Inhomogeneous Tissue Studies for Clinical Proton Therapy:

Universal Scaling and Interfacial Buildup Effects

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## Computing at Walter Reed

<table>
<thead>
<tr>
<th></th>
<th>Master Node</th>
<th>Cluster Node</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of Units</strong></td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td><strong>Number of Processors</strong></td>
<td>2</td>
<td>2 (10 total)</td>
</tr>
<tr>
<td><strong>Processor Type</strong></td>
<td>G5, 64-bit</td>
<td>G5, 64-bit</td>
</tr>
<tr>
<td><strong>Processor Speed</strong></td>
<td>2.5 GHz (4.5 GHz Intel)</td>
<td>2.5 GHz (4.5 GHz Intel)</td>
</tr>
<tr>
<td><strong>RAM</strong></td>
<td>1GB/processor</td>
<td>512MB/processor</td>
</tr>
</tbody>
</table>
Characterizing % Depth–Dose

• Investigate properties of the clinical proton depth–dose in homogeneous and inhomogeneous materials.

• For quality assurance measures we need to understand properties of dose in heterogeneous structures.
Experimental Validation

![Graph showing % Depth Dose vs Scaled Depth in Water, z/r, and comparison between SRIM Peak Normalized % Ionization, Experiment (MGH, Gottschalk, 1991), NIST PTRAN3d, Difference Between SRIM and Exp., GEANT 4.5.0 Peak Normalized Eng. Deposition - No Hadronic, GEANT 4.5.0 Peak Normalized Eng. Deposition - With Hadronic, GEANT 4.7.0 - With Hadronic - PreCompound, excitation.]

- SRIM
- Experiment (MGH, Gottschalk, 1991)
- NIST PTRAN3d
- Difference Between SRIM and Exp.
- GEANT 4.5.0 Peak Normalized Eng. Deposition - No Hadronic
- GEANT 4.5.0 Peak Normalized Eng. Deposition - With Hadronic
- GEANT 4.7.0 - With Hadronic - PreCompound, excitation.

- Target cm Depth: H
- Target cm Depth: O Slab
- SRIM
- d = 1
- m = 1
- n = 4
- 4.5.0: GEANT
- 5 = 10
- Difference: 9.3%
Material–Dependent Scaling?

Analogy to heavy ion scaling in foil strippers:

\[
\left( \frac{\nu}{\nu_0} \right) Z^{-\gamma} \rightarrow E^{1/2} (1836E_0)^{-1/2} Z^{-\gamma}
\]

What is \( Z \) for a compound?

1. Mean \( Z \)

\[
Z_{\text{eff}} = \sum_{i=1}^{N} a_i Z
\]

\[
a_i = \left( \frac{N_{\text{av}} Z_i w_i}{A_i} \right) / \sum_{i=1}^{N} \frac{N_{\text{av}} Z_i w_i}{A_i}
\]

2. Ratio of Moments

\[
Z_{\text{eff}} = \sum_{i=1}^{N} \frac{a_i Z^2}{\sum_{i=1}^{N} a_i Z_i}
\]

\[
a_i = \left( \frac{N_{\text{av}} Z_i w_i}{A_i} \right) / \sum_{i=1}^{N} \frac{N_{\text{av}} Z_i w_i}{A_i}
\]

3. Power law - photoelectric cross section

\[
x = E^{1/2} (1836E_0)^{-1/2} Z_{\text{eff}}^{-\gamma}
\]

\[
a_i = \left( \frac{N_{\text{av}} Z_i w_i}{A_i} \right) / \sum_{i=1}^{N} \frac{N_{\text{av}} Z_i w_i}{A_i}
\]
Distal Edge Width

\[ x = E^{1/2} \left( \frac{1836E_0}{Z_{eff}} \right)^{-1/2} \]

- ICRU Compact Bone
- ICRU Bone Equiv Plastic
- Amorphous Aluminum
- Calcium Hydroxyapatite

Distal Edge Width, \( d \) [mm]

Incident Proton Energy, \( E \) [MeV]

\[ Z_{eff} = \left( \frac{a_i Z_i}{m} \right)^{1/m}, \quad a_i = 2.94 \]
Lateral Penumbra

\[ x = E^{1/2} \left( \frac{1836E_0}{Z_{eff}} \right)^{-1/2} \]

Incident Proton Energy, \( E \) [MeV]

Lateral Edge Width [mm]

H\(_2\)O (STP)
ICRU Compact Bone
ICRU Bone Equiv. Plastic, B-100
Amorphous Aluminum
Calcium Hydroxyapatite
Bragg Peak FWHM

\[ x = E^{1/2} \left( \frac{1836E_0}{Z_{eff}} \right)^{-1/2} \]

Incident Proton Energy, \( E \) [MeV] vs. Bragg Peak FWHM, \( x \) [mm]

- ICRU Compact Bone
- ICRU Bone Equiv Plastic B-
- Amorphous Aluminum
- Calcium Hydroxyapatite
Peak-to-Entrance Dose Ratio

\[ S_w = \frac{S_{water}(E)}{S_X(E)} \]

\[ X = \text{CompactBone, B – 100, Al, ...} \]
Bone–$\text{H}_2\text{O}$ Interface Effects

![Graph showing the percentage depth-dose curve for bone and water interfaces.](image)

- **% Depth-Dose**
  - 0
  - 20
  - 40
  - 60
  - 80
  - 100
  - 120
  - 140
  - 160

- **Depth, $d$ [mm]**
  - 0
  - 20
  - 40
  - 60
  - 80
  - 100
  - 120
  - 140
  - 160

- **E=$150$ MeV, $s=150$, $H_2O$**

- **D$x$**

- **Bone-H$_2$O Interface Effects**

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Relative Energy Loss From Bone

\[ \Delta E = E_1 - E_2 \approx S(E_1) \Delta x \]

- Mean Proton Energy [MeV]

- \( D \) / [%]

- \( \text{ICRU Compact Bone} \)

- \( r = 1.859 / \text{g cm}^3 \)
Particle-Specific Energy Deposition

![Graph showing energy deposition per primary proton over depth.](image)

- Energy Deposited Per Primary Proton [MeV]
- Depth, d [mm]

Primary H +
Secondary H +
e-
a+

G4NAMU/SLAC 2006
Composite Distal Edge

\[ Z_{\text{eff}} = \frac{1}{V} \sum_{i=1}^{N} v_i Z_{\text{eff},i} \]

\[ x = E^{1/2} (1836E_0)^{-1/2} Z_{\text{eff}}^{-0.33} \]
Composite FWHM

\[ Z_{eff} = \frac{1}{V} \sum_{i=1}^{N} v_i Z_{eff,i} \]

\[ x = E^{1/2} (1836 E_0)^{-1/2} Z_{eff}^{-0.33} \]
Future Work

• Phantom Development – CTSim and 3d Rapid Prototyping (collaboration with the WRAMC 3D Medical Applications Center, Dr. Erge Edgu-Fry).

• Full 3d heterogeneity corrections.
Integrated Dose Fraction

\[ N_0 = 10^6 \]

Phantom: 40cm X 40cm ICRU Compact Bone

Incident Proton Energy, \(E\) [MeV]

Integrated Dose Fraction in Compact Bone

- primary proton
- secondary proton
- electron
- gamma
- positron
- alpha
- deuteron
- triton