Stereotactic Body Radiation Therapy (SBRT) II: Physics and Dosimetry Considerations

Kamil M. Yenice, Ph.D.
University of Chicago

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Overview

- SBRT planning and delivery considerations
  - Beam margins – lung
  - Beam geometry
  - Image-guidance and system accuracy, QA
- Institutional experience
  - U of Chicago Multiple Mets Trial
  - Treatment process
    - Planning
    - Delivery
    - Verification and QA
- Summary

Beam Geometry: most dominant factor for SRS dose

Increased conformity and dose gradients require many well-separated beams in 3D!

Limited non-coplanar Beam Geometry for SBRT

Lung: geometrically optimized beams

<table>
<thead>
<tr>
<th>Beam Configuration</th>
<th>Dose (cGy)</th>
<th>PTV Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field 1</td>
<td>25</td>
<td>90.2</td>
</tr>
<tr>
<td>Field 2</td>
<td>15</td>
<td>100.0</td>
</tr>
<tr>
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<td>10</td>
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Liver: geometrically optimized beams

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<td>100.0</td>
</tr>
</tbody>
</table>

Restricted deliverable beam space for SBRT (Li et al PMB, 2004)
Beam “penumbra” margin

For the same prescription dose at the tumor:
- smaller beam margin ⇒ higher MU and higher dose to lung in the beam path
- larger beam margin ⇒ less MU and more normal lung outside tumor

What is the optimal beam/block margin that minimizes normal tissue toxicity?

Study 1. Cardinale et al (UROBP, 1999) – DVH parameters (PTV, V100%, V50%, D50) and NTCP for lung and liver for 6MV photon beam margins of -2.5 to 18 mm:

<table>
<thead>
<tr>
<th>Beam Margin (mm)</th>
<th>PTV=14 cm³</th>
<th>55 cm³</th>
<th>22 cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2.5</td>
<td>-2.5</td>
<td>-2.5</td>
<td>-2.5</td>
</tr>
<tr>
<td>-1.0</td>
<td>-1.0</td>
<td>-1.0</td>
<td>-1.0</td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>1.0</td>
<td>1.0</td>
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<td>1.0</td>
</tr>
<tr>
<td>2.5</td>
<td>2.5</td>
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<td>2.5</td>
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<tr>
<td>5</td>
<td>5</td>
<td>5</td>
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<tr>
<td>10</td>
<td>10</td>
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<tr>
<td>15</td>
<td>15</td>
<td>15</td>
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</tr>
<tr>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
</tbody>
</table>

Beam margins of 0-4 mm yield optimal normal lung sparing based on V20 Gy. Zero beam margins result in best V10Gy lung sparing.

Test of Overall Accuracy

- CT scan phantom with “hidden” targets
- Localize target on segmented images (coordinates, etc)
- Position target/phantom in treatment beam isocenter
- Image phantom and determine deviation of target position
  - Image registration accuracy
  - Evaluate concordance of treatment and imaging isocenters

QA procedure must test all steps including verification of image guidance and treatment beam.

University of Chicago Oligomet Trial

- Five or less metastatic lesions
  - Lung
  - Liver
  - Abdomen
  - Extremity
  - Life expectancy > 3 months
  - No prior RT to currently involved sites
  - Each site ≤10 cm or 50cc
  - Normal organ and marrow function

Dose Limiting Toxicities (DLT)
- Grade 3-5 non-hematological toxicities
- Grade 4-5 hematological toxicities
- Grade 3 mucositis or esophagitis lasting 5-7 days will not be considered a DLT.
**UC SBRT Simulation Procedure**

- Near full-body immobilization: upper and lower alpha cradles, knee cushion, indexing to CT and treatment tables
- Gated CT and 4DCT for all abdominal and lung sites, free-breathing for others
- Treatment planning CT scans
  - Gated non-contrast ⇒ dose calculations
  - Gated contrast ⇒ tumor volume delineation (augmented by PET-CT/MR)
  - Retrospective (4DCT) ⇒ customized ITV’s

**Treatment Planning**

- Nine to thirteen coplanar and non-coplanar non-opposing static conformal beams
- Beams eye-view blocking with MLC at the isocenter with a margin of 0-2 mm
- PTV (Rx Dose) ≥ 95%
- Normal tissue dose limits: hard constraints

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**Normal Tissue Tolerances**

<table>
<thead>
<tr>
<th>Organ</th>
<th>RTOG</th>
<th>Karolinska</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinal Cord</td>
<td>2 Gy/h</td>
<td>No published recommendation</td>
</tr>
<tr>
<td>Heart</td>
<td>10 Gy/</td>
<td>8 Gy per fraction</td>
</tr>
<tr>
<td>Trachea/Pulmonary</td>
<td>5 Gy/</td>
<td></td>
</tr>
<tr>
<td>Trachea/Bronchial</td>
<td>5 Gy/</td>
<td></td>
</tr>
<tr>
<td>Esophagus</td>
<td>5 Gy/</td>
<td></td>
</tr>
<tr>
<td>Lung</td>
<td>V13&lt;10%</td>
<td>1 - 2.8 Gy</td>
</tr>
<tr>
<td>Liver</td>
<td>V70&lt;5 Gy/normal liver</td>
<td>Max &lt; 7 Gy per for 4.5 fractions</td>
</tr>
<tr>
<td>Stomach/Small Bowel</td>
<td>7 Gy/</td>
<td>7 Gy x 4 fractions</td>
</tr>
<tr>
<td>Kidney</td>
<td>≤ 5 Gy/ 60% kidney</td>
<td>Primary ≤ 10 ≤ 5 Gy x 5 fractions</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Metastases in remaining kidney: 10 Gy x 3</td>
</tr>
</tbody>
</table>

**Lung Mets: The “Good”..**

ITV derived from 4DCT, free-breathing tx delivery 11 non-coplanar beams Rx= 3 x 1400 cGy PTV: V4000cGy = 96% Lung-ITV(2000cGy) = 8%
Lung Mets: The Bad..
(Metastatic Melanoma: 4 lesions in lung)

All lesions: 3x1200 cGy
Static conformal plan
38 total beams
V20 (WLung-GTV)=14%

Lung Mets: The Ugly..
(Four lung metastases + two new)

New lesion
New lesion

Beam Placement and Dose Shaping
(restrict the beam overlap with already treated volume)

How much more lung is damaged?

Composite dose cloud of 1300Gy from both courses of SBRT
How much more lung is damaged?

Dose cloud of 1300Gy from course 1 and course 2

New V1300: 78 cc

Image-Guidance: Treatment Verification

- Pre-treatment verification: 3D
  - Non-contrast gated CT (big-bore, 16-slice scanner)
  - CBCT
- On-board kV/MV imaging: 2D
  - Image registration to reference DRR’s
  - Orthogonal and portal verification gated images
- Mid and post procedure imaging
  - Evaluation of intrafraction patient/target motion

Lung DVH Characteristics versus RTOG0236

<table>
<thead>
<tr>
<th>Patient</th>
<th>Toxicity</th>
<th>Location</th>
<th>PTV max dimension (cm)</th>
<th>PTV (cc)</th>
<th>Prescription</th>
<th>Max dose at 2cm from PTV (Gy)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IC on</td>
<td>IC off</td>
<td>RTOG 0236</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>R PL</td>
<td>2.5</td>
<td>27.28</td>
<td>28.05</td>
<td>21.68-22.51</td>
<td></td>
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<tr>
<td>2</td>
<td>R LUL</td>
<td>2.5</td>
<td>23.20</td>
<td>22.18</td>
<td>16.0-21.6</td>
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</tr>
<tr>
<td>3</td>
<td>L LUL</td>
<td>2.5</td>
<td>24.27</td>
<td>21.5</td>
<td>21.68-22.51</td>
<td></td>
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<tr>
<td>4</td>
<td>R RUL</td>
<td>2.5</td>
<td>34.26</td>
<td>32.71</td>
<td>25.69-27.05</td>
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<tr>
<td>5</td>
<td>R NUL</td>
<td>2.5</td>
<td>41.46</td>
<td>40.97</td>
<td>19.63-20.59</td>
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</tbody>
</table>

Patient 1: CBCT Verification

(Excellent match for upper lung lesions- free-breathing)
Patient 2: CBCT Verification
(Good match in bone and lung)
Registered CBCT overlaid on planning CT: Patient setup adjusted 5 mm post

Patient 2: MV Portal Verification
Tumor is captured in portal images

Patient Immobilization Issues with Spine
Early Memorial experience in room CT guidance: Venes, IJROBP (2003)
L4 Spinal Met: 3 x 1200 cGy
11-coplanar beams and IMRT Planning
UC Trial Clinical Outcome Analysis
(Clinical Cancer Research 2008- in press)

An Initial Report of a Radiation Dose Escalation Trial in Patients with One to Five Sites of Metastatic Disease

Aim: To determine the safety and efficacy of a dose-escalation trial in patients with one to five sites of metastatic disease.

Methods: Patients were treated with escalating radiation doses from 24 Gy to 43 Gy in 3 Gy increments. The dose was escalated based on the preliminary results of the first two patients.

Results: The study was terminated early due to safety concerns. No significant adverse events were observed.

Conclusion: The dose-escalation trial was safe and well tolerated. Further studies are needed to evaluate the potential benefits of dose escalation in patients with metastatic disease.

Metastatic Lung/Mediastinal Lesions

<table>
<thead>
<tr>
<th>Lesion</th>
<th>24 Gy</th>
<th>30 Gy</th>
<th>36 Gy</th>
<th>40 Gy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial Response</td>
<td>Initial Response</td>
<td>Initial Response</td>
<td>Initial Response</td>
</tr>
<tr>
<td>Lung NSC</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
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<td>NSCLC</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
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<tr>
<td>SCLC</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
</tr>
<tr>
<td>RCC</td>
<td>PR (1/1)</td>
<td>PR (1/1)</td>
<td>PR (1/1)</td>
<td>PR (1/1)</td>
</tr>
<tr>
<td>Sarcoma</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
</tr>
<tr>
<td>Melanoma</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
</tr>
<tr>
<td>Basal Cell</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
</tr>
<tr>
<td>Thyroid</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
</tr>
<tr>
<td>Ovarian</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
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<tr>
<td>Breast</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
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<tr>
<td>Melanoma Local Control</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
<td>CR (1/1)</td>
</tr>
</tbody>
</table>

Note: CR - Complete Response, PR - Partial Response, SD - Stable Disease
### Metastatic Abdominal Lesions

<table>
<thead>
<tr>
<th>Lesion type</th>
<th>Initial Response/LRC</th>
<th>Total Dose</th>
<th>SD (4/4)</th>
<th>1/1 (100%)</th>
<th>5/6 (83%)</th>
<th>11/11 (100%)</th>
<th>2/6 (33%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarcoma</td>
<td>PR (1/1)</td>
<td>36 Gy</td>
<td>CR (1/1)</td>
<td>PR (1/1)</td>
<td>CR (1/1)</td>
<td>1D (1)</td>
<td>3R (3)</td>
</tr>
<tr>
<td>Chromophobe</td>
<td>PR (1/1)</td>
<td>36 Gy</td>
<td>CR (1/1)</td>
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<td>1D (1)</td>
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</tr>
<tr>
<td>NACC</td>
<td>PR (1/1)</td>
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<td>CR (1/1)</td>
<td>PR (1/1)</td>
<td>CR (1/1)</td>
<td>1D (1)</td>
<td>3R (3)</td>
</tr>
<tr>
<td>SCC</td>
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<td>36 Gy</td>
<td>CR (1/1)</td>
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<td>CR (1/1)</td>
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<td>3R (3)</td>
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<td>PR (1/1)</td>
<td>CR (1/1)</td>
<td>1D (1)</td>
<td>3R (3)</td>
</tr>
<tr>
<td>Gastric</td>
<td>CR (1/1)</td>
<td>36 Gy</td>
<td>CR (1/1)</td>
<td>PR (1/1)</td>
<td>CR (1/1)</td>
<td>1D (1)</td>
<td>3R (3)</td>
</tr>
<tr>
<td>Small bowel</td>
<td>CR (1/1)</td>
<td>36 Gy</td>
<td>CR (1/1)</td>
<td>PR (1/1)</td>
<td>CR (1/1)</td>
<td>1D (1)</td>
<td>3R (3)</td>
</tr>
<tr>
<td>Metastatic Local Control</td>
<td>SD (4/4)</td>
<td>36 Gy</td>
<td>CR (1/1)</td>
<td>PR (1/1)</td>
<td>CR (1/1)</td>
<td>1D (1)</td>
<td>3R (3)</td>
</tr>
</tbody>
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### Q1. The optimal beam margin for SBRT planning with 6 MV photon beams in the lung that minimizes the normal tissue complication probability is typically

0%  1. - 2 mm
0%  2. 0 to 4 mm
0%  3. 5 to 9 mm
0%  4. 10 mm
0%  5. 18 mm

### Q2. Unlike conventional radiotherapy, SBRT uses a greater number of beams to achieve

0%  1. larger dose heterogeneities
0%  2. smaller hot spots
0%  3. better target dose conformity and rapid dose fall-off away from the target
0%  4. a shallower dose gradient
Q2. Unlike conventional radiotherapy, SBRT uses a greater number of beams to achieve:

1. larger dose heterogeneities
2. smaller hot spots
3. better target dose conformity and rapid dose fall-off away from the target
4. a shallower dose gradient

Q3. The most important aspect of a rigorous QA program for an image guided SBRT approach is:

0% 1. Room lasers are accurately calibrated
0% 2. Stereotactic Frame is indexed to the treatment table
0% 3. Patient skin marks are consistently documented
0% 4. An end to end test confirms the link between imaging and dose delivery steps in the overall treatment process

Summary

- SBRT requires multi-disciplinary team approach
- Clinical experience with conventional radiotherapy does not extrapolate to SBRT
- Verification of each step in the SBRT treatment process is a must
“We are like blind men peeping through a fence”

*Japanese Proverb*

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References


