Optimization of a Fast CT System for More Accurate Radiotherapy

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Problem: motion during treatment

Fix: PHASER

- PHASER = Pluridirectional High-Energy Agile Scanning Electron Radiotherapy
- Basic idea: deliver entire radiation treatment in a few seconds to effectively freeze motion
- Mechanism: use high-energy electrons, which can be steered electronically (no moving parts)
- 100 MeV electrons can deliver a dose with similar accuracy to 2 MeV photons (mean energy)
PHASER Setup

Array of high energy electron source lines

Region of interest

Diverging electron beam

Not shown: patient table, beam stop, imaging system, outer casing
Work Flow

Acquire pre-treatment raw data

Reconstruct image

Register image

Adjust therapy plan

Deliver therapy

Verify correct tissue was irradiated
Goals of Pre-Treatment Imaging System

• Acquire a high-quality image to adjust treatment plan
  – Image within a breath hold
  – Adequate contrast to identify important structures
  – 40-cm axial FOV, 50-cm diameter patient

• Acquire a fast-image of the tumor to verify position immediately prior to treatment
  – Speed is more important than quality
  – 10-cm axial FOV, 50-cm diameter patient

• Don’t break the bank: 64-slice scanner ~ $1 million, 128-slice scanner ~ $2 million*

* The internet, don’t quote this
Geometry 1: Helical Scan

- Detector arclength = 102.3 cm
- pitch = 0.95
- Axial field of view = 40 cm
- In-plane field of view = 50 cm (diameter)
Geometry 2: Cone Beam Scan

Axial field of view = 10 cm
In-plane field of view = 50 cm (diameter)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Clinical Scanner</th>
<th>PHASER Scanner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source to detector distance</td>
<td>1040 mm <em>(too small to laterally shift patients)</em></td>
<td>1300 mm</td>
</tr>
<tr>
<td>Detector rows/pixel size</td>
<td>64 rows, 1 x 1 mm(^2) <em>(FOV too small)</em></td>
<td>16 low res (4 x 4 mm(^2)) + 32 higher res (2 x 2 mm(^2)) + 16 low res (4 x 4 mm(^2))</td>
</tr>
<tr>
<td>Pixels/row</td>
<td>672-888 <em>($$$)</em></td>
<td>512</td>
</tr>
<tr>
<td>Voxel size</td>
<td>0.5 – 1.0 mm(^3) at detector <em>(unnecessary resolution, $$$)</em></td>
<td>2.0 mm(^3) at detector</td>
</tr>
<tr>
<td>Antiscatter grid</td>
<td>Varies</td>
<td>2D, 35 mm lamellae</td>
</tr>
</tbody>
</table>
CT Simulation with XCAT Phantom

- Full dataset is the sum of two simulations
  - Primary photons (deterministic)
  - Scattered photons (Monte Carlo)
- Numerical phantom used to simulate patient
Primary Simulation

Software generates cone beam projection images, includes tools for 3D volume reconstruction, DOES NOT include scatter

X-ray attenuation, one energy, one material

\[ I(L) = I_0 \exp(-\mu L) \]

X-ray attenuation, polyenergetic, several materials

\[ I(x_{tot}) = \int_{E_{min}}^{E_{max}} I_{0,E} \prod_{i=1}^{n} \exp(-\mu_{iE}L_i) dE \]
Scatter Simulation: Why Bother?

Ideal CT: X-rays either go straight to detector or are absorbed

Real CT: Some x-rays are deflected to the wrong detector location
More About Scatter

• Most accurately modeled with a Monte Carlo simulation (accounts for random physical processes responsible for scattering)
• Can be reduced with an anti-scatter grid (see right)
Results

Phantom

Primary only

Primary and scatter

Scatter corrected
Results: Shoulders

- Primary only
- Primary and scatter
- Scatter corrected
- Current system
Results: Lungs, middle

Primary only

Primary and scatter

Scatter corrected

Current system
Results: Lungs, bottom

Primary only

Primary and scatter

Scatter corrected

Current system
Conclusions

• Current system design produces reasonable image quality fast and at a reasonable price
• Some remaining work on cone beam and truncation artifact reduction
• Extremely general CT simulation can evaluate image quality in other new systems
Future Work

• Simulate imaging phantoms with low-contrast tumors and use system to evaluate ease of lesion recognition
• Apply system to real patient data
• Next step of imaging pipeline: use registration software to compare registration accuracy with XCAT phantoms and real patient data
Acknowledgements

• Meng Wu and Rebecca Fahrig
• PHASER team
• Stanford Cancer Imaging Training Fellowship
• Department of Defense
Questions?