Imaging of Scattered Radiation for Real-Time Tracking of Tumor Motion During Lung SBRT

Gage Redler, Damian Bernard, Alistair Templeton, Chithra Nair, Julius Turian, and James C. H. Chu
• Lung cancer is the most lethal cancer:
  - Over 224,000 new diagnoses in the U.S. predicted for 2015
  - 159,000 expected deaths in the U.S. predicted for 2015
  - More lung cancer related deaths than breast cancer related deaths in women

• Various treatment options:
  - Chemotherapy
  - Targeted therapy (e.g., monoclonal antibodies)
  - Surgery (e.g., wedge resection, lobectomy, pneumonectomy, cryosurgery)
  - Radiation therapy (e.g., 3D, IMRT, SBRT)

“Cancer facts and figures 2015”
Lung SBRT

• Promising alternative to surgery
  – Large radiation dose in few fractions (e.g., 18Gy×3 or 12Gy×5)
  – Increased TCP
  – Increased NTCP

• Requires accurate target localization
  – Radiation delivery accuracy ~1mm
  – Lung tumor motion ~2-3cm
  – Internal target not directly visible
### Lung SBRT Image Guidance

#### Current tumor localization methods:

- EPID
- CBCT
- FBCT (kV: CT-on-rails or MV: Tomotherapy)
- Stereoscopic kV imaging (snapshots or fluoroscopic)
- Ultrasound
- Optical Imaging (surface tracking)
- MRI
- Electromagnetic transponder tracking
- Chest expansion/contraction
- Hybrid modalities (e.g., ExacTrac)

#### Current limitations:

- Only 2D or limited 3D information
- Additional radiation dose
- Not available during treatment
- Not real-time
- Logistically complex (limited positioning options, collision danger)
- Invasive fiducial implants required
- Poor image contrast
- Not directly imaging the target

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Scatter Imaging

General Concept:

- Incident radiation interacts within patient
- Energy not deposited carried away
- Scatter from internal structures dependent on material composition
- Image of spatial distribution of scatter gives 2D anatomical information

Benefits:

- No additional radiation dose
- No required fiducial implants
- Flexible detector placement
- Multiple detectors \(\Rightarrow\) 3D
- Rapid image formation \(\Rightarrow\) real-time imaging
Scatter Imaging

**Analytic System Model:**

\[
H_{jk} = \left[ \exp \left( - \sum_n \mu_n l_n \right) \right] \times [C_k] \times [T_k] \times \left[ \exp \left( - \sum_m \mu'_m l'_m \right) \right]
\]

\( H_{jk} \) – signal contribution from scattering element \( v_k \) to detector element \( d_j \)

- Incident beam attenuation
- Probability of scatter event
- Probability of scattering angle \( \theta_{jk} \)
  - Geometric considerations (pinhole size, object-pinhole distance, pinhole-detector distance)
  - Klein-Nishina differential cross section
- Scattered radiation attenuation

\[ (g_{j\times1} = H_{j\times k} f_{k\times1}) \]
Contrast Between Materials

Scatter Imaging – Monte Carlo Simulation

6MV

BEAM

(lung)

(water)

(bone)

\[ d = 0.5\text{cm} \]
Contrast Between Materials

- Dose to water cylinder = 0.065 cGy
  - $\text{SNR}_L = 1.9$, $\text{SNR}_W = 3.3$, $\text{SNR}_B = 3.5$

- Assuming $N \propto \frac{1}{\sqrt{Dose}}$, for 1.0 cGy
  - $\text{SNR}_L = 7.6$, $\text{SNR}_W = 12.7$, $\text{SNR}_B = 13.7$

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<thead>
<tr>
<th>Material</th>
<th>Monte Carlo</th>
<th>Analytic Calculation</th>
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<tbody>
<tr>
<td>Water</td>
<td>1.00 ± 0.28</td>
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<tr>
<td>Lung</td>
<td>0.31 ± 0.12</td>
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Lung Tumor Phantom

BEAM →

\[ d = 0.5\text{cm} \]

6MV
Lung Tumor Phantom

- Dose to isocenter = 0.153 cGy
  - SNR = 8.3
  - CNR = 4.8
  - 1200 cGy/min $\Rightarrow$ 0.153 cGy $< 0.01$ sec

- Assuming $N \propto \frac{1}{\sqrt{\text{Dose}}}$, for 1.0 cGy
  - SNR = 21.2
  - CNR = 12.3
  - 1200 cGy/min $\Rightarrow$ 1.0 cGy = 0.05 sec

$\text{CNR} = \frac{|S_T - \bar{S}_L|}{\sigma_T}$
Lung Tumor Phantom

- Clear contrast between water and lung
- Beam intensity attenuates through object

(average over 8 central pixels)

(148x148 pixels, each 0.169x0.169 cm$^2$)

# of Detected Particles

# of Detected Particles
Contrast Between Materials

- Lung SBRT treatment parameters used:
  - Varian TrueBeam Linac
  - 6MV FFF
  - Dose rate = 1200 MU/min
- 5000 MU delivered
- Diagnostic flat panel detector
- Nuclear medicine pinhole camera
- Background image acquired/subtracted
## Contrast Between Materials

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Lung Tumor Phantom

Solid Water = 9.1 ± 3.4  Bolus = -7.1 ± 3.7  Cork = -828.5 ± 13.2
Lung Tumor Phantom
Lung Tumor Phantom

- Lung SBRT treatment parameters used:
  - Varian TrueBeam Linac
  - 6MV FFF
  - Dose rate = 1200 MU/min

- Various MU delivered

- Diagnostic flat panel detector

- Nuclear medicine pinhole camera

- Background image acquired/subtracted
### Lung Tumor Phantom

<table>
<thead>
<tr>
<th>Dose (MU)</th>
<th>5000</th>
<th>1000</th>
<th>500</th>
<th>200</th>
<th>100</th>
<th>50</th>
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<tbody>
<tr>
<td>Time (sec)</td>
<td>250</td>
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<td>149.9</td>
<td>99.3</td>
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<td>49.8</td>
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<td>30.0</td>
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<td>6.7</td>
<td>5.5</td>
<td>4.1</td>
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Lung Tumor Phantom
Summary and Conclusions

• Scatter imaging may be useful for image based tumor tracking
  - No additional radiation dose
  - No required fiducial implants
  - Flexible detector placement
    - Multiple detectors ➔ 3D
    - Rapid image formation ➔ real-time imaging

• Analytic model developed to describe scatter imaging

• Preliminary Monte Carlo simulations
  - Scatter imaging differentiates objects of different composition
  - Using a simplified lung tumor model the target can be clearly identified

• Preliminary experimental measurements agree qualitatively with simulation results
  - Images as fast as 0.5sec (10MU) begin to resolve target ➔ Real-time imaging
Thank You

Questions?
Analytic System Model

\[ H_{jk} = \left[ \exp \left( - \sum_n \bar{\mu}_n l_n \right) \right] \times [\bar{C}_k] \times [\bar{T}_k] \times \left[ \exp \left( - \sum_m \bar{\mu}'_m l'_m \right) \right] \]

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(Assume scatter at 90°, so ignore \( \bar{T}_k \))
Defining SNR

- Specifically looking at “tumor” in image

\[ SNR = \frac{S_T}{\sigma_T} \]

- \( S_T \) is the image intensity, averaged over a central region within the tumor
- \( \sigma_T \) is the standard deviation of the image intensity over the same central region within the tumor

Note: SNR and CNR should be approximately proportional to \( \sqrt{dose} \) and to linear pixel dimension
Defining CNR

- Specifically looking at “tumor” in image
- Tumor is embedded in lung
- CNR is a metric to quantify how well tumor can be differentiated from the surrounding lung relative to the random noise present in the image

\[
CNR = \frac{|S_T - \bar{S}_L|}{\sigma_T}
\]

- \(S_T\) is the image intensity, averaged over a central region within the tumor
- \(\bar{S}_L = \frac{S_{L_1} + S_{L_2}}{2}\), where \(S_{L_1}\) and \(S_{L_2}\) are image intensity, averaged over regions within the lung surrounding the tumor
- \(\sigma_T\) is the standard deviation of the image intensity over the same central region within the tumor used to calculate \(S_T\)

Note: SNR and CNR should be approximately proportional to \(\sqrt{dose}\) and to linear pixel dimension
Contrast Between Materials

- Signal ➔ Average over 18,216 pixel cylinder ROI
- Noise ➔ Standard deviation in cylinder ROI
- Background ➔ Average over surrounding 189,880 pixel ROI

- $\text{SNR}_L = 6.1, \quad \text{SNR}_W = 6.7, \quad \text{SNR}_B = 5.3$
- $\text{CNR}_L = 4.4, \quad \text{SNR}_W = 5.3, \quad \text{SNR}_B = 4.1$
Lung SBRT Image Guidance

Current limitations:

- Only 2D or limited 3D information
- Additional radiation dose
- Not available during treatment / Not real-time
- Logistically complex (limited positioning options, collision danger)
- Invasive fiducial implants required
- Poor image contrast
- Not directly imaging the target
# Scatter Imaging - Experimental Data

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