Uncertainties and Quality Assurance of Localization and Treatment in Lung SBRT

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Imaging in Lung SBRT

CT
MRI
PET

Fluoroscopy
Optical
X-ray
DTS
CBCT
SPECT

CT
MRI
PET

Imaging Simulation (3D/4D)
Treatment Planning
Patient Specific Quality Control
On-Board Imaging (3D/4D)
Treatment Delivery
Treatment Assessment
The Process: Image Guidance

- **X-Ray**
- **(ExacTrac)**
- **CBCT**
- **Fluoroscopy**
- **(X-Ray/CBCT)**
- **Cine-MV, X-Ray**
- **X-Ray/CBCT**
- **RPM**
Free-breath 3D CBCT Match

Wang et al Ref J 2007
Uncertainties in lung SBRT IGRT

- Tumor volume in CBCT
- Soft-tissue contrast
- Inter-observer variations
- Reproducibility of tumor location at breath-hold
- Internal-external motion correlation
- Changes of tumor size and motion
- Changes of anatomy
- Shifts and rotations in matching
- .......
Which CT for CBCT Matching?

4DCT-AIP v.s. CBCT
Which CT for CBCT Matching?

3D FB-CT v.s. CBCT
CBCT Matching: Tiny Tumor

Tumor Size ~ 5 mm; Tumor Motion ~ 20 mm
CBCT Matching: Large Anatomical Change

Pleural effusion at Sim
Largely disappeared at 1 fx

Re-simed, Re-planned
CBCT ITV Uncertainty

ITV at different Inspiration/Expiration (I/E) Ratio

1.0  0.52  0.35  0.26  0.21

CBCT ITV Uncertainty

<table>
<thead>
<tr>
<th>Tumor</th>
<th>Free-Breathing ITV ($cm^3$)</th>
<th>4D ITV ($cm^3$)</th>
<th>Volume Underestimation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.78</td>
<td>2.97</td>
<td>40.1</td>
</tr>
<tr>
<td>B</td>
<td>35.62</td>
<td>46.98</td>
<td>24.2</td>
</tr>
</tbody>
</table>

Vergalasova et al, Med Phys 2011
Target Matching Uncertainty

Turner et al
2013 AAPM
Image Registration Uncertainty: Inter-observer Variation

Table 2  Registration differences between institutions and reviewers (for different protocols)

<table>
<thead>
<tr>
<th>Protocol no. (disease site)</th>
<th>No. of datasets</th>
<th>Absolute value of difference of shifts (mm), mean ± SD (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0915 (lung)</td>
<td>71</td>
<td>Left-right: 1.8 ± 1.2 (0.0-6.4)  Superior-inferior: 2.0 ± 1.1 (0.0-6.9)  Anterior-posterior: 2.0 ± 0.9 (0.0-5.0)</td>
</tr>
<tr>
<td>0813 (lung)</td>
<td>21</td>
<td>Left-right: 1.7 ± 0.8 (0.1-5.1)  Superior-inferior: 2.2 ± 1.0 (0.3-5.0)  Anterior-posterior: 2.0 ± 1.1 (0.1-4.8)</td>
</tr>
</tbody>
</table>

**MVCT for Lung SBRT IGRT**

![Imaging modalities](Day1, Week2, Week4)

**Siker et al, Red J, 2006**

**Table 3**  Registration differences between institutions and reviewers (for different imaging modalities)

<table>
<thead>
<tr>
<th>Imaging modality</th>
<th>No. of datasets</th>
<th>Left-right</th>
<th>Superior-inferior</th>
<th>Anterior-posterior</th>
</tr>
</thead>
<tbody>
<tr>
<td>kV CBCT</td>
<td>96</td>
<td>1.7 ± 1.1 (0.0-6.7)</td>
<td>1.6 ± 0.9 (0.0-6.9)</td>
<td>1.7 ± 1.1 (0.0-5.0)</td>
</tr>
<tr>
<td>MVCT</td>
<td>37</td>
<td>1.5 ± 1.0 (0.1-5.1)</td>
<td>3.7 ± 1.7 (0.1-8.2)</td>
<td>1.9 ± 0.9 (0.0-7.3)</td>
</tr>
<tr>
<td>Overall</td>
<td>133</td>
<td>1.7 ± 1.0 (0.0-6.7)</td>
<td>2.2 ± 1.5 (0.0-8.2)</td>
<td>1.8 ± 1.0 (0.0-7.3)</td>
</tr>
</tbody>
</table>

**Cui et al, Red J, 2011; 81:305-312.**
**Question:** Which one of the following answers represents the best estimate of the inter-observer variation in image registration in lung SBRT?

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>1.</td>
<td>1 mm</td>
</tr>
<tr>
<td>20%</td>
<td>2.</td>
<td>2 mm</td>
</tr>
<tr>
<td>20%</td>
<td>3.</td>
<td>3 mm</td>
</tr>
<tr>
<td>20%</td>
<td>4.</td>
<td>5 mm</td>
</tr>
<tr>
<td>20%</td>
<td>5.</td>
<td>&gt;5 mm</td>
</tr>
</tbody>
</table>
Discussion

Correct Answer:
2. 2 mm

Reference:

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Rotational Shifts in Lung SBRT

**Net Average of Pitch & Roll**

<table>
<thead>
<tr>
<th></th>
<th>Pitch</th>
<th>Roll</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average °</td>
<td>0.10</td>
<td>-0.10</td>
</tr>
<tr>
<td>SD °</td>
<td>1.07</td>
<td>0.65</td>
</tr>
</tbody>
</table>

**Absolute Corrections of Pitch/Roll**

<table>
<thead>
<tr>
<th></th>
<th>Pitch</th>
<th>Roll</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Mean °</td>
<td>0.87</td>
<td>0.60</td>
</tr>
<tr>
<td>Variance °</td>
<td>0.33</td>
<td>0.30</td>
</tr>
<tr>
<td>Cases &gt;0.5 °</td>
<td>69.2%</td>
<td>50.0%</td>
</tr>
<tr>
<td>Pitch or Roll &gt;0.5 °</td>
<td>89.4%</td>
<td></td>
</tr>
<tr>
<td>Pitch or Roll &gt;1.0 °</td>
<td>51.0%</td>
<td></td>
</tr>
</tbody>
</table>
Dosimetric Effects of Rotations

- 95.6% of all differences were <1% or <1Gy.
- Overall small dosimetric effects of uncorrected rotations.
Dosimetric Effects of Rotations

- Large inter-subject variations at large rotation angles.
- Up to 4% reduction in PTV coverage, 6 Gy increase in cord D0.35cc, and 4 Gy in Esophagus D0.35cc observed.
Cine MV: tumor motion during TX

Tumor motion during 5-fx lung SBRT

Zhang et al, RPO 2013

4D-CT

Mean $R_{MV}$ (mm)

$Y = 0.8X$

$r = 0.50$

Max $R_{MV}$ (mm)

$Y = 0.7X$

$r = 0.88$

$Y = 1.7X$

$r = 0.49$

$Y = 1.3X$

$r = 0.83$
Intra-fractional Mean Tumor Position Shift

- Intra-fractional variation:
  - AP: 0.0 ± 1.7 mm
  - ML: 0.6 ± 2.2 mm
  - SI: −1.0 ± 2.0 mm
  - 3D: 3.1 ± 2.0 mm

- 3D vector variation:
  - > 2mm in 67.8%
  - > 5mm in 14.3%

- Depending on immobilization (Range: 2.3 – 3.3 mm)
  - Body Frame < Alpha Cradle < Body Fix < Wing Board


409 Patients
427 Tumors
1593 Fractions

Intrafraction Variation
Change of Tumor Size During Lung SBRT

- Initial tumor size: 0.7-7.3 cm
- Change of tumor diameter:
  Range: -34.2% to 33.0%
  Mean: -7.9 ± 11.45%

Qin et al, Red J, 2013

40 lung SBRT patients
ExacTrac

<table>
<thead>
<tr>
<th>ExacTrac 6D v.s. CBCT 6D</th>
</tr>
</thead>
<tbody>
<tr>
<td>ML: 1.06 mm</td>
</tr>
<tr>
<td>Pitch: 1.22°</td>
</tr>
<tr>
<td>AP: 1.43 mm</td>
</tr>
<tr>
<td>Row: 0.64°</td>
</tr>
<tr>
<td>SI: 1.43 mm</td>
</tr>
<tr>
<td>Yaw: 1.66°</td>
</tr>
</tbody>
</table>

- Small but maybe clinically significant discrepancies between ExacTrac X-ray 6D and CBCT 6D match

Chang et al, Radiother Oncol, 2010
Cyberknife

- **Targeting error**: 0.1 – 0.3 mm
- **Correlation error**: 0.3 – 2.5 mm
- **Prediction error**: 1.5 ± 0.8 mm
- **Total error**: 0.7 – 5.0 mm

Pepin et al, Med Phys. 2011
**Question:** Which one of the following answers represents the best estimate of the mean intra-fractional 3D tumor position shift in lung SBRT?

<p>| | | | | | |</p>
<table>
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<tr>
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<tr>
<td>1</td>
<td>20%</td>
<td>1 mm</td>
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<td></td>
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</tr>
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<td>4</td>
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<td>5</td>
<td>20%</td>
<td>&gt;5 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Correct Answer: 
3. 3 mm

Reference:
Onboard DTS Imaging

Free-breathing Reference DTS

Phase-matched Reference DTS

On-board Acquired DTS

Better Match

Courtesy from Dr. Ren of Duke University
MRI for Image Guidance
On-Board SPECT

- SPECT on robotic arm
- Molecular targeting
- Multi-Pinhole collimation

4-min scans
7, 10 mm hot spots

Courtesy from Dr. Bowsher of Duke University
Summary

- Uncertainties exist in each step of image guidance of lung SBRT
- Understanding root causes and characteristics of these uncertainties is important for successful implementation of lung SBRT
- Next generation of on board imaging techniques has the potential to minimize uncertainties of image guidance of lung SBRT