Radiation Protection: Are We Doing Enough to Protect our Patients and Staff?

Proton Beam Therapy: Lecture #4
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Proton Therapy Course, 2008-03-25, Houston

Objectives – Lecture 4
- Review the basics of radiation protection
  - Guiding principles
  - Methods of calculation and measurement
  - Examples
- Review shielding of the equipment rooms
- Review shielding of the treatment head
- Discuss exposures to the patient to stray radiation
- Provide conceptual framework and methods to address the question: Are we doing enough?

Review: Deterministic Effects
- Nature of Deterministic Effects
  - Effect increases in severity with increasing dose above a threshold
  - Effect usually occurs after large doses
  - Effects may occur within hours or days, or months or years after exposure
- Examples
  - Skin damage
  - Lens opacification
  - Fibrosis
  - Sterility or reduction in fertility

After NCRP Report 116, 1993
Review: Stochastic Effects

• Probability of the effect occurring is defined as one in which the probability of the effect occurring increases continuously with increasing absorbed dose
• Severity of effect in an individual is independent of absorbed dose
• “All or nothing” effect
• Principal effect after exposure to low doses
• Examples
  – Cancer
  – Genetic effects

Goals of Radiation Protection

• Prevent occurrence of serious radiation-induced conditions in exposed persons. These include acute and chronic deterministic effects.
• Reduce stochastic effects in exposed persons to a degree that is acceptable in relation to the benefits to the individual and society from the activities that generate such exposure.

Specific Objectives

• To prevent the occurrence of clinical significant radiation induced deterministic effects by adhering to dose limits that are below the apparent threshold levels.
• To limit the risk of stochastic effects, cancer and genetic effects, to a reasonable level in relation to societal needs, values, benefits gained and economic factors.
Methods

- Radiation safety training
- Time, distance, shielding
- Administrative controls on use, occupancy
- Interlocks, annunciators, and other safety systems
- Radiation survey measurements
- Area monitoring of radiation levels (independent from treatment control system)
- Personnel dosimetry
- Oversight by radiation safety committee
- As low as reasonably achievable (ALARA)
- And so on ...

For Context: A Breakdown of “Average” Exposure

Natural background ~82% (from BEIR VII 2006)
Total is about 3.6 mSv/y (360 mrem/y) from NCRP 93.

Radiation Should be a Safe Industry.
Risk of Fatal Ca Should ~10^{-4}/y or less

<table>
<thead>
<tr>
<th></th>
<th>[10^{-4}] (v/yr(^2))</th>
<th>[10^{-4}] (v/yr(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>All groups</td>
<td>1.42</td>
<td>0.94</td>
</tr>
<tr>
<td>Trode</td>
<td>6.64</td>
<td>0.44</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>6.08</td>
<td>0.46</td>
</tr>
<tr>
<td>Station</td>
<td>0.40</td>
<td>0.36</td>
</tr>
<tr>
<td>Government</td>
<td>0.11</td>
<td>0.06</td>
</tr>
<tr>
<td>Transport and public utilities</td>
<td>3.13</td>
<td>2.59</td>
</tr>
<tr>
<td>Construction</td>
<td>9.88</td>
<td>2.18</td>
</tr>
<tr>
<td>Health and safety</td>
<td>4.23</td>
<td>4.30</td>
</tr>
<tr>
<td>Agriculture</td>
<td>5.03</td>
<td>4.60</td>
</tr>
</tbody>
</table>

References:
1. NCRP Report 116, 1993
2. Lawrence Berkeley National Laboratory, 1991
Formalism to Compute Risk

- Effective dose
  - Sums over all tissues and organs (T)
  - \( w_T \) is the tissue weighting factor
  \[
  E = \sum_T H_T \cdot w_T
  \]

- Equivalent dose
  - Sums over all radiation (\( R \)) types
  - \( w_R \) is the radiation weighting factor
  \[
  H_T = \sum_R w_R \cdot D_T
  \]

Formalism to Compute Risk

- Absorbed dose in organ or tissue \( T \) of mass \( m \)
  \[
  D_T = \frac{1}{m} \int_D dm
  \]

  - What is interesting about \( D_T \)?
    - Purely physics, does not take into account any biology
    - Measurable and calculable

  See Homework Problem 4.1

Formalism to Compute Risk

- Radiation weighting factor \( w_R \) (\( \sim \) RBE)
  \[
  H_T = \sum_R w_R \cdot D_T
  \]

  - For neutrons as a function of neutron energy
    \[
    w_R = 2.5 \left[ 2 \cdot e^{-4E_n} + 6 \cdot e^{-0.6(E_n)^{1/2}} + e^{-0.6(E_n)^{1/2}/2} \right]
    \]

  - What is interesting about \( w_R \)?
    - Takes into account biology, not physics
    - Not directly measurable or calculable
    - Values represent a useful approximation, not an exact relation
Tissue Weighting Factors

### Table 2. Tissue weighting factors

<table>
<thead>
<tr>
<th>Tissue or organ</th>
<th>Tissue weighting factor, wT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connective tissue</td>
<td>0.20</td>
</tr>
<tr>
<td>Bone marrow (red)</td>
<td>0.12</td>
</tr>
<tr>
<td>Cerebrospinal fluid</td>
<td>0.12</td>
</tr>
<tr>
<td>Lung</td>
<td>0.12</td>
</tr>
<tr>
<td>Sclera</td>
<td>0.12</td>
</tr>
<tr>
<td>Skin</td>
<td>0.05</td>
</tr>
<tr>
<td>Breast</td>
<td>0.05</td>
</tr>
<tr>
<td>Liver</td>
<td>0.05</td>
</tr>
<tr>
<td>Osseous</td>
<td>0.05</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.05</td>
</tr>
<tr>
<td>Skin</td>
<td>0.05</td>
</tr>
<tr>
<td>Other soft tissue</td>
<td>0.01</td>
</tr>
<tr>
<td>Remainder</td>
<td>0.05</td>
</tr>
</tbody>
</table>

From ICRP Publication 60 (1990)

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Radiation Weighting Factors

### Table 1. Comparison of existing wR values and those proposed in the ICRP

<table>
<thead>
<tr>
<th>Type of incident radiation</th>
<th>Radiation weighting factor (wR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons, all energies</td>
<td>1</td>
</tr>
<tr>
<td>Protons, (light)</td>
<td>1</td>
</tr>
<tr>
<td>Protons, (heavy)</td>
<td>1</td>
</tr>
<tr>
<td>Neutrons, energy &lt; 1 MeV</td>
<td>1</td>
</tr>
<tr>
<td>Neutrons, energy 1-10 MeV</td>
<td>1</td>
</tr>
<tr>
<td>Neutrons, energy &gt; 10 MeV</td>
<td>1</td>
</tr>
<tr>
<td>Alpha particles, fission fragments, and heavy ions</td>
<td>20</td>
</tr>
</tbody>
</table>

* Use the proposed wR for energies above 0.1 MeV.

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Neutron Radiation Weighting Factor

![Graph of Neutron Radiation Weighting Factor](image)

**ICRP Publication 92 (2003)**
Where Do $w_R$ and $w_T$ Come From?

- An end user should use recommended values
  - For regulatory compliance, values generally taken from state regulations.
  - For research, values typically taken from an advisory body (ICRP, NCRP, and the BEIR Committee).

- The recommended values were derived based largely from studies of survivors of the atomic bomb, and occupational and medical exposure.

What Are Exposure Limits to People?

- Occupational exposures
  - Annual: $E < 50$ mSv
  - Cumulative: $E_{cum} < (10 \text{ mSv}) \times \text{age in years}$
  - Lens of eye: < 150 mSv/y
  - Skin, hands, feet: < 500 mSv/y
- Public (one tenth of occupational limits)
- Embryo and Fetus: < 0.5 mSv/month
- Negligible Individual Dose: < 0.01 mSv/y

Condensed from NCRP Report 116, 1993. Check your local regs!
What Are Limits in an Area?

- **Uncontrolled Area**
  - $E < 500 \text{ mSv/y}$
  - $< 0.02 \text{ mSv in any one hour}$
- **Designation of Radiation Areas**
  - “Radiation Area”: $> 0.05 \text{ mSv/h}$
  - “High Radiation Area”: $> 1 \text{ mSv/h}$
  - “Very High Radiation Area”: $> 5 \text{ Sv/h}$

Condensed from NCRP Report 116, 1993

See Homework Problem 4.2

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2008: Many New Centers ...

Hospital (existing)  Research complex (under construction)

Typical setting for contemporary proton therapy facility

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Shielding of Equipment Rooms

- Usually use ordinary reinforced concrete
- Sometimes use soil (subgrade or burms)
- Occasionally use high-density concrete if space is constrained. Expensive!
Common Design Assumptions

- Vault shielding is determined by neutrons, not by protons or photons
- Therapeutic protons should never be incident on the primary shielding barriers
- Workload, Use Factors, and Occupancy Factors are conceptually analogous (but numerically different) to those for linac-based photon therapy (See NCRP Report 151, 2005)
Concrete Composition

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight</th>
<th>Volume</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>9.2</td>
<td>8.5</td>
<td>0.99</td>
</tr>
<tr>
<td>Lime</td>
<td>20.1</td>
<td>10.1</td>
<td>2.35</td>
</tr>
<tr>
<td>Sand</td>
<td>19.7</td>
<td>19.7</td>
<td>1.70</td>
</tr>
<tr>
<td>aggregate</td>
<td>19.3</td>
<td>19.3</td>
<td>2.75</td>
</tr>
<tr>
<td>Total</td>
<td>74.9</td>
<td>74.3</td>
<td>1.76</td>
</tr>
</tbody>
</table>

From M. F. Kaplan, 1989

Hydrogen content and mass density are particularly important!

Shielding Design Challenges

Complexity
- Many sources and barriers
- Radiation transport physics
- Regulatory requirements

Uncertainty
- Facility usage patterns
- Equipment performance
- Basic data

Neutron Shielding Calculations

Neutron Source
- Neutron Shield
- Dose Calc Point
Burton Moyer
Father of Accelerator Health Physics

From Paterson and Thomas, Eds., 1994

Moyer Model for Slab Shielding

Production Angular Distribution
Attenuation, Inverse Square

See Homework Problem 4.3

Monte Carlo, To the Rescue

Stanisław Marcin Ulam in the 1950s [1].
John von Neuman in the 1940s [2].
### Comparison of Methods

<table>
<thead>
<tr>
<th>$H_m$</th>
<th>$H_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>1.1</td>
</tr>
<tr>
<td>0.9</td>
<td>1.3</td>
</tr>
<tr>
<td>100</td>
<td>7.1</td>
</tr>
</tbody>
</table>


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### IBA / NPTC Cyclotron

- **Cyclotron**: 235 MeV, 300 nA
- **Extraction Channel**
- **Radial Probe**
- **Energy Degrader Wheel**
Real World Problem: Post-Construction Shield Modifications

See Homework Problem 4.4

How to Measure Neutron Dose Equivalent

Portable: Surveys  Fixed: Area Monitoring

Area Monitoring System

See Newhauser et al Rad Prot Dosim 115 149-153 (2005)
Now for the hard question, “Are we doing enough to protect our patients?”
Is There a Problem with Radiotherapy?

In a study published in the New England Journal of Medicine in 2006, which looked at outcomes in more than 10,000 survivors, CCSS researchers found that almost two-thirds of patients reported at least one chronic health problem, one-quarter had a severe condition, and one-third reported four or more chronic health problems. Late effects observed most frequently in this study were second cancers, cardiovascular disease, kidney disease, musculoskeletal conditions, and endocrine abnormalities. The risk of developing a health problem related to cancer treatment in childhood increased over time.

Women face higher risks than men for late effects including breast cancer, cognitive dysfunction, heart disease, and hypothyroidism. Other factors influencing late effects include age at diagnosis, type of cancer, and type of treatment received. Radiation treatment, especially to the brain— and, in women, the chest— carries a high risk of long-term effects.

“Both the magnitude and the diversity of the long-term health effects have been striking,” says CCSS principal investigator Dr. Les Robison of St. Jude Children’s Research Hospital in Memphis. “At 30 years after their diagnosis, more than 70 percent of childhood cancer survivors have a late-effect chronic health condition.”

From NCI CaBk, March 18, 2008 • Volume 5 / Number 6

Is There a Problem in Diagnostic?

“There may be disagreement within the medical community about the accuracy of the risk models ... These arguments will not be settled in the near term. However, one fact is indisputable: We must continue our efforts to do a better job of reducing radiation dose to children if and when they need a CT scan.”


Is Photon Therapy the Problem?

<table>
<thead>
<tr>
<th></th>
<th>Photons (6 MV, 1 field)</th>
<th>Photon IMRT (15 MV, 9 field)</th>
<th>Protons (SOBP, 1 field)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd ca [%/y]:</td>
<td>0.8</td>
<td>0.4</td>
<td>0.05</td>
</tr>
<tr>
<td>Rel. risk:</td>
<td>15</td>
<td>9</td>
<td>1</td>
</tr>
</tbody>
</table>

Goske et al., IJROBP 2002; Mirabel et al., IJROBP 2003.
Is Proton Therapy the Problem?

Hall (2007) recently posed the important question, “Does it make any sense to spend over $100 million on a proton facility, with the aim to reduce doses to normal tissues, and then to bathe the patient with a total body dose of neutrons, the RBE of which is poorly known, when the technology to avoid it is available and already in use elsewhere?” In the same article, Hall opined that “Protons are a major step forward for radiotherapy, but neutrons are bad news and must be minimized by the use of spot scanning techniques.”

See Hall, Technol in Ca Res Treat 2007;6:31-34

Are Neutrons the Problem?

Fontenot et al, Phys Med Biol 2008

Are External Stray Neutrons a Problem?

Fontenot et al, Phys Med Biol 2008

Figure 2: Equivalent dose per therapeutic absorbed dose (H/ED) in selected organs (arranged in an order of increasing distance from the source) for the simulated prostate treatment, including contributions from stray radiation produced inside the anode collimator and inside the patient (phantom).
For Prostate Therapy, What Do We Know With Confidence Thus Far?

“Our results revealed that a two-field 76 Gy passively scattered proton treatment delivers an effective dose of only 415 mSv due to stray radiation. This corresponds to a lifetime risk for developing a fatal second malignancy from stray radiation exposure of only 2%, assuming that the population-averaged risk coefficient of 5% per Sv (ICRP 1991) is applicable. However, we cannot exclude the possibility that the true risk coefficient for a cancer patient is substantially larger and clinically significant. For example, the lifetime risk would approach 20% if the assumed neutron radiation weighting factor were 100, as suggested by Kellner et al (2006).”

See Homework Problem 4.5

W. Newhauser, Proton Therapy Course, 2008-03-25

Protons versus Photons

Figure 4. R(20) as a function of lateral distance (along the patient axis) from the source from this work compared to IMRT values collected from Lee et al (2007) and Hong et al (2006).

W. Newhauser, Proton Therapy Course, 2008-03-25

Are There Ways to Reduce Stray Radiation?

• Brenner and Hall (2008) wrote "... it would be highly desirable to optimize ... passively modulated proton beamlines, in order to reduce the ... neutron-related second cancer risk."
• Taddei et al (2008) recently showed that large improvements are possible; for a typical proton treatment for prostate cancer, an optimized collimation design reduced the neutron exposures from 567 to 355 mSv, which is only 109 mSv more than predicted for a scanned beam treatment.

W. Newhauser, Proton Therapy Course, 2008-03-25
Are There Ways to Reduce Stray Radiation?

From Taddei et al, Phys Med Biol (in press)

The scope of this study was to investigate whether simple methods could be used to reduce stray radiation exposure for patients undergoing proton therapy for prostate cancer. The results of this study suggest that such modifications are feasible and effective. In addition, it appears likely that the effectiveness and compactness of these enhancements may be substantially optimized relative to the nozzle designs unique to each proton therapy facility.

Summary of Key Points

1) Shielding of proton therapy facilities is predominated by high energy neutrons

2) Important design parameters include concrete composition and density, use factors, workload, and occupancy factors.

3) Are we doing enough to protect our patients?
   1) Much recent progress in understanding the physics that govern these risks.
   2) The existence of a problem is controversial, as are solutions.
   3) Available data suggest protons carry less risk than photons for risk of 2nd Ca.
   4) More and better risk assessments are needed to resolve this conclusively.

End of Lecture #3
Homework Problems on Radiation Protection of Patients and Staff

See Homework Problems 4.1 – 4.5

Suggested Reading

General References

