Sources of Motion: Imaging and Monitoring

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Outline
- Within the context of photon Stereotactic Body Radiation Therapy (SBRT)
  - Definition SBRT and margin consideration
  - Sources of motion and management
  - Special consideration in SBRT for various sites

Why SBRT needs special attention on motion management?
Definition of SBRT

- Important characteristics:
  - High fractional dose
  - Precise target definition
  - Margin in millimeter range
  - Direct imaging monitoring and accurate dose delivery
- SBRT is used in various sites: lung, liver, pancreas, prostate, spine, head-and-neck, and others

Benedikt et al. AAPM TG101

PTV Margin Consideration

- Tight margin:
  \[ \text{PTV} = \text{GTV} + 3-7\text{mm margin} \]
- Rapid dose fall-off:
  \[ \text{Prescription line at 80\%, } 105\% \text{ line confines GTV, and maximum dose at iso-80\% line or } D_{\max} \text{ at } 2\text{cm also tightly restricted} \]

Achieve Precision in SBRT Workflow

- PRECISION is the key for the success of SBRT treatment
- Consider motion management in every step
Sources of motion and their management

Sources of Motion in RT

- Level One: patient position/external motion:
  - Patient position at treatment differs from the planning scan
  - i.e. moving a limb, head tilt, body rotation, etc.
- Level two: Inter-fractional organ/target motion:
  - GTV/CTV position changes on a day-to-day level;
  - OARs position/volume changes, i.e. bladder, rectum, bowel, etc.
- Level three: Intra-fraction organ/target motion
  - HN region: upper airway motion and swallowing
  - Lung/upper abdominal region: respiratory motion, cardiovascular system motion, etc.
  - Lower abdominal region: prostate, cervix, etc.

Level One Management: Patient Immobilization

- Importance:
  - Provide an initial approximate patient setup and target localization
  - Provide body fixation, high reproducibility and accuracy
  - Solely relying on image guidance is not allowed
- Typical devices:
  - Thermoplastic mask,
  - Platform/couch top, vacuum cushion, bridge with respiratory plate or belt
  - Knee fix, feet fix, etc.
Inter-fraction Organ Motion

- Daily organ displacement can be significant
  - Prostate: bladder, rectum, prostate, etc.
  - Liver, pancreas, kidney all have day-to-day displacement
- Level two motion management strategies
  - Organ immobilization
  - IGRT localization

Organ Immobilization

- Bladder
  - Full bladder protocol (volume change still significant >20%)
- Rectum
  - Endorectal balloon (ERB): high dose of the anterior rectal surface, deformation
  - Rectal spacers: biocompatible liquid gel to create physical separation, no evidence of prostate immobilization
  - Endorectal immobilization system, intra-fraction motion<3mm

IGRT for Target Localization

- Daily In-room Image Guidance
  - Target visualization and localization
  - Online correction (minimal 3 orthogonal directions)
- Available imaging modalities:
  - Volumetric 3D: kV-CBCT, MV-FBCT, MV-CBCT, CT-on-rail, MRgRT,
  - 3D orthogonal with metal/EM fiducials: kV OBI, ExacTrac, Cyberknife, etc.
  - Others: 4D CBCT, 3D Ultrasound, 6D couch, etc.
Intra-fraction Target/Organ Motion

- Level three motion management: further minimize and/or monitor target motion to meet the tight margin requirement (3-7mm)

- Thoracic and abdominal sites:
  - Respiratory motion
  - Cardiovascular system motion, etc.

- Prostate motion

- HN: upper airway motion, swallowing

Intra-fractional Monitoring

- 2D Modalities:
  - Onboard kV-Fluoroscopy
  - Onboard MV-Cine
  - Floor/ceiling mount kV-kV: ExacTrac and CyberKnife
  - MR-Cine

- Application
  - Motion assessment at simulation
  - Motion monitoring during treatment
  - Others: Surface imaging, Ultrasound, EM system, etc.

Special Consideration for Lung/Abdominal SBRT
Lung Tumor Motion Pattern

- 145 lung SBRT patient treated with CyberKnife
- Motion range in SI direction during treatment

The larger the tumor motion amplitude, the higher the intra-fraction amplitude variability observed.

Abdominal Compression

- Lung SBRT with compression:
  - Mean motion reduction: 3.5mm for lower lobe and 0.8mm for upper/middle lobe
  - Mean ITV reduction: 3.6cc for lower lobe and 0.2cc for upper/middle lobe

Liver SBRT with compression:

- Mean liver motion measured with 4D CBCT prior to treatment: 1.2 mm (LR), 2.3mm (AP) and 4.7 mm (SI)

ITV volume reduction with the abdominal compression

Uncertainties should be taken into account for ITV → PTV margin
Simulation with Motion

- **Common Practice:**
  - 4D CT Imaging using surface motion trajectory \( \rightarrow \) phases CT, MIP, AIP, MinIP
  - Additional scans: FB-CT, Inhale/Exhale BH-CT
- **4D CT Image Quality Challenges:**
  - Poor soft tissue contrast
  - Breathing irregularity, rely on only one breathing cycle
  - Poor correlation between internal target and external surrogates

Uncertainties in ITV Definition

- **ITV uncertainties caused by**
  - Different breathing pattern
  - Phase binning vs. amplitude binning
  - Different imaging mode
  - Tumor size

Uncertainties in 3D Target Matching

- 4DCT-AIP (planning) vs. CBCT
- **Inter-observer variations:**
- **KV CBCT vs. MVCT**

<table>
<thead>
<tr>
<th>Table 1: Registration difference between various cut angles (for different imaging modality)</th>
<th>MIP</th>
<th>CBCT</th>
<th>CBCT - FBCT</th>
<th>CBCT - AIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient</td>
<td>No. of images</td>
<td>Mean value of difference of shifts (000,100,000)</td>
<td>Mean value of difference of shifts (000,100,000)</td>
<td>Mean value of difference of shifts (000,100,000)</td>
</tr>
<tr>
<td>Head</td>
<td>17</td>
<td>1.4 (0.66, 0.7)</td>
<td>1.5 (0.64, 0.8)</td>
<td>1.7 (0.89, 0.90)</td>
</tr>
<tr>
<td>Neck</td>
<td>10</td>
<td>1.0 (0.1, 1)</td>
<td>1.0 (0.1, 1)</td>
<td>1.0 (0.1, 1)</td>
</tr>
<tr>
<td>Chest</td>
<td>11</td>
<td>1.0 (0.01, 0.001)</td>
<td>1.0 (0.1, 0.2)</td>
<td>1.0 (0.1, 0.2)</td>
</tr>
</tbody>
</table>

Cai et al, AAPM 2015
Uncertainties in Treatment Planning

- 4DCT AIP vs. MIP
  - MIP has slightly better target coverage
  - MIP is susceptible to motion artifacts
  - MIP is prone to under- or over-estimate both OAR and target volumes
- 4DCT AIP is recommended for planning

Tian et al, Med Phys 2012

Tumor Motion and Overall Uncertainties

- Inter- and Intra-fractional Tumor Motion
- Uncertainties during simulation, treatment planning, treatment delivery
- Can we safely conform target dose within the required margin?
- Other strategies...

Image courtesy of Ben Cooper

Special Consideration for other SBRT Sites: Prostate, HN, Heart, etc.
Prostate Motion

- Prostate SBRT requires high fraction dose and tight margin (3-5mm)
- Intra-fractional prostate motion is observed
  - Prostate motion and volume deformation
  - Involuntary prostate motion due to bowel gas movement (>1cm)

Prostate motion due to rectal distention

NRG GU005 Prostate SBRT protocol
RTOG 0938
PTV = CTV + 3 mm posterior margin and 5 mm in all other dimensions.

If necessary, the anterior margin can be reduced to 3 mm.

Electromagnetic System

- Calypso system: EM source coils, EM transponders (Beacon™), and sensor array
- Advantages: patient positioning and intra-fraction monitoring;
  - Accuracy 1-2 mm

- Limitations:
  - Invasive, need to implementing 3 markers
  - Special Calypso kVue™ couch
  - Patient size, metal implants, pacemaker

CyberKnife

- CyberKnife system
  - Robotic gantry, 6D couch, tracking system
  - Transrectal Implant 3 gold markers
  - kV/kV images acquired during treatment, at intervals 5-90s

- Achieve sub-millimeter accuracy
  - 36.25Gy/4 fractions to PTV (margin: 5mm, 3mm posterior)
  - 38Gy/4 fractions to PTV (virtual HDR dose, with 2-5mm margin, 0mm posterior)
3D Ultrasound System

- Clarity Autoscans System
  - TPUS probe, a baseplate, knee rest, IR camera tracking the probe
  - Acquired baseline image at time 0
  - Intra-fractional monitoring and correction, compared with the baseline image
- Autoscans vs. marker-measured motion: median error <3 mm

<table>
<thead>
<tr>
<th>Time</th>
<th>Error (mm)</th>
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<tbody>
<tr>
<td>0%</td>
<td>-2.1±3</td>
</tr>
<tr>
<td>10%</td>
<td>-0.9±0.5</td>
</tr>
<tr>
<td>75%</td>
<td>-0.8±1.5</td>
</tr>
<tr>
<td>90%</td>
<td>-0.6±1.1</td>
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</table>

MRgRT

- MRgRT for Localization
  - No need for gold marker/EM beacon implantation
  - Improved image quality and visualization
- MR-Cine for Target Monitoring
  - Intra-fractional prostate motion (thin red line)
  - due to rectal distension from bowel gas movement
  - Treat with 3 mm PTV margin, Gated delivery with dose shut off at <3 mm

Heart SBRT

- Heart motion monitoring and management is needed for Ventricular Tachycardia Ablation (25 Gy in one fraction)
- Heart volume change and centroid shift (2-8 mm)
- MR-Cine application: in-treatment motion analysis and heart margin assessment

![Image of heart monitoring and management](image_courtesy_of_hua_li_washington_university)

- Targeting the arrhythmogenic scar regions, matching with CBCT

![Image of heart monitoring and management](image_courtesy_of_hua_li_washington_university)
Head and Neck SBRT

- Upper airway motion during resting
  - Non-symmetric displacements of anterior (mean 2.6mm), posterior (2.9mm), inferior (3.5mm), and superior (0.7mm) boundaries
  - For patients with tracheostomy tube, displacement > 4 mm
- Displacement can be higher during swallowing

Summary

- SBRT indicates high fraction dose, tight PTV margin, and rapid dose falloff
- Sources of motion and different levels of management strategies
- Special motion management consideration for all SBRT sites
  - Lung/abdomen SBRT
  - Prostate SBRT
  - Heart and HN SBRT

Thank You