An optimization scheme to produce patient-specific HU-RSP calibration curves based on proton radiographs

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Range uncertainties in proton therapy

<table>
<thead>
<tr>
<th>Source of range uncertainty in the patient</th>
<th>Range uncertainty without Monte Carlo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent of dose calculation</td>
<td></td>
</tr>
<tr>
<td>Measurement uncertainty in water for commissioning</td>
<td>±0.3 mm</td>
</tr>
<tr>
<td>Compensator design</td>
<td>±0.2 mm</td>
</tr>
<tr>
<td>Beam reproducibility</td>
<td>±0.2 mm</td>
</tr>
<tr>
<td>Patient setup</td>
<td>±0.7 mm</td>
</tr>
<tr>
<td>Dose calculation</td>
<td></td>
</tr>
<tr>
<td>Biology (always positive)</td>
<td>+~0.8%</td>
</tr>
<tr>
<td>CT imaging and calibration</td>
<td>±0.5%b</td>
</tr>
<tr>
<td><strong>CT conversion to tissue (excluding I-values)</strong></td>
<td>±0.5%b</td>
</tr>
<tr>
<td>CT grid size</td>
<td>±0.3%c</td>
</tr>
<tr>
<td><strong>Mean excitation energy (I-values) in tissues</strong></td>
<td>±1.5%d</td>
</tr>
<tr>
<td>Range degradation; complex inhomogeneities</td>
<td>-0.7%e</td>
</tr>
<tr>
<td>Range degradation; local lateral inhomogeneities</td>
<td>±2.5%f</td>
</tr>
<tr>
<td>Total (excluding *, ^)</td>
<td>2.7% + 1.2 mm</td>
</tr>
<tr>
<td>Total (excluding ^)</td>
<td>4.6% + 1.2 mm</td>
</tr>
</tbody>
</table>

Proton therapy treatment planning

- Convert CT number to RSP (relative stopping power).

- Uses literature tissue composition (stoichiometric calibration) based on:
  - Average
  - Healthy
  - Adults

\[
F = \begin{cases} 
0 & \text{if } H \leq -1000; \\
 a + bH & \text{if } -1000 < H \leq 0; \\
a' + b'H & \text{if } 0 < H \leq 40; \\
& \vdots
\end{cases}
\]

Schneider 1996 PMB
Woodard 1986 BJR
White 1987 BJR
ICRU 1989 Report 44
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**Proton radiography**
- Direct mapping of the RSP
- Poor spatial resolution due to multiple Coulomb scattering

**X-ray CT**
- High spatial resolution
- Requires the Hounsfield units to be converted to RSPs

**Optimization**
- Direct mapping of the RSP
- Use high spatial resolution of X-ray CT

Schneider 2005 *PMB*
Optimization

Export xCT DICOM

Use Plastimatch to find all voxels that proton beam intersects

Store in matrix file for each ray: length of ray in each voxel and the HU value of voxel

Use clinical calibration curve as start

Compute simulated DRR_{WEPL}

Calculate difference between DRR_{WEPL} and measured proton radiographic measurement

Change calibration curve to minimise difference

Measured proton radiograph

Key
- Matlab
- Plastimatch
- Measurement
- Optimization loop

DRR = digitally reconstructed radiograph
**Optimization**

**Clinical curve**

- Y-axis variation only
- Monotonic
- CT=0, RSP=1

**25 material bins**

- Material 1, HU = -1000 to -950
- Material 2, HU = -950 to -120
- Material 3, HU = -120 to -83
- Material 4, HU = -83 to -53
- Material 5, HU = -53 to -23
- Material 6, HU = -23 to 7
- Material 7, HU = 7 to 18
- Material 8, HU = 18 to 80
- Material 9, HU = 80 to 120
- Material 10, HU = 120 to 200
- Material 11, HU = 200 to 300
- Material 12, HU = 300 to 400
- Material 13, HU = 400 to 500
- Material 14, HU = 500 to 600
- Material 15, HU = 600 to 700
- Material 16, HU = 700 to 800
- Material 17, HU = 800 to 900
- Material 18, HU = 900 to 1000
- Material 19, HU = 1000 to 1100
- Material 20, HU = 1100 to 1200
- Material 21, HU = 1200 to 1300
- Material 22, HU = 1300 to 1400
- Material 23, HU = 1400 to 1500
- Material 24, HU = 1500 to 2995
- Material 25, HU = 2995 to 2996

**Schneider 2000 PMB**
Example (1) Multiple material phantom

- 5 x 5 x 5 cm cubes of 28 different materials, with chemical composition as defined by ICRU Report 44.
Results (1) Heterogeneous material phantom

WEPL = water-equivalent path length

Clinical calibration curve

Optimized calibration curve

RMSE
0.69 mm 1.5%
0.09 mm 0.2%
Results (2) Lung

Clinical calibration curve

Optimized calibration curve

Known WEPL

Known (cropped) WEPL

DRR\textsubscript{WEPL}

Difference

RMSE 3.92 mm

RMSE 0.01 mm
Example (3) Gammex

Experimental setup

- Solid water
- Gammex phantom
- Radiography device

Registration

- Register images in Slicer

- For optimization, exclude differences >10 mm

Testa 2013 PMB
Results (3) Gammex

Clinical calibration curve

- Clinical RMSE = 1.7%
- $\mu = -1.4\%$
- $\sigma = 2.3\%$

Optimized calibration curve

- Optimized RMSE = 1.3%
- $\mu = -0.1\%$
- $\sigma = 2.0\%$
Summary

- Constructed optimizer on perfect (no CT noise) simulated datasets:
  - Single materials
  - Multiple materials
  - Heterogeneous, simple
  - Heterogeneous, complex
  - Anthropomorphic
  - Field-specific of human geometry

- Real proton radiographs
  - Anthropomorphic phantom
  - Animal tissues

In all cases, the RMSE in the difference map was significantly reduced (79-99%).
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References
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Schneider U, Pedroni E and Lomax A 1996 The calibration of CT Hounsfield units for radiotherapy treatment planning Physics in Medicine and Biology 41 111-124.