LINAC RADIATION MONITORING AND SURVEYS: INSTRUMENTS AND METHODS

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“Doing the right thing, doing it right”

Impact of Pulsed Operation on Linac Monitoring

- Repetition rates vary from ~ 100 to 400 pulses per second
- Pulse widths range from ~ 1 to 10 microseconds
- Duty factor (DF) = pulse width x repetition rate
  - For e.g., DF = 100 pulses/s x 1 x 10^4 s = 1 x 10^{−4}
- Very small DF imposes severe restrictions on instruments
- Peak Intensity = Average Intensity/DF
  - I_{peak} = 10,000 x I_{avr}

Impact of Pulsed Operation on Instrument Response

- Intense photon pulse overwhelms active detector that detects particles electronically
- Instruments with long dead times (GM tubes and proportional counters) saturate and count repetition rate
- Scintillation survey meters may become non-linear at high dose rates because of PM tubes
- Ionization chambers are less influenced but must be operated with adequate voltage to overcome recombination losses
Photon Monitoring Outside Room

- Use ionization chamber with rate and integrate modes
- Integrate mode is handy for measurements outside maze
- Range up to 50 mGy/h
- Several commercial instruments are available

Photon Monitioring

NIMBY = Neutrons In My Back Yard

- Photoneutron production occurs at photon energies above ~ 6.2 MeV
- Monitor the neutrons
- Neutron monitoring discussed in Appendix C, NCRP 151

Photoneutron Production In Accelerator Head

- Photoneutrons produced by interaction of photon beam with accelerator components
- Produced mainly in the target, primary collimator, flattener and jaws/collimators, etc.
- Typical materials are copper, iron, gold, lead and tungsten
- Neutron production in electron mode is lower than in photon mode
  - Direct production of neutrons by electrons is at least 2 orders of magnitude lower
  - Lower electron current

Photoneutron Production

- Photoneutrons consist of direct emission and evaporation neutrons
- **Direct Emission**
  - Average energy of direct neutrons is ~ few MeV
  - Angular distribution of direct neutrons follows a \( \sin^2 \theta \) distribution
  - Contributes about 10-20% of neutron yield for bremsstrahlung with upper energies of 15 to 30 MV
Photoneutron Production

- **Evaporation Neutrons**
  - Dominant process in heavy nuclei
  - Emitted isotropically
  - Spectral distribution is independent of photon energy for energies that are a few MeV above neutron production threshold
  - Average energy is ~ 1-2 MeV
  - Evaporation spectra closely resemble fission spectra

Photoneutron Spectra Inside Primary Beam

- Simulations in patient plane with Monte Carlo Code MCNP-GN
- Field size = 10 cm x 10 cm
- Isocenter = 100 cm from target
- Neutron fluence includes room scattered neutrons and direct neutrons from accelerator head

Integral Photoneutron Spectra for 15 MeV Electrons Striking a Tungsten Target (NCRP 79)

Photoneutron Spectrum

- Photoneutron spectrum from accelerator head resembles a fission spectrum
- Spectrum changes after penetration through head shielding
- Since linac is in concrete vault, room scattered neutrons will further soften the spectrum
- Spectrum outside the concrete shielding resembles that of a heavily shielded fission spectrum
  - Average energy is significantly less than inside room
  - Most neutrons are < 0.5 MeV in energy
## Neutron Energy Classification

- **Thermal:** $E_n = 0.025$ eV at $20^\circ$C
- Typically $E_n \leq 0.5$ eV (Cd resonance)
- Intermediate: $0.5 \text{ eV} < E_n \leq 10$ keV
- Fast: $E_n > 10$ keV
- Epithermal $E_n > 0.5$ eV

For therapy linacs neutron spectrum can be divided into two energy regions:
- Thermal (0 – 0.5 eV)
- Epithermal (> 0.5 eV)

## Neutron Detector Calibration

- **Calibration Sources**
  - PuBe, $E_{av} = 4.2$ MeV, AmBe, $E_{av} = 4.5$ MeV
  - $^{252}$Cf, $E_{av} = 2.2$ MeV
  - PuF, $E_{av} = 0.9$ MeV, PuLi, $E_{av} = 0.5$ MeV

- Use of PuBe and AmBe can lead to systematic uncertainties because of higher energies
- Spectrum of fission neutrons from $^{252}$Cf is in general similar to a typical photoneutron spectrum
- Detector calibrated with $^{252}$Cf may be adequate for neutrons in primary beam
- Spectrum outside primary beam and outside room shielding is a heavily shielded photoneutron spectrum
- Thus assumption of fission spectrum may lead to errors in the above case

## Neutron Monitoring

- Measurement of fluence (n cm$^{-2}$)
- Measurement of dose equivalent (ambient dose equivalent) or dose equivalent rate
- Measurement of neutron spectrum

## Determination of Neutron Dose Equivalent (H)

- Radiation protection quantities defined in human body
- Not amenable to measurement
- ICRU developed operational quantities (ambient, directional, personal dose equivalent)
- Numerical value determined
  - Measuring a physical quantity, fluence ($\Phi(E)$) which characterizes field
  - Converting to dose equivalent using conversion coefficients ($h(E)$)
  - $H^*(10) = \int h(E) \Phi(E) \, dE$

Conversion Coefficients

- Higher neutron energies encountered at particle therapy facilities
  - Proton ~ 250 MeV
  - Carbon Ions ~ 1 GeV

Neutron Spectra From Carbon Ions On Tissue

Spectra at 0-10° extends to ~1 GeV
Spectra at 80-100° extends to ~400 MeV

Difficulties With Neutron Monitoring Inside Treatment Room

- Photon interference from primary and leakage photons
  - Photon fluence inside beam is 1000 - 4000 x higher than neutron fluence
  - Photon fluence outside beam is 10 - 100 x higher than neutron fluence
  - Intense photon pulse overwhelms active detector
  - Photon pulse pile up
  - Photon induced responses in passive detectors from primary beam

Difficulties With Neutron Monitoring Inside Treatment Room

- For moderated detectors measured neutron readings are higher than the repetition rate because
  - Scattered radiation in room
  - Neutron moderation time allows an event to be detected after pulse has ended
- Neutron detection spread over decades of energy (0.025 eV – several MeV)
  - No single detector can accurately measure fluence or dose equivalent over entire range
- Only passive detectors can be used, except at the outer maze area
**Neutron Monitoring Outside Room**

- Neutron pulse spread over several 100 µs because of moderation
- Neutron spectrum resembles heavily shielded fission source—many low energy neutrons (100’s of keV and less)
- Most neutrons have energies less than 0.5 MeV outside well shielded room
- Average neutron energy at outer maze area ~ 100 keV
- Active and passive detectors can be used

**Neutron Monitoring Techniques**

- **Active**
  - Relies on slowing down or moderating fast neutrons until they reach thermal energies
  - Thermal detector used to detect thermal neutrons
  - Instrument is designed to measure dose equivalent (rem-meters) or fluence (fluence meters)
  - Can be used for measurements outside room
- **Passive**
  - Relies on similar principle or direct interactions
  - Method of choice for measurements inside room

**Thermal Detectors**

1. **BF3 Proportional Counter**
   - $^{10}$B ($n_{th}$, α)$^7$Li, $E_Q = 2.31$ MeV, $\sigma = 3840$ barns
   - α and recoil $^7$Li nucleus produce large pulse, orders of magnitude higher than photon pulse
   - Excellent photon rejection, low cost
   - Most commonly used outside shielded therapy rooms

2. **$^3$He Proportional Counter**
   - $^3$He($n_{th}$, p)$^3$H, $E_Q = 0.76$ MeV, $\sigma = 5330$ barns
   - More sensitive, more stable, much more expensive

3. **LiI(Eu) scintillator:**
   - $^7$Li(n$_{th}$, α)$^4$He, $E_Q = 4.78$ MeV, $\sigma = 940$ barns
   - Very high sensitivity, poor photon rejection
   - Difficult to use in mixed photon-neutron fields

\(E_Q = \) kinetic energy released
\(\sigma = \) thermal neutron cross section
Cross sections drop roughly as \(E_Q^{1/2}\)
Detectors without moderators are sensitive only to thermal neutrons
**Active Detectors**

- Rem-meters (outside room, and outer maze entrance, NOT inside room)
- Moderated BF3 Detectors (outside room, and outer maze entrance, NOT inside)

**Rem-Meters**

- Consist of a neutron moderator (hydrogenous like material e.g. polyethylene) surrounding a thermal detector
- Moderator slows down fast and intermediate neutrons which are then detected by the thermal detector
- Useful in radiation fields for which spectrum is not well characterized
- Important to have a rough idea of the spectrum

**Rem-Meter Response**

\[
H^{\text{r}}(10) = \int h(E) \Phi(E) \, dE 
\]

where
- \( h(E) \) is the fluence to ambient dose equivalent conversion coefficient
- \( \Phi(E) \) is the neutron fluence as a function of energy for a given neutron field.

\[
R = \int C r_d(E) \Phi(E) \, dE
\]

where
- \( r_d(E) \) is the rem meter’s response function in units of counts per unit fluence, and \( C \) is the calibration constant in units of Sievert per count.

- Energy response is determined by size and geometry
- Response is shaped to fit an appropriate fluence to dose-equivalent conversion coefficient over a particular energy range
- Most rem-meters over respond in intermediate energy range
- Provide adequate measure of dose equivalent between 100 keV and 6 MeV
- Pulse pile up at high photon dose rates
- Dead time corrections at high neutron dose rates

- Consist of a neutron moderator (hydrogenous like material e.g. polyethylene) surrounding a thermal detector
- Moderator slows down fast and intermediate neutrons which are then detected by the thermal detector
- Useful in radiation fields for which spectrum is not well characterized
- Important to have a rough idea of the spectrum
Rem-Meter Response

• As long as \( r_\Phi(E) \) has a similar energy response to that of \( h_\Phi(E) \), the rem meter measurement can be said to be accurate.

• The ratio \( r_\Phi(E) / h_\Phi(E) \) defines the traditional energy response of the rem meter in terms of counts per unit dose equivalent.

Victoreen Portable Neutron Survey Meter Model 190n

• Andersson Braun remmeter
• Polyethylene cylinder 24 cm long, 21.6 cm in diameter containing BF3 tube
• Fill gas is 96% enriched 10B
• Range: 0 µSv/h to 0.75 Sv/h
• Integrate: 0 µSv to 10 Sv
• Gamma rejection: up to 500 R/h for 137 Cs
• Directionality: Less than 20% in orthogonal directions
• Weighs 9.52 kg

Thermo Electron Corporation ASP/2e NRD Neutron Survey Meter

• Portable, battery operated
• BF3 tube in 22.9 cm diameter cadmium-covered polyethylene sphere
• Tissue equivalent from thermal to ~10 MeV
• Dose equivalent range: 1 - 100 mSv/h
• Background gamma rejection: up to ~5 Gy/h

Thermo Electron Corporation ASP/2e NRD Neutron Survey Meter

• Dead Time: 10 µs nominal
• Directional response: within 10%
• Response time: Slow, Medium, Fast (programmable from 0 - 255 µs)
• Dual Analog/Digital display
• Ratemeter: integrate and scalar
• Count range: 1 – 1.3 million cpm
Response of Thermo Electron Corporation NRD Neutron Survey Meter and AB rem-meter

Higher Neutron Energies

WENDI-II – Extended Energy to 5 GeV

Fluence Meters - Moderated BF3 Detector

- Rare BF3 detector measures thermal neutron fluence rate
- Moderator enclosed in 0.5 mm cadmium eliminates incident thermal neutrons
- Moderated BF3 measures epithermal neutron fluence rate
- Fluence converted with appropriate coefficients to obtain dose equivalent
- Use requires knowledge of spectrum
- Moderated BF3 is useful to monitor relative variations of neutron field with time (e.g. IMRT)
- Ratio of rem-meter and moderated BF3 detector readings provides rough estimate of neutron spectrum
Neutron Spectrometer - Bonner Spheres

- Series of hydrogenous spheres with varying diameters surrounding a thermal detector
- Amount of moderation varies in each sphere
- Calculate spectrum by folding responses into a series of equations
- Requires computer program, large number of spheres and long measurement times
- Process is laborious
- Can be used with active and passive detectors

Bonner Spheres - The PTB NEMUS

The response $R_d(E_n)$ of sphere $d$ as a function of neutron energy $E_n$ for the bare and cadmium shielded SP9 counter (yellow), for the regular polyethylene spheres (brown) and for the modified spheres with embedded copper (green) and lead shells (cyan, red and blue)

Passive Detectors

- Activation Detectors (inside room, and in primary beam)
- Bubble Detectors (inside and outside room, NOT in primary beam)
- Solid State Track Detectors (inside room, NOT in primary beam)
Photon Induced Effects in Bubble and Track Detectors*

1. $^{2}$D(γ,n)p, $E_{th} = 2.23$ MeV,
   ($E_{th}$ = threshold energy, 0.02% of hydrogen is deuterium)
2. $^{16}$O(γ, α)$^{12}$C, $E_{th} = 7.2$ MeV
3. $^{12}$C(γ, α)$^{8}$Be→2α, $E_{th} = 7.4$ MeV


Activation Detectors

- Stable and reproducible
- Photon interference must be considered
- Thermal neutron detectors
  - Gold (thermal)
  - Indium (thermal)
- Threshold detectors
  - Phosphorus (thermal and fast)

http://www.thermocom.com/edu/product/detail/1,10551111617.html

Thermal Neutron Detectors

- Bare foil and cadmium covered foil can be used for thermal neutron fluences
- Moderated foil for fast neutrons
- Neutron absorption by foil results in production of radioactive nucleus
- Radioactivity can be correlated with incident thermal neutron fluence
- Gold and Indium foils counted with thin window GM, proportional counter, scintillation counter or GeLi detector

Moderated Activation Foils

- Moderator consists of a cylinder of polyethylene, 15.2 cm in diameter, 15.2 cm in height
- Covered with 0.5 mm of cadmium (or with boron shield)
- Moderator provides an energy independent thermal neutron fluence, proportional to incident fast fluence
- For in beam exposures:
  - Use only at energies ≤ 20 MV because of photon-induced response in cadmium and moderator lining
  - Field size wide enough to irradiate entire moderator
- Distance between moderators should be ≥2X diameter of the moderator
More moderators, and then some! Some more effective than others!

Threshold detectors

- Radioactivity produced by fast neutron interaction when neutron energy is above some threshold
- Phosphorous counted with liquid-scintillation counter

Threshold detectors

Activation Detectors (AAPM Report No. 19)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Cross Section (b)</th>
<th>Percent Abundance</th>
<th>Product Half Life</th>
<th>Decay Radiation (MeV)</th>
<th>Branching Intensity</th>
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</thead>
<tbody>
<tr>
<td>$^{153}$In ($n_\gamma$,7$^{154}$In)</td>
<td>194</td>
<td>95.7</td>
<td>54 m</td>
<td>β : 1.00</td>
<td>1.00</td>
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<tr>
<td>$^{197}$Au ($n_\gamma$,7$^{198}$Au)</td>
<td>99</td>
<td>100</td>
<td>2.098 d</td>
<td>β : 0.962</td>
<td>0.99</td>
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<tr>
<td>$^{31}$P ($n_\gamma$,p)$^{30}$S</td>
<td>Varies with energy</td>
<td>100</td>
<td>2.62 h</td>
<td>β : 1.48</td>
<td>0.99</td>
</tr>
<tr>
<td>$^{19}$F ($n_\gamma$,7$^{19}$F)</td>
<td>0.190</td>
<td>100</td>
<td>14.28 d</td>
<td>β : 1.71</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Bubble Detectors, Bubble Technology Industries, Canada

- Easy to use
- High sensitivity
- Reusable
- Integrating
- Allow instant visible detection of neutrons
- Isotropic response
- Variations in sensitivity within a batch

http://www.bubbletech.ca/b_info.htm

*Ipe et al, SLAC PUB 4398, 1987*
Bubble Detectors, BTI, Canada

- Consist of minute droplets of a superheated liquid dispersed throughout an elastic polymer
- Detector sensitized by unscrewing the cap
- Neutrons strike droplets producing secondary charged particles
- Charged particles cause droplets to vaporize, producing bubbles
- Bubbles remain fixed in polymer
- Bubbles can be counted by eye or in automatic reader
- Dose is proportional to the number of bubbles

Bubble Detectors (BTI, Canada)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>BDPND</th>
<th>BD100R</th>
<th>BD100R</th>
<th>BDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Range</td>
<td>&lt;200 keV- &gt;15MeV</td>
<td>&lt;200 keV- &gt;15MeV</td>
<td>Thermal ~1V</td>
<td>6 distinct thresholds: 10, 100, 600, 1000, 2500, 10 000 keV</td>
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<tr>
<td>Dose range</td>
<td>0.1 - 500 mrem</td>
<td>0.1 - 500 mrem</td>
<td>0.1 - 10 mrem</td>
<td>50 mrem</td>
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<tr>
<td>Sensitivity (Typical)</td>
<td>0.33 - 33 mRem/mRem</td>
<td>0.33 - 33 mRem/mRem</td>
<td>0.33 - 3.3 mRem/µSv</td>
<td>30 mRem/mRem</td>
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<tr>
<td>Gamma Sensitivity</td>
<td>None but photon induced effect</td>
<td>None but photon induced effect</td>
<td>None but photon induced effect</td>
<td>None but photon induced effect</td>
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<tr>
<td>Tissue Equivalence</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Temperature Compensation</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
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<tr>
<td>Optimum Temp. Range</td>
<td>20-37°C</td>
<td>10-35°C</td>
<td>20-37°C</td>
<td>20°C</td>
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<td>Angular Response</td>
<td>Isotropic</td>
<td>Isotropic</td>
<td>Isotropic</td>
<td>Isotropic</td>
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<tr>
<td>Size</td>
<td>145mm x 19mm dia</td>
<td>120mm x 16mm dia</td>
<td>145mm x 9mm dia</td>
<td>80mm x 16mm dia</td>
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<tr>
<td>Weight</td>
<td>58g</td>
<td>33g</td>
<td>58g</td>
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<tr>
<td>Re-use</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>&gt;10 cycles</td>
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<tr>
<td>Warranty</td>
<td>90 days</td>
<td>90 days</td>
<td>90 days</td>
<td>90 days</td>
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<tr>
<td>Other</td>
<td>T Response Curve Provided</td>
<td>Thermal/Fast Sensitivity 10/1</td>
<td>Special Recompression Chamber Available</td>
<td></td>
</tr>
</tbody>
</table>

Response of BD-PND as a Function of Energy
Normalized Response of BDS as a Function of Energy

Solid State Nuclear Track Detector
Neutrak® 144, Landauer, Inc.

- CR-39 (di allyl glycol carbonate) solid state track detector
- Fast neutron option: polyethylene radiator
  - Recoil proton from fast neutron interaction leaves sub microscopic damage trails
- Thermal neutron option: boron loaded teflon radiator + polyethylene radiator
  - $^{10}$B($n$,x)2Li
- Detector is chemically etched to reveal tracks
- Tracks are counted in an automatic counter
- Neutron dose is proportional to number of tracks
  - Fast: 40 keV to 30 MeV, 20 mrem minimum
  - Thermal: < 0.5 eV, 10 mrem minimum

Neutrak® ER

- Neutrak® 144 + TLD albedo
- Fast: 40 keV to 30 MeV
- TLD Albedo: 0.5 eV - 100 keV
- Minimum dose: 20 mrem

Note: Track etch detectors suffer from directional dependence

Sensitivity of Neutrak 144® as a Function of Neutron Energy

http://www.landauerinc.com/neutron.htm

Neutron Monitoring

- Neutron monitoring inside treatment room may be performed to determine
  - Neutron leakage from accelerator head
  - Neutron dose equivalent in patient plane, inside and outside primary beam
- Prudent to perform spot checks outside treatment room with hydrogenous barriers
- Laminated barriers shall be monitored for neutrons
- Neutrons shall be monitored at door, maze entrance and any opening through shielding

Radiation Surveys For Shielding Evaluation

1. Record name of individual performing surveys
2. Record facility name and linac information
3. Record survey instrument manufacturer, model no., and date of calibration
4. Set machine to desired energy
5. Use maximum field size
6. Set machine to highest dose rate
7. Remove phantom
8. Record linac parameters
Accelerator Head Leakage

- Wrap film around accelerator head to identify hot spots
- Measure with ion chamber at 1 m from source for locations - M(L)
- Measure 10 cm x 10 cm open field at isocenter with ion chamber - M(IC)
- % Leakage = \( \frac{M(L)}{M(IC)} \times 100 \)

Courtesy of C. Ma