Imaging for Proton Treatment Planning
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Outline

• Impact of Geometric Errors
• Calibrating CT for Proton Dose Calculation
• Potential Improvements in Stopping Power Measurements
• Clinical Examples of Anatomical Changes
Photon Planning: Relative Electron Density

- Scan commercial phantom with known RED
- Measure HU in scan
- Enter HU-RED curve in photon planning system

Proton Planning: Stopping Power

- Proton stopping power comes from Bethe-Bloch equation:
  \[ S = \frac{4\pi}{m_e c^2} \left( \frac{e^4}{4\hbar^4} \right) \rho^2 \left( \ln\left( \frac{m_e c^2 \beta^2}{1 - \beta^2} \right) - \rho^2 \right) \]
  - \( n \) is electron density of the medium
  - \( I \) is ionization potential of the medium
  - HU – RSP degeneracies
  - Phantom materials are not like human tissues
  - Stoichiometric Calibration Process

Stoichiometric Calibration

1. Measure HU of materials with known RED
   - Plugs have well known RED values
   - Elemental composition not tissue equivalent
   - Scan one plug at a time in center of phantom
   - Use fixed, clinical CT protocol
Stoichiometric Calibration

2. Parameterize CT Scanner by Fitting HUs

\[ HU_{\text{eq}} = \rho^{\text{eq}} Z (A \cdot \tilde{Z} + B \cdot \tilde{Z} + C) \]

- \( Z \) and \( \tilde{Z} \) are material properties for photoelectric and Compton
- Scanner parameters:
  - A: photoelectric
  - B: Compton
  - C: Klein-Nishina

Schneider et al., PMB 1996

Stoichiometric Calibration

Parameterize CT Scanner by Fitting HUs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>( K^P )</td>
<td>0.68 x 10^{-5} [-1.66 x 10^{-5}, 3.46 x 10^{-5}]</td>
</tr>
<tr>
<td>( K^N )</td>
<td>0.003086 [-0.003086, 0.003086]</td>
</tr>
<tr>
<td>( K^M )</td>
<td>0.0034 (0.75)</td>
</tr>
</tbody>
</table>

Final values: \( K^P=3.46 x 10^{-5} \), \( K^N=0.003086 \), and \( K^M=0.0034 \)
Stoichiometric Calibration

3. Calculate Predicted HU for ICRU Tissues

\[ \text{HU}_{\text{tissue}} = \rho_{\text{tissue}}^0 (A \cdot Z + B \cdot Z^2 + C) \]

Stoichiometric Calibration

4. Calculate Relative Stopping Power for Reference Tissues

\[ S_p = e^{\frac{-m_{\text{e}}}{I_{\text{water}}}(1 - \beta)} \]

- \( I \) is ionization potential for material
- \( I \) is assumed to be ~75 eV for water
- More uncertainty in \( I \) for other materials

Schneider et al., PMB 1996

Stoichiometric Calibration

5. Plot Relative Stopping Power vs. Calc. CT

- Nominally fit to bi-linear curve
- More segments used in soft tissue region to cover tissues with differing H composition

Schneider et al., PMB 1996
Every chef and every proton physicist should be friends with their butcher.

Bone
Liver
Muscle
Fat
Brain
Uncertainties in HU to SP

- Fitting experimental results for planning system curve
- Degeneracy in SP values for tissues with same HU
- HU value uncertainty
  - Technique
  - Position in scanner
  - Artifact
- Uncertainties in mean excitation value
- Variations in human tissue composition
- Expected Range Uncertainty: ~3.5% ± 1 mm

Patient Outside FOV

Barrett, Radiographics 2004

Metal Artifact Reduction

Barrett, Radiographics 2004
Manual Artifact Reduction

Potential Improvements in RSP Measurement
- Dual Energy CT
- MegaVoltage CT
- Proton CT

Dual Energy CT

Taasti et al., PMB 2018
Robust Treatment Planning

- Geometric and range uncertainties are estimated at time of planning
- Treatment plans are optimized in a way to account for range and setup variations
- A robust plan provides CTV coverage and critical organ sparing in presence of errors
- Physicians review coverage of CTV in light of expected variations
Robust Optimization

Proton Plan Robustness Evaluation

- Nominal Plan
- +/- 3 mm x
- +/- 3 mm y
- +/- 3 mm z
- +/- 3% range

Nominal Plan
Robust Proton Plan
Patient Contour Variations

- Range uncertainty also arises from changes in patient external contour
  - Variations in posterior tissue on immobilization device
  - Folds in posterior neck
  - Excess adipose tissue in pelvis

CT Guided SBRT
Prostate SBRT Variation

Original Plan  VerificationPlan

Conclusion

• Converting HU to RSP is not trivial
• Increasing our knowledge of stopping power is important, but not the only concern
  • A clinically viable plan already has lots of margin in the beam direction
  • Anatomical variation is a much greater variable than error in stopping power
• Critical to validate anatomy before Tx (Dr. Winey)
• Ideally validate dose after Tx (Dr. Polf)