Lung SBRT
4D simulation, Planning, and QA

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Learning Objectives

• To understand the physiological characteristics of tumor motion in different treatment sites.
• To understand what data set to employ for ITV definition and dose calculation
• To understand the available technology for planning in SBRT
• To understand the importance in performing and End to end QA for any new motion management system introduced into a clinical program

Motivation

• SBRT, if misdirected or used too liberally, could lead to debilitating toxicity
• Lung SBRT due to motion complicates the situation
• Capture the 4th dimension accurately
• Deliver the intended plan dose to the tumor
• Minimize healthy tissue toxicity -> escalate dose to tumor

Safety Margins
Measurements of tumor motion

- **Lung tumors**: Liu HH et al IJROBP 2007; 68: 531-540 – 152 patients
  - Up to 3cm inferior motion
  - 95% of lung tumors move <1.3cm I/S, <0.4cm L/R, and <0.6cm A/P
  - Tumor motion is highly correlated with diaphragm motion and tumor location in S/I

- **Abdominal tumors**: Bradner GS et al IJROBP 2006; 65: 554-560
  - 13 patients
  - Up to 2.5cm inferiorly for all tumors, motion up to 1.2 cm A/P observed for liver and kidneys
  - Mean S/I displacements: Liver 1.3cm; Spleen 1.3 cm; Kidneys 1.2cm

GTV motion inhale vs. exhale

2.5 cm displacement in craniocaudal direction

GTV motion with time
Hysteresis of lung tumor motion

1-5mm hysteresis of breathing trajectories measured
Seppenwoolde Y. et al. “Precise and real-time measurement of 3D tumor motion in lung due to breathing and heartbeat measured during radiotherapy” IJROBP 2002; 53:822-834

Ideally what we want to do (IGRT)

Gold Standard
4D Radiotherapy

4D CT Imaging
Acquisition of a sequence of CT image sets over consecutive phases of a breathing cycle

4D Treatment Planning
Designing treatment plans on CT image sets obtained for each phase of the breathing cycle

4D Treatment Delivery
Continuous delivery of the 4D treatment plans throughout the breathing cycle

Courtesy of Paul Keall
4D treatment planning in the clinic

手动 vs. 自动描边结果的比较，针对单个患者，横截面、矢状面和冠状面的视图来自Pinnacle 7.7。红色边界是吸入相的。过渡色边界是手动描边的呼气相。自动边界从吸入到呼气为：黑色（GTV），黄色（颈椎、心脏），粉色（食道），白色（肺）。


DVF to warp dose distributions to propagate them from end expiratory phase to all other phases

Deformable Image Registration

- Technique by which a single moving voxel is matched on CT slices that are taken in different phases of respiration
- The treatment is planned on a reference CT – usually the end expiration (for Lung)
- Matching the voxels allows the dose to be visualized at each phase of respiration
- Several algorithms under evaluation:
  - Finite element method
  - Optical flow technique
  - Large deformation diffeomorphic image registration
  - Splines thin plate and b

• Enormous requirements on:
  – Personnel
  – Computational resources
  – Time resources
• New class of uncertainties
• Calculated dose is good only for a given respiratory pattern – respiratory motion unpredictable
• Clinical benefit is still unknown

4D Radiotherapy is still clinically prohibitive
Some examples of limitations...

- Computing resource intensive – Parallel calculations require computer clusters at present
- No commercial TPS allows 4D dose calculation
- Respiratory motion is unpredictable – calculated dose good for a certain pattern only
- Incorporating respiratory motion in dynamic IMRT means MLC motion parameters become important constraints
- Tumor tracking is needed for delivery if true potential is to be realized
- The time delay for dMLC response to a detected motion means that even with tracking gating is important

Simplified Approach to 4D Treatment Planning

- 4DCT acquisition
- Accurate tumor volume definition that encompasses all tumor locations – motion envelope
- A 3D plan performed on the ITV + margins
- On an appropriate reference dataset

Accounting for respiratory motion at simulation

- Respiratory correlated CT/4DCT
  - Cine CT – couch stationary while repeat CT for images acquired corresponding to different phases of respiratory cycle, couch incremented
  - Helical CT – reducing the pitch 0.5-0.1, and adjusting CT parameters such that CT beam on for at least on respiratory cycle at each couch position.
Philips Multi-slice CT Scanners with RPM Respiratory Gating

Retrospective 4D CT Image Acquisition - cine mode

4D CT Image Definitions

**Helical CT:** Helical CT without 4D CT. Snap shot of the anatomy.

**MIP (Maximum Intensity Projection image):** Reflect the highest data (hyper-dense) value encountered along the viewing ray for each pixel of volumetric data, giving rise to a full intensity display of the brightest object along each ray on the projection image.

So if you are interested in identifying high contrast objects (lung tumor, stents etc.) better to have a MIP
4D CT Image Definitions

MinIP (Minimum Intensity Projection image): projections reflect the lowest data (hypodense) value encountered along the viewing ray for each pixel of volumetric data.

So if you are interested in identifying low contrast objects (liver, pancreas etc...) better to have a MinIP

4D CT Image Definitions

Helical MIP MinIP

Sources of Error in 4DCT

Irregular patient breathing – regular and reproducible breathing by coaching
CT image reconstruction algorithm
Resorting of reconstructed CT images with respiratory signal (phase/amplitude or combination of two)
Mismatch of respiratory phase between adjacent couch positions

Amplitude binning is better than phase binning

W/L Matters
Very small tumors 5cc or less, with large motion amplitudes >1.5cm, due to sampling resolution will show discrete volumes even in FULL_MIP in mediastinum window.

MIPs can be problematic, helpful to review phases:

- Drawback for target delineation: where background and tumor have similar HU, tumor is not as clearly defined.
- Example: Caudal extent of ITV may not be correct due to overlap with diaphragm.
- Review individual phases.
- For this case, send additional scans, e.g. max inhale and max exhale scans to help MD assess tumor motion.
Tumor adjacent to diaphragm

Underberg RWM et al IJROBP 2005; 63:253-260

UVA planning for lung

- Scan the full thorax/abdomen
- Obtain the 10 phased 4D CT image sets
- Reconstruct a MIP image Using the 10 4D CT image sets – if treat with no gating
- Reconstruct a MIP image Using the gated window (eg:30% -70%)4D CT image sets – if treat with gating
- Plan on average intensity image with ITV defined from MIP/PET images

FFF VMAT for lung SBRT

Left – FFF, Right –FF. Notice the better conformity of the 50% isodose (green) line in FFF beams in all three dimensions.
FFF VMAT for lung SBRT

FFF beams (in squares) and FF beams (in triangles). PTV – red, 50% prescription isodose – pink, dose distribution beyond 2cm from PTV – green, cord – orange, esophagus – khaki, and total lung – GTV – yellow. Notice that in all cases, FFF beams give a lower out of field dose to different extent when both plans are normalized to cover 95% of PTV to receive the prescription dose.

0915 Reductions with FFF

• Reductions (mean, STD, p-value, maximum) are:
  • High dose spillage location (-0.09%, 0.17%, 0.028, -0.57%)
  • High dose spillage volume (-0.98%, 1.67%, 0.017, -6.1%)
  • Low dose spillage volume (-3.01%, 3.33%, 0.001, -11.59%)
  • V20 (2.38%, 3.08%, 0.032, -5.77%)
  • V12.4 (2.27%, 1.73%, 0.003, -4.99%)
  • V11.6 (2.26%, 1.44, 0.001, 5.00%)

Table 3: Mean and standard deviation for conformity criteria, lung doses, and integral doses as a percentage difference and as absolute difference for FFF VMAT (pared to VMAT).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Mean</th>
<th>STD</th>
<th>p-value</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prescription Isodose Surface</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.05%</td>
<td>0.69%</td>
<td>0.05</td>
<td>0.000</td>
</tr>
<tr>
<td>% PTV covered by 100% No dose</td>
<td>0.01%</td>
<td>0.04%</td>
<td>0.01</td>
<td>0.024</td>
</tr>
<tr>
<td>Low dose spillage</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High dose spillage location</td>
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0813 Reductions with FFF

- Reductions (mean, STD, p-value, maximum) are:
  - Low dose spillage volume (-3.27%, 3.87%, 0.026, -11.23%)
  - V20 (3.63%, 2.97%, 0.004, 9.88%)
  - V13.5 (4.47%, 4.48%, 0.04, 12.77%)
  - V12.5 (4.29, 4.51, 0.04, 11.75%).

1. What type of image/images should be used for tumor volume delineation when the lung tumor is attached to the diaphragm?

7%  1. Maximum intensity projection image (MIP)
20%  2. MIP image and the phase images of inhalation phases
10%  3. Time average (untagged) image
30%  4. 3DCT image with no time information
27%  5. Minimum intensity projection image
• Answer: 2

• References: Underberg RWM et al IJROBP 2005; 63:253-260

What dataset should be chosen for planning?

• Dose computation should be close to cumulative 4D dose computed using all datasets

• Anatomy of this image set should correlate well with the tumor image of pre-treatment image (CBCT/MVCT)

• Average intensity image should be used for planning

2. What is the optimum dataset for dose calculation of a lung Tx?

- 10%: 3DCT image which carries a snapshot of the tumor position
- 7%: Maximum intensity projection image (MIP)
- 23%: Minimum intensity projection image (Minip)
- 30%: Time average (untagged) image
- 20%: CBCT image
Gated Radiotherapy

To ensure an Accurately Gated Treatment, QA steps:

- During patient setup, tumor home position at this fractionation should be matched to the reference home position – image guidance (x-ray, ultrasound, implanted E.M transponders), lung tumor or diaphragm, liver: implanted fiducial markers.
To ensure an Accurate Externally Gated Treatment, QA steps

During patient setup tumor home position at this fractionation should be matched to the reference home position – Image guidance in ray: ultrasound, implanted E.M transponders, lung: tumor or diaphragm, liver: implanted fiducial markers – to avoid inter-fraction variation

To Ensure an Accurate Externally Gated Treatment, QA Steps Continued...

During Tx delivery, measures should be taken to ensure constant tumor home position (tumor should be at the same position when the beam is on) visual coaching, visual aids - stable EOE position by two straight lines for amplitude gating

(A), (c) - free breathing – baseline shift & irregular breathing
(b), (d) - audio-visual coaching

How to ensure treatment accuracy when internal target position is predicted using external surrogates

Surrogates used to generate gating signals
1. External surrogates: markers placed on the patient’s outside surface
   1. Varian RPM system
   2. Active breathing control using spirometry
   3. Siemens Anzai pressure belt: bellows system
   4. Medspira respiratory monitoring bellows system
Diaphragm as an internal surrogate


Three Phases of 4D QA

- Typical QA measures
- Initial testing of equipment and clinical procedures: CT scanner, fluoroscope, linac, gating
- Frequent QA examination during early stage on implementation


4DCT scan QA


- 9 centers, 8 Philips, Siemens, GE CT scanners, 1 Siemens PET-CT scanner
- Widely varying imaging protocols
- No strong correlation found between specific scan protocol parameters and observed results
- Average MIP volume deviations 1.9% ($\varphi$15, R =15mm), and 12.3% ($\varphi$15, R =25mm) -0.9% ($\varphi$30, R =15)
- End expiration volume deviations -13.4%, $\varphi$15, 2.5%, $\varphi$30
- End inspiration volume deviations -20.7%, $\varphi$15, 4.5%, $\varphi$30
- Mid ventilation volume deviations -32.6%, $\varphi$15, 8.0%, $\varphi$30
- Variations in mid-ventilation origin position - mean, 0.2mm; range, 3.6-4.2
- Variations in MIP origin position - mean, -0.1mm; range, -2.5-2.5
- Range motion is underestimated - mean, -1.5mm; range, -5.5-1
Annual QA – 4DCT

Measurement Setup:
Set the motion range 10 mm –SI of Quasar phantom and image using 4DCT (slice thickness: 0.2 cm) synchronized with RPM.
9.87 mm (0.13 mm deviation)

Annual QA – Treatment with gating

Annual QA – Temporal accuracy of phase/amplitude gating

TG-142 tolerance: 100 ms of expected

Measurement Setup:
Using OmniPro IMRT software, set 20 ms/ frame (50Hz) and measure the images synchronized with RPM measurement.
RPM signal has a time resolution 33ms/frame (30 Hz)

Annual QA – Treatment with gating

TG 142
Prior to establishing a lung SBRT program in your clinic, how do you verify the accuracy of motion management program in your clinic?

20%  1. Perform an end to end QA requesting a RPC motion phantom for lung or Quasar motion phantom with lung density material
27%  2. Perform end to end QA using your IBA matrixx system
27%  3. Perform end to end QA using your Delta4 device
13%  4. Perform end to end QA using your annual scanning system
10%  5. Measure the energy of the machine with and without gating
Answer: 1
References:
  • TG 101

Summary/Conclusion

1. Motion envelope should be measured prior to ITV definition
2. Particular care should be given to tumors attached to chest wall/diaphragm
3. Planning CT should be a time averaged CT image
4. Gated image reference position should be verified prior to Tx
5. End to end QA program should be established prior to going clinical

Acknowledgements

• Thanks to University of Virginia Dept. of Radiation Oncology!