring Instruments

Geiger-Müller Counters

Ionization chamber operated in Geiger region of the chamber response curve. Therefore a single event creates an “avalanche” of ionizations.

Useful for qualitative measurement of very low levels of radiation.
Radiation Monitoring Instruments

**Neutron Counters**

Activation detectors: contain materials e.g., gold foils that become radioactive upon neutron bombardment. Examples – $^{31}\text{P}(n,p)^{31}\text{Si}$, $^{31}\text{P}(n,\gamma)^{32}\text{P}$

Moderated activation detectors: use hydrogenous material to convert neutrons to H atoms or protons. Counter can be calibrated as a remmeter, including quality factor $W_R$ (ex. see photo).

Outside the treatment room, one typically uses two detectors: one sensitive to photons, and one to both photons and neutrons.
NRC Regulations; State Regulations for Radiation-Producing Machines [Linear Accelerators]

Teletherapy

- Radiation surveys
- Safety Instructions
- Dosimetry Equipment
- Calibration before Use
- Periodic spot checks
- Maintenance
- Five-year Inspection
General Safety Requirements

• Clear Indicators shall be provided at the control console and in the treatment room to show when the equipment is in operation.

• Have at least two independent 'fail to safety' systems for terminating the irradiation. These could be:
  – two independent integrating in-beam dosimeters
  – two independent timers
  – integrating dosemeter and timer

• Each system shall be capable of terminating the exposure.
Radioactive Materials License

NRC Regulations

License required for use of by-product material
The **USNRC** is a federal agency that controls use of all reactor-produced materials. They enact regulations recommended by the **International Commission on Radiological Protection (ICRP)**, the **National Council on Radiation Protection and Measurements (NCRP)**, and the **American Association of Physicists in Medicine (AAPM)**.

A license from the NRC (or the State, if in an “Agreement State”) is required for use of radioactive materials. A license is awarded after review of a substantial application.
Administrative Requirements

• ALARA Program
• Radiation Safety Officer (RSO)
• Radiation Safety Committee
• Quality Management Program
Technical Requirements

- Dose calibrator
- **Survey Instruments**
  - Survey program
  - Regular calibration of instruments
- **Source storage**
  - Appropriate shielding
  - Leak test program
- Isolation of radioactive patients
- Radiation safety instructions
Brachytherapy Source Storage

- Lockable storage room with signage
- Lead safes
- Sinks with filter or trap to prevent loss of sources
- Lead-lined carts for transport of sources
Brachytherapy Leak Testing

Periodic testing required by state regulations

Wipe tests measured in scintillation counter

Removable activity must be less than $0.005 \, \mu\text{Ci}$
PET Tracer Shielding and Storage

Need shielding for workers during:
1. Dose transport
2. Dose preparation and calibration
3. Injection and patient management

Need shielding of room to minimize:
dose to personnel outside hot lab

Need to account for radioactive waste (sharps, gloves)
Personnel Monitoring

Film Badges
TLD badges
  - Chest
  - Hands

Pocket dosimeters
  More frequent monitoring during a particular procedure
General Safety Requirements

• Warning Signals and Signs

RADIATION
DO NOT ENTER
When
RED LIGHT
is on.
# Shipping Labels

<table>
<thead>
<tr>
<th>Transport Index (T.I.) [D.R. @ 1m]</th>
<th>Maximum exposure rate on container surface</th>
<th>Label Category</th>
</tr>
</thead>
</table>
| 0                                 | 0 – 5 µSv/h  
5 µSv/h – 0.5 mSv/h  
0.5 mSv/h – 2 mSv/h  
2 mSv/h – 10 mSv/h | White - I |
| 0 - 1                             | 0 – 5 µSv/h  
5 µSv/h – 0.5 mSv/h  
0.5 mSv/h – 2 mSv/h  
2 mSv/h – 10 mSv/h | Yellow - II |
| 2 - 10                            | 0 – 5 µSv/h  
5 µSv/h – 0.5 mSv/h  
0.5 mSv/h – 2 mSv/h  
2 mSv/h – 10 mSv/h | Yellow - III |
| >10                               | 0 – 5 µSv/h  
5 µSv/h – 0.5 mSv/h  
0.5 mSv/h – 2 mSv/h  
2 mSv/h – 10 mSv/h | Yellow - III Exclusive Provisions |
## Radiation Warning Signs

<table>
<thead>
<tr>
<th>Condition</th>
<th>Posting</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mrem (0.05 mSv) in 1 hour at 30 cm from the source or shield surface</td>
<td>Caution, Radiation Area</td>
</tr>
<tr>
<td>100 mrem (1 mSv) in 1 hour at 30 cm from the source or shield surface</td>
<td>Caution, High Radiation Area</td>
</tr>
<tr>
<td>500 rads (5 Gy) in 1 hour at 1 m from the source or shield</td>
<td>Grave Danger, Very High Radiation Area</td>
</tr>
<tr>
<td>Air concentration exceeding the Derived Air Concentration</td>
<td>Caution, Airborne Radioactivity Area</td>
</tr>
<tr>
<td>Use or storage of ten times the Quantities of Licensed Material Requiring Labelling</td>
<td>Caution, Radioactive Material</td>
</tr>
</tbody>
</table>
References


Radiation Protection

Gary Luxton, Ph.D. Sept. 14, 2009