Inelastic nuclear interactions in MC simulations for clinical proton beams

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Overview

1. Proton therapy beams
2. Inelastic nuclear versus Coulomb interactions
3. Monte Carlo calculations
4. Ionisation chambers
5. Fluence correction factors
6. Water equivalence of graphite (graphite calorimetry)
7. Clinical dose calculations
1. Proton (and $^{12}\text{C}$) therapy beams worldwide
1. Proton therapy beams: depth dose characteristics

![Diagram showing depth dose characteristics for modulated and non-modulated proton beams.](image)
1. Proton therapy beams: 
Range modulation
2. Inelastic nuclear versus Coulomb interactions (ICRU 49 & ICRU 63)
3. Monte Carlo calculations

- PTRAN_MEDIA (ICRU 49 + ICRU 63 data)

- MCNPX
- GEANT4
4. In ionisation chamber dosimetry

Primary proton beam

$\delta$-electrons

Secondaries from inel. nucl. int.
4. In ionisation chamber dosimetry

- Usually: only $s_{w,\text{air}}$

- IAEA TRS-398: Spencer-Attix $s_{w,\text{air}}$

- Secondary electron perturbations: 0-1%  
  (Verhaegen and Palmans, Med. Phys. 28:2088-2095)

- Inelastic nuclear interactions:
  - Secondary charged particles (protons) in slowing down spectrum
  - Charged particles generated in cavity
4. In ionisation chamber dosimetry: secondary protons in Sl. D. S.

Spectra at 0.9 x r₀

Δ(sₗ,ₐᵢʳ) = +0.03%  
Δ(sₗ,ₐᵢʳ) = -0.04%  
Δ(sₗ,ₐᵢʳ) = -0.15%
4. In ionisation chamber dosimetry: S. Ch. P. generated in cavity

- Under investigation
- Rough estimate:
  - Protons escape, other heavy charged particles not
  - Yields:

![Graph showing the relationship between energy (E, MeV) and collision stopping powers (S_{sw,air})]
5. Fluence correction factors: definition (cfr. electron beams)

\[ D_w(z_w) = D_{pl}(z_{pl}) \cdot s_{w,pl} \cdot \phi_{pl}^{w} \]

\[ z_w = z_{pl} \cdot \frac{(z_0)_w}{(z_0)_{pl}} \]

\[ h_{pl} = \frac{M^w}{M^{pl}} \]
5. Fluence correction factors: calculated depth dose curves
5. Fluence correction factors:
calculated corrections

Janni ICRU 63
5. Discussion: stopping power data versus non-elastic nuclear cross sections

ICRU 63
Janni (1982)
5. Fluence correction factors: correct dose conversion

\[ D_w(z_w) = \left[ D_{pl,C}(z_{pl}) \cdot s_{w,pl} + D_{pl,N}(z_{pl}) \cdot E \cdot (\sigma_n/A)_{w,pl} \right] \phi^w_{pl} \]

\[ Z_w = Z_{pl} \cdot \frac{(z_0)_w}{(z_0)_{pl}} \]
5. Fluence correction factors: calculated corrections
5. Fluence correction factors: correction versus penetration
5. Fluence correction factors: correction per cm penetration

<table>
<thead>
<tr>
<th>Phantom material</th>
<th>Janni (1982)</th>
<th>ICRU report 63</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Unmodulated beams</td>
<td>Modulated beams</td>
</tr>
<tr>
<td>PMMA</td>
<td>0.14%/cm</td>
<td>0.15%/cm</td>
</tr>
<tr>
<td>polystyrene</td>
<td>0.19%/cm</td>
<td>0.20%/cm</td>
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</tbody>
</table>
5. Fluence correction factors: without inelastic nuclear interactions
5. Fluence correction factors: experiment at LLN (75 MeV)
5. Fluence correction factors: experiment at NAC(*) (191 MeV)

(*) Now iThemba Labs
5. Fluence correction factors: very little experimental information

• Schneider et al. 2002 *Med. Phys.* 29:2946-2951


6. Graphite calorimetry

![Diagram of graphite calorimetry setup with labeled components: Sensing thermistors, Expanded polystyrene, and Graphite body.]

![Graph showing Dcal/Dion values for modulated and non-modulated beams, with data points for NE2561 (Co-60), NACP02 (Co-60), Markus (Co-60), NACP02 (e-19), and Markus (e-19).]
6. Graphite calorimetry

- Fluence corrections

PTRAN

GEANT4

MCNPX

![Graph showing fluence correction factor vs. water equivalent depth for PTRAN, GEANT4, and MCNPX.]
6. Graphite calorimetry: water equivalence – measured pdds

![Graph showing the comparison of Markus in water, scan 1 and 2, NACP in graphite with constant SDD, and NACP in graphite with SSD = 150 cm and fluence correction.]
7. Clinical dose calculations

The image shows a graph with various tissue types represented by different lines. The x-axis is labeled as $z/r_0$, and the y-axis represents the fluence correction factor. Different tissues are indicated by distinct colors and markers:

- Water: Gray line
- Adipose tissue: Yellow line
- Bone, compact: Blue line
- Bone, cortical: Cyan line
- Muscle, skeletal: Red line
- Muscle, striated: Magenta line

The graph illustrates how the fluence correction factor changes with $z/r_0$ for each type of tissue.
7. Clinical dose calculations

![Graph showing Clinical dose calculations]

- Clinical dose calculations are illustrated with graphs showing depth (mm water) vs. dE/dz (Mev cm² g⁻¹). The graphs indicate changes in dose distribution with depth for bone and water.

- The graph also shows the ratio D_{bone}/D_{water} and D_{(water/bone)}/D_{water} over depth.

- The data points suggest a decrease in the ratio as depth increases, indicating a higher dose absorption in bone compared to water.

- Clinical implications for these calculations are significant in radiation therapy planning, ensuring accurate dose distribution to target areas while minimizing side effects in surrounding tissues.
7. Clinical dose calculations

![Graph showing depth (mm water) vs. dE/dz (Mev cm^2 g^-1) with different curves for \(D_{\text{adipose}}/D_{\text{water}}\) and \(D_{(\text{water/adipose})}/D_{\text{water}}\).]
Conclusions

- Inelastic nuclear interactions:
  - Generally small effects
  - Small effects in ionisation chambers, but need further investigation
  - Fluence correction factors can be substantial
  - Effects in tissues can be substantial
  - Experimental evidence required