Quality Control of Lung SBRT: from 4D Simulation to 4D Verification

Learning Objectives:
1. Provide an evidence-based systematic review of uncertainties during lung SBRT
2. Discuss the root causes of the uncertainties and corresponding quality control strategies
3. Present data-driven practical and effective solutions to minimize the uncertainties

Speaker List and Topics

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<tr>
<th>Topic</th>
<th>Speaker (Institution)</th>
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<tr>
<td>Uncertainty and QA for simulation and planning</td>
<td>Fang-Fang Yin, PhD Duke University</td>
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<tr>
<td>Uncertainty and QA for target delineation</td>
<td>Jeffrey Bradley, MD Washington University</td>
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<td>Uncertainty and QA for delivery techniques</td>
<td>Stanley Benedict, PhD UC Davis Health System</td>
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<td>Uncertainty and QA in localization and tacking in the treatment room</td>
<td>Krishni Wijesooriya, PhD University of Virginia</td>
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<td>Uncertainty and QA for machine and patient specific QA</td>
<td>Jing Cai, PhD Duke University</td>
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Uncertainty and QA for Simulation and Planning
Fang-Fang Yin, PhD
Duke University Medical Center

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Workflow for Lung SBRT

Salama, Kirkpatrick, and Yin
Nature Reviews/Clinical Oncology 2012

Uncertainties in Simulation and Planning

- Patient and motion constraints
  - Immobilization consideration
  - Surrogates (if applicable)
- Motion management
  - 3D-FB, 3D-BH, 4D-10 phase
  - MAX-IP (MIP), AVE-IP (AIP), MIN-IP (MinIP)
- Image fusion/interpolation
- Tumor ITV delineation based on 4DCT
- Interplay effect
  - tumor motion and MLC leaf motion
- Dose calculation
Approaches to Minimize Uncertainties

- Minimize motion
  - Patient motion: immobilization
  - Organ motion: motion management, organ “immobilization”
- Minimize target volume delineation
  - Better imaging:
- Improve dose calculation
  - Better algorithm
  - Better images
  - Interplay
- Ensuring the accuracy – phantom based process QA

Patient Motion: Immobilization

- Body Immobilization
  - BodyFix
  - Body frame
  - Styrofoam

Goals for immobilization:
- To minimize patient and organ motion
- Comfortable, stable, reproducible, or predictable motion

IGRT does not replace immobilization, only checks and monitors motions

Active Breathing Control

- The residual errors of GTV
  - ML: 0.3±1.8 mm
  - AP: 1.2±2.3 mm
  - SI: 1.1±3.5 mm


- Remains some inter-breath hold variability in peripheral lung
- Limited reduction of PTV margin

Abdominal Compression

- Mean motion reduction:
  - 3.5 mm for lower lobe tumors
  - 0.8 mm for upper/middle lobe

- Sometime, compression increased tumor motion

- Mean ITV reduction:
  - 3.6 cc for lower lobe lesions
  - 0.2 cc for upper/middle lobe lesions

- Dosimetric gain for lung sparing was not clinically relevant

- Boullhol et al, 2012, Phys Med

Organ “Constraints” in SBRT

- Total intravenous anesthesia (TIVA)
- High-frequency jet ventilation (HFJV)

- Animal study:
  - Motion range: < 3 mm

Organ Motion: Surrogates/Imaging

- Anatomical surrogates
  - Diaphragm
  - Bony structures
  - Tumor
- Implanted surrogates
  - Gold seeds
  - Coils
  - Devices

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Needle Gauge</th>
<th>Prostate</th>
<th>Breast</th>
<th>Lung</th>
<th>Cervix</th>
<th>Liver</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45 mm</td>
<td>21 g</td>
<td>1 cm</td>
<td>1 cm</td>
<td>1 cm</td>
<td>1 cm</td>
<td>1 cm</td>
</tr>
<tr>
<td>0.85 mm</td>
<td>18 g</td>
<td>1 cm</td>
<td>2 cm</td>
<td>1 cm</td>
<td>1 cm</td>
<td>1 cm</td>
</tr>
<tr>
<td>1.15 mm</td>
<td>17 g</td>
<td>1 cm</td>
<td>2 cm</td>
<td>1 cm</td>
<td>1 cm</td>
<td>2 cm</td>
</tr>
</tbody>
</table>

**Imaging Modality**

<table>
<thead>
<tr>
<th>Diameter</th>
<th>CT-kV</th>
<th>Fluoro-TAS/US</th>
<th>EPID-Portal-kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45 mm</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>0.85 mm</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>1.15 mm</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

Challenges:
- Poor soft-tissue contrast
- Only produce one breathing cycle
- Correlation between internal target and external surrogates
- Imaging dose...

Errors from recorded breathing pattern from surface marker

Deviated Corrected

Errors from recorded breathing pattern from surface marker

Organ Motion: 4DCT Imaging

Verification of 4DCT

Sample Images in Lung SBRT

3D-FB 4DCT-AIP 4DCT-MIP


Jing et al
4DCT Imaging – Treatment Validation

Is 4-D CT enough for motion pattern?

Cine 4D MRI

Portal image

Fluoroscopic imaging

4DCT Validation: XCAT Phantom

• Segars et al. Realistic CT simulation using the 4D XCAT phantom Med. Phys. 35(8). 2008
• Segars et al. 4D XCAT phantom for multimodality imaging research Med. Phys. 37(9). 2010

4DCT Validation: XCAT Phantom

Contouring Variation in NSCLC

Data from multi-institutional pre-clinical trial planning study of RTOG 1106


Target Delineation: Multimodality Imaging

Courtesy from Dr. Kong, U. Michigan

Which CT for ITV Delineation?

ITV_{10phase} (blue line)

ITV_{4D} (green line)

GTV_{30} (red line)

Ge et al, Red J 2012
**Tumor ITV Individualization**

- 3DCT
  - MIP
  - ITV1
  - ITV3
  - ITV5

- 4DCT
  - 10-phase
  - AIP

With irregular breathing patterns, ITV is always an approximation.

- Tumor Motion
- Tumor Size
- Tumor Location
- Breathing Irregularity

**Case: ITV, PTV Determination**

- ITV = GTV_FB + GTV_MIP
- PTV = ITV + Setup Margin (3-5mm)

**Caution: Proper Margin Design**

- Motion
  - Immobilization
  - Motion management
- Motion management technique
  - Breath hold
  - Gated treatment
  - Free breathing
- Delivery technique
  - Dose rate
  - 3D CRT
  - IMRT/VMAT

- Margin should be estimated by imaging.
- Margin should be added for each uncertainty.
- If all have been considered, 5 mm margin is still recommended.

**Respiratory Gating Planning**

- MIP_GatedPhases
- MIP_AllPhases

- MIP_AllPhases (0%-90%)
- MIP_GatedPhases (30%-70%)
- AIP_AllPhase (0%-90%)
- AIP_GatedPhases (30%-70%)

- ITV, PTV
- CBCT online match
- Dose calculation

**How Accurate is 4DCT AIP?**


- '4DCT' Truth

**Organ Motion: ITV Variation from MIP**

- 3 MIP ITV's

- ITV varies with breathing pattern

- Turner, et al AAPM 2012
Organ Motion: ITV Underestimation

<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>
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Vergalasova et al, Med Phys 2011

Considerations for Planning

- Beam design/Clearance
- Delivery technique
- Dose calculation
- Image guidance strategy
- Motion management strategy
- Verification method
- Treatment adaptation

Beam Design and Planning Techniques

- Dynamic Arcs
- VMAT
- IMRT
- 3D-CRT

Which CT for Dose Calculation?

- FB
- AIP
- MIP


QA: Which CT for Dose Calculation?

- AIP vs. FB
  - Dosimetric similarity
  - Target volume better for AIP
- AIP vs. MIP
  - MIP has slightly better target coverage
  - MIP datasets are prone to under- or over-estimate both OAR and target volumes
- AIP dataset is more suitable for planning


Caution: Inhomogeneity Correction

With heterogeneity corrections applied:

- Volume of PTV receiving 60 Gy or more (V60) decreased on average 10.1% (SE=2.7%) from 95% (p=0.001)
- Maximum dose to any point 2 cm or greater away from the PTV increased from 35.2 Gy (SE =1.7 Gy) to 38.5 (SE=2.2 Gy)

**Beam-on timing**
Beam-on at different points in breathing period

**Differences in delivered dose**

**Cautions: MLC Interplay Effect**

**Interplay Between Tumor Motion and MLC Leaf Motion**

**Patients:** 10
**GTV:** 2.9 – 138.1 cm³
**Motion:** 0.8 – 2.8 cm

**CONCLUSIONS:** Both VMAT and IMRT plans experienced negligible interplay effects between MLC sequence and tumor motion. For the most part, the 3D-dose to the GTV and critical structures provided good approximations of the 4D dose calculations.

**When Tumor Is Too Small**
- PTV margin
- MLC leaf width
- Image guidance
- Small field dose calculation

**Lung Motion Displacement Vectors**

**Deformable Registration**
**Truth**

**Deformation from inhalation to exhalation**
Cai, et al

**Caution: Dose Deformation**

**Adaptation: Is Replanning for Lung SBRT Needed?**

Qin et al, Red J, 2012
Summary

- Treatment uncertainty could be reduced
  - Proper selection immobilization method
  - Patient specific motion management strategy
  - Comprehensive patient-specific plan design
- Each step needs to be carefully validated
- A phantom-based QA process could provide a tool to validate the treatment.

Thank you for your intention!