Spinal SBRT

Timothy D. Solberg, PhD
Professor and Vice Chair
Division of Medical Physics
University of California, San Francisco

The Beginning of SBRT

Reproducibility 5-8 mm for 90% of setups
Diaphragmatic movement limited to 5-10 mm with pressure.

Lax et al, Acta Oncol. 33:677-83, 1994

Original clinical report (1995) of first 31 patients, primarily solitary tumors in the liver and lung. Doses from 7.7 to 45 Gy in 1 to 4 fractions.

Blomgren et al, Acta Oncol. 34:861-70, 1995

Setup accuracy evaluated in 30 patients using CT and port films; conclude that a 5 mm margin for PTV is sufficient if CT is performed prior to every treatment. Deviation of < 10 mm (AP and Lat) in 98% of targets.

Wulf et al, Radiotherapy Oncology 55:225-236, 2000
1995 – 1st successful spinal radiosurgery

Rigid skeletal fixation above and below the involved segments
Linac delivery with circular collimators / arcs or IMRT
System accuracy ≤ 2.0 mm
8-10 Gy Rx with no portion of cord receiving > 3 Gy

Hamilton et al, Neurosurgery 36; 311-319, 1995

Spine Mets - Why Radiosurgery?

Effective treatment for oligometastatic disease
Fewer fractions, more convenient, shorter break from chemotherapy
Higher doses should be more effective
Faster, more durable palliation
Less normal tissue irradiated
Ability to retreat

But …..
Technically challenging, little margin for error,
paucity of data on cord tolerance to single fraction
Other potential complications include: mucositis, laryngitis, esophageal stricture, and compression fracture
7 Participating Institutions

24 item questionnaire covering 5 broad areas:

(1) policies and procedures,
(2) training requirements,
(3) surgeon involvement,
(4) the role of industry and professional organizations,
(5) perceptions regarding the importance of credentialing requirements.

Strong Agreement
- Formal credentialing process for all physicians, physicists, and therapists;
- Need for a written policy specific for spine radiosurgery credentialing;
- Reliance upon in-house proctoring system for physicians, physicists, and therapists;
- Credentialing should be device specific;
- Professional organizations develop guidelines for institutions credentialing requirements;
- Importance of credentialing for safety and clinical outcomes.

Some Agreement
- Requirement to have more than one specialist trained to perform spine radiosurgery as a back up.
### Clinical practice of image-guided spine radiosurgery - results from an international research consortium

Matthias Guckenberger, Reinhardt A. Seiwien, John C. Hickman, Peter C. Gensten, Ronald Kersh

Jason Sheehan and Ajay Sahgal. *Radiation Oncology* 2011, 6:172

#### Tolerance doses Spinal Cord

<table>
<thead>
<tr>
<th>Dosimetric parameter</th>
<th>Single fraction</th>
<th>3 fractions</th>
<th>5 fractions</th>
<th>10 fractions</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHW</td>
<td>Dmax to 0.1 cc</td>
<td>16-24 Gy in 1; Most frequently 17 Gy in 1</td>
<td>20-24 Gy in 1; Most frequently 20 Gy in 1</td>
<td>24 Gy in 3</td>
</tr>
<tr>
<td>UPMC</td>
<td>Dmax</td>
<td>30 Gy in 10 PTV-rectal 463 Gy in 10 PTV -macroscopic</td>
<td>463 Gy in 10 PTV -macroscopic</td>
<td>463 Gy in 10 PTV -macroscopic</td>
</tr>
<tr>
<td>UoFF</td>
<td>Dmax</td>
<td>24 - 27 Gy in 2 - 3</td>
<td>24 Gy in 3</td>
<td>30 Gy in 3</td>
</tr>
<tr>
<td>UVAMC</td>
<td>D10</td>
<td>30 Gy in 3</td>
<td>30 Gy in 3</td>
<td>30 Gy in 3</td>
</tr>
<tr>
<td>RSNC</td>
<td>D10</td>
<td>18 Gy in 3</td>
<td>18 Gy in 3</td>
<td>18 Gy in 3</td>
</tr>
</tbody>
</table>

#### Tolerance doses Cauda equina

<table>
<thead>
<tr>
<th>Dosimetric parameter</th>
<th>Single fraction</th>
<th>3 fractions</th>
<th>5 fractions</th>
<th>10 fractions</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHW</td>
<td>Dmax to 0.1 cc</td>
<td>25 Gy</td>
<td>37.5 Gy</td>
<td>37.5 Gy</td>
</tr>
<tr>
<td>UPMC</td>
<td>Dmax</td>
<td>12 Gy</td>
<td>18 Gy</td>
<td>18 Gy</td>
</tr>
<tr>
<td>UoFF</td>
<td>Dmax</td>
<td>12 Gy</td>
<td>18 Gy</td>
<td>18 Gy</td>
</tr>
<tr>
<td>UVAMC</td>
<td>D10</td>
<td>15 Gy</td>
<td>20 Gy</td>
<td>20 Gy</td>
</tr>
<tr>
<td>RSNC</td>
<td>D10</td>
<td>18 Gy</td>
<td>30 Gy</td>
<td>30 Gy</td>
</tr>
</tbody>
</table>

---

#### Use of single fraction radiosurgery

<table>
<thead>
<tr>
<th>Criteria for selection of hypofractionated regimes</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHW: No, all patients are treated with either five or ten fractions.</td>
</tr>
<tr>
<td>UoFF: Single fraction radiosurgery for 95% of the patients unless very close to spinal cord.</td>
</tr>
<tr>
<td>UPMC: Majority is treated with two or three fractions and specific cases for single fraction.</td>
</tr>
<tr>
<td>UVAMC: Majority is treated with a single fraction of radiosurgery, occasionally up to 3 fractions.</td>
</tr>
<tr>
<td>RSNC: No, majority are treated with three fractions with treatments given one week apart.</td>
</tr>
</tbody>
</table>

#### Fractionation schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th># fractions and single fraction dose</th>
<th>Good life expectancy: 30 Gy in 10 PTV-rectal 463 Gy in 10 PTV -macroscopic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10 Gy</td>
<td>16-24 Gy in 1; Most frequently 17 Gy in 1</td>
</tr>
<tr>
<td>2</td>
<td>20 Gy in 5 PTV-rectal 35 Gy in 5 PTV -macroscopic</td>
<td>24 - 27 Gy in 2 - 3</td>
</tr>
<tr>
<td>3</td>
<td>30 Gy in 3 (for sarcomas)</td>
<td>30 Gy in 3 (for sarcomas)</td>
</tr>
</tbody>
</table>
### Clinical practice of image-guided spine radiosurgery

<table>
<thead>
<tr>
<th>Treatment</th>
<th>UHW</th>
<th>UPMC</th>
<th>UoF</th>
<th>UVAMC</th>
<th>RSMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging modality, which is used for GIN definition</td>
<td>MRI and CT</td>
<td>MRI and CT, FDG-PET if available</td>
<td>MRI and CT</td>
<td>CT and MRI</td>
<td>CT, MRI and FDG-PET</td>
</tr>
<tr>
<td>Use of an anatomical target volume concept</td>
<td>Anatomical two-dose-level target volume concept</td>
<td>Anatomical target volume concept</td>
<td>Anatomical target volume concept</td>
<td>Anatomical target volume concept</td>
<td>Anatomical target volume concept</td>
</tr>
<tr>
<td>GTV to PTV safety margin</td>
<td>3 mm</td>
<td>2 mm; 3 mm in the sacrum</td>
<td>2 mm</td>
<td>2 mm</td>
<td>None</td>
</tr>
<tr>
<td>Protocol if PTV overlaps with the spinal cord</td>
<td>Two dose-level approach: The OAR spinal cord is always in the PTV-toxic and is always excluded from the higher dose PTV; macroscopic PTV within 1 mm to the spinal cord is excluded from the PTV</td>
<td>PTV is limited by the cord or thecal sac for cauda equina</td>
<td>If this occurs, we either operate to resect par of the tumor or fractionate the radiation</td>
<td>GTV down to edge of OAR</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Treatment of the vertebrae superior and inferior to the metastatic vertebra</th>
<th>No</th>
<th>No</th>
<th>No</th>
<th>No</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging modality for definition of the spinal cord</td>
<td>Spinal cord in MRI</td>
<td>Spinal cord in MRI</td>
<td>Spinal cord in MRI</td>
<td>Spinal cord in MRI</td>
<td>Spinal cord in CT</td>
</tr>
<tr>
<td>Delineation of the spinal cord in caudal direction</td>
<td>At least 1 level above and below PTV</td>
<td>1 level above and below PTV</td>
<td>At least 1 level above and below PTV</td>
<td>1 level above and below PTV</td>
<td>1 level above and below PTV</td>
</tr>
<tr>
<td>Safety margins around the spinal cord in lateral direction</td>
<td>1 mm</td>
<td>1 mm</td>
<td>1.5 mm</td>
<td>No</td>
<td>2 mm anterior and 1 mm lateral</td>
</tr>
</tbody>
</table>

### Timmerman Dose Constraints

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Volume (mL)</th>
<th>Volume Max (Gy)</th>
<th>Max Point Dose (Gy)</th>
<th>Endpoint (Grade 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optic pathway</strong></td>
<td>&lt;0.2</td>
<td>8</td>
<td>10</td>
<td>Neuritis</td>
</tr>
<tr>
<td><strong>Cochlea</strong></td>
<td>&lt;1</td>
<td>10</td>
<td>15</td>
<td>Cranial neuropathy</td>
</tr>
<tr>
<td><strong>Brainstem</strong></td>
<td>&lt;1.2</td>
<td>7</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td><strong>Cauda equina</strong></td>
<td>&lt;5</td>
<td>14</td>
<td>16</td>
<td>Neuritis</td>
</tr>
<tr>
<td><strong>Sacral plexus</strong></td>
<td>&lt;2</td>
<td>14.4</td>
<td>16</td>
<td>Neuritis</td>
</tr>
<tr>
<td><strong>Spinal cord</strong></td>
<td>&lt;0.26</td>
<td>10</td>
<td>14</td>
<td>Myelitis</td>
</tr>
<tr>
<td><strong>Esophagus</strong></td>
<td>&lt;5</td>
<td>14.5</td>
<td>16</td>
<td>Cranial neuropathy</td>
</tr>
<tr>
<td><strong>Heart-pericardium</strong></td>
<td>&lt;15</td>
<td>16</td>
<td>22</td>
<td>Pericarditis</td>
</tr>
<tr>
<td><strong>Great vessels</strong></td>
<td>&lt;10</td>
<td>31</td>
<td>37</td>
<td>Aneurysm</td>
</tr>
<tr>
<td><strong>Trachea and bilateral bronchus</strong></td>
<td>&lt;4</td>
<td>8.8</td>
<td>22</td>
<td>Stenosis/fistula</td>
</tr>
<tr>
<td><strong>Skin</strong></td>
<td>&lt;10</td>
<td>14.4</td>
<td>16</td>
<td>Ulceration</td>
</tr>
<tr>
<td><strong>Stomach</strong></td>
<td>&lt;10</td>
<td>13</td>
<td>16</td>
<td>Ulceration/fistula</td>
</tr>
<tr>
<td><strong>Duodenum</strong></td>
<td>&lt;5</td>
<td>8.8</td>
<td>18</td>
<td>Ulceration</td>
</tr>
<tr>
<td><strong>Jejunum/ileum</strong></td>
<td>&lt;5</td>
<td>9.8</td>
<td>19</td>
<td>Enteral obstruction</td>
</tr>
<tr>
<td><strong>Colon</strong></td>
<td>&lt;29</td>
<td>11</td>
<td>22</td>
<td>Colitis/fistula</td>
</tr>
<tr>
<td><strong>Rectum</strong></td>
<td>&lt;29</td>
<td>11</td>
<td>22</td>
<td>Proctitis/fistula</td>
</tr>
<tr>
<td><strong>Bladder wall</strong></td>
<td>&lt;15</td>
<td>8.7</td>
<td>22</td>
<td>Cystitis/fistula</td>
</tr>
<tr>
<td><strong>Penile bulb</strong></td>
<td>&lt;3</td>
<td>14</td>
<td>34</td>
<td>Impotence</td>
</tr>
<tr>
<td><strong>Femoral heads (right and left)</strong></td>
<td>&lt;10</td>
<td>14</td>
<td>16</td>
<td>Neovascularity</td>
</tr>
<tr>
<td><strong>Renal hilum-vesaic intum</strong></td>
<td>&lt;2/3 volume</td>
<td>10.6</td>
<td></td>
<td>Malignant hypertension</td>
</tr>
</tbody>
</table>

### Timmerman et al, Sem Rad Onc, 2008
### Timmerman Dose Constraints

**Serial Tissue** | **Volume (mL)** | **Volume Max (Gy)** | **Max Point Dose (Gy)** | **Endpoint or Grade (3)**
--- | --- | --- | --- | ---
Optic pathway | <0.2 | 15.5 Gy | 16.5-16.5 Gy | Neuritis
Orbits | <0.2 | 19.1 Gy | 20.9 Gy | Hearing loss
Brainstem | <1 | 18.1 Gy | 23.8 Gy | Cerebral necrosis
Spinal cord | <0.25 | 18.8 Gy | 22.6 Gy | Myelitis
Cauda equina | <5 | 21.9 - 7.3 Gy | 24.8 Gy | Neuritis
Rectal tissues | <3 | 22.6 - 7.3 Gy | 24.8 Gy | Neuroprathy
Esophagus* | <5 | 21.7 Gy | 27.9 Gy | Stenosis/fistula

**THREE-FRACTION TREATMENT**

| Serial Tissue | Volume (mL) | Volume Max (Gy) | Max Point Dose (Gy) | Endpoint or Grade (3) |
--- | --- | --- | --- | ---
Optic pathway | <0.2 | 15.5 Gy | 16.5-16.5 Gy | Neuritis
Orbits | <0.2 | 19.1 Gy | 20.9 Gy | Hearing loss
Brainstem | <1 | 18.1 Gy | 23.8 Gy | Cerebral necrosis
Spinal cord | <0.25 | 18.8 Gy | 22.6 Gy | Myelitis
Cauda equina | <5 | 21.9 - 7.3 Gy | 24.8 Gy | Neuritis
Rectal tissues | <3 | 22.6 - 7.3 Gy | 24.8 Gy | Neuroprathy
Esophagus* | <5 | 21.7 Gy | 27.9 Gy | Stenosis/fistula

**Heart/periarterium** | <1.5 | 24.4 Gy | 30.0 Gy | Pericarditis
Great vessels | <10 | 39.13 Gy | 45.13 Gy | Aneurysm
Trachea and ipsilateral bronchus* | <1.5 | 30.5 Gy | 36.1 Gy | Stenosis/fistula
Skin | <1.5 | 22.5 Gy | 24.8 Gy | Ulceration
Stomach | <1.5 | 21.7 Gy | 24.8 Gy | Ulceration/fistula
Duodenum* | <5 | 15.0 Gy | 26.7 Gy | Ulceration
Jejunum/ileum* | <5 | 15.0 Gy | 26.7 Gy | Ulceration
 Colon* | <5 | 15.0 Gy | 26.7 Gy | Ulceration
Rectum* | <5 | 20.4 Gy | 30.1 Gy | Ulceration
Bladder wall | <5 | 20.4 Gy | 30.1 Gy | Ulceration
Penile bulb | <3 | 21.9 - 7.3 Gy | 42.4 - 7.3 Gy | Impotence
Female breasts (right and left) | <10 | 21.9 - 7.3 Gy | 42.4 - 7.3 Gy | Necrosis
Renal Hilum/vascular trunk | <0.3 mL | 18.6 - 6.2 Gy | 18.6 - 6.2 Gy | Malignant hypertension

---

**Critical Volume (mL)** | **Critical Volume Max (Gy)** | **Endpoint or Grade (3)**
--- | --- | ---
Lung (right and left) | 1.596 | 10.9 (3.5 Gy) | Basic lung function
Lung (right and left) | 1.056 | 11.4 (3.5 Gy) | Pneumonitis
Liver | 790 | 17.1 (3.5 Gy) | Basic liver function
Renal cortex (right and left) | 290 | 14.6 (3.5 Gy) | Basic renal function

---

**Five-Fraction Treatment**

**Serial Tissue** | **Volume (mL)** | **Volume Max (Gy)** | **Max Point Dose (Gy)** | **Endpoint or Grade (3)**
--- | --- | --- | --- | ---
Optic pathway | <0.2 | 20.4 Gy | 25.3 Gy | Neuritis
Orbits | <0.2 | 27.3 Gy | 55.5 Gy | Hearing loss
Brainstem | <1 | 20.9 Gy | 33.3 Gy | Cerebral necrosis
Spinal cord | <0.25 | 22.5 Gy | 30.6 Gy | Myelitis
Cauda equina | <1.2 | 15.5 Gy | 21.7 Gy | Neuritis
Rectal tissues | <3 | 32.6 Gy | 38.4 Gy | Neuroprathy
Esophagus* | <5 | 27.6 - 6.2 Gy | 36.8 Gy | Stenosis/fistula

**Heart/periarterium** | <1.5 | 32.0 Gy | 38.7 Gy | Pericarditis
Great vessels | <10 | 47.9 - 4.0 Gy | 53.1 - 4.0 Gy | Aneurysm
Trachea and ipsilateral bronchus* | <1.5 | 38.7 Gy | 43.7 Gy | Stenosis/fistula
Skin | <1.5 | 30.6 Gy | 36.8 Gy | Ulceration
Stomach | <1.5 | 28.6 Gy | 33.3 Gy | Ulceration/fistula
Duodenum* | <5 | 30.0 Gy | 36.1 Gy | Ulceration
Jejunum/ileum* | <5 | 30.0 Gy | 36.1 Gy | Ulceration
Colon* | <5 | 30.0 Gy | 36.1 Gy | Ulceration
Rectum* | <5 | 30.0 Gy | 36.1 Gy | Ulceration
Bladder wall | <5 | 30.0 Gy | 36.1 Gy | Ulceration
Penile bulb | <3 | 30.0 Gy | 36.1 Gy | Impotence
Female breasts (right and left) | <10 | 30.0 Gy | 36.1 Gy | Necrosis
Renal hilum/vascular trunk | <0.3 mL | 22.4 Gy | 22.4 Gy | Malignant hypertension

---

**Critical Volume (mL)** | **Critical Volume Max (Gy)** | **Endpoint or Grade (3)**
--- | --- | ---
Lung (right and left) | 1.599 | 12.6 (3.5 Gy) | Basic lung function
Lung (right and left) | 1.000 | 13.5 (2.7 Gy) | Pneumonitis
Liver | 790 | 21.4 Gy | Basic liver function
Renal cortex (right and left) | 290 | 17.3 (3.5 Gy) | Basic renal function

---

Avoid inadvertent irradiation.

---

Timmerman et al, Sem Rad Onc, 2008
Risk of Spinal Myelopathy

max. dose

Some patients previously irradiated:

- U. Pitt (241)
- Stanford (243)
- Dukes (145)
- MDACC (137)
- UAB (246)
- UCSF (244)

All patients previously irradiated:

No patients previously irradiated:

- Henry Ford (128)
- MSKCC (142)
- Multi-inst. (147)

Comprehensive list available at reference cited.
RTOG 0631 – Phase II/III study of image-guided radiosurgery / SBRT for localized spine metastases

- Localized (1-3) spine metastasis with NRPS score ≥ 5

- **Radiosurgery (16 Gy)**
  - **Phase 2 (43 pts)**

- **Spinal cord defined based on image fusion between CT and MRI**

- **Systematic use of dose constraints**

- **IGRT Required**

- **Follow-up**
  1. Pain score & QoL survey every month
  2. Clinical and neurologic exams every month
  3. Imaging (MRI) every 2 months

- **Primary endpoint is complete or partial pain relief**

---

**Spine Planning**

- MR carefully fused to CT
- Delineate cord and canal

- Generally single fraction, occasionally up to 3
- Almost always IMRT

---

**Images**

- Spinal cord images showing fusion of CT and MRI.
RTOG 0631 – Phase II/III study of image-guided radiosurgery / SBRT for localized spine metastases

Allowed vertebral levels and target definition

<table>
<thead>
<tr>
<th>Serial Tissue</th>
<th>Volume</th>
<th>Volume Max (Gy)</th>
<th>Endpoint (G2 Grade 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spinal Cord</td>
<td>&lt;0.035 cc</td>
<td>14 Gy</td>
<td>myelitis</td>
</tr>
<tr>
<td></td>
<td>&lt;0.35 cc</td>
<td>10 Gy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&lt;1.2 cc (SBRT only)</td>
<td>7 Gy (SBRT only)</td>
<td></td>
</tr>
<tr>
<td>Cauda Equina</td>
<td>&lt;0.035 cc</td>
<td>16 Gy</td>
<td>neuritis</td>
</tr>
<tr>
<td></td>
<td>&lt;5 cc</td>
<td>14 Gy</td>
<td></td>
</tr>
<tr>
<td>Sacral Plexus</td>
<td>&lt;0.035 cc</td>
<td>18 Gy</td>
<td>neuropathy</td>
</tr>
<tr>
<td></td>
<td>&lt;5 cc</td>
<td>14.4 Gy</td>
<td></td>
</tr>
</tbody>
</table>

Spinal cord definition and constraints

Spine Planning

Multiple coplanar beams / VMAT

Spinal Cord defined 6 mm above and 6 mm below target vertebral body

Cord constraints:
- Max point dose 14 Gy
- <0.35 cc receives 10 Gy
- <1.2 cc receives 7 Gy
Spine SRS: GTV (red), CTV (blue)

Spine SRS: 20 Gy to GTC, 14 Gy to CTV
GTV - Pencil Beam

Max Dose 2423 cGy

91.3% receives ≥ 20 Gy
GTV - Monte Carlo

- Max Dose 2255 cGy
- 47.3% receives ≥ 20 Gy
- Mean Dose 1671 cGy

CTV - Pencil Beam

- Mean Dose 1671 cGy
- 95.0% receives ≥ 14 Gy
79.3% receives ≥ 14 Gy

Mean Dose 1532 cGy

Max Dose 961 cGy
Image Guidance for Spine is Essential

**BrainLAB ExacTrac 6D**
- X-ray tubes recessed in floor
- Flat panels mounted to ceiling

**Accuray CyberKnife**
- X-ray tubes mounted to ceiling
- Flat panels recessed in floor
CBCT for Spine Localization

Reference CT  CBCT

Fusion
Automatic
Manual
Reset

Shift
Vertical  0.00  0.00
Longitudinal  0.00  0.00
Lateral  0.00  0.00

Overlay
Condition  CT
Add

View
Contours
Locators
Anatomical Lines
Bones

2/27/2017
Mock targets contoured in a specialized spine phantom per RTOG 0631

(a) vertebral body,
(b) all elements of a single vertebral level completely encircling the spinal cord,
(c) the posterior spinous process,
(d) two consecutive vertebral bodies

Repeated in both thoracic and lumbar spine

Planned and delivered on

Tomo: 2 helical passes superposition/convolution

Vero: 13 coplanar IMRT beams
       Monte Carlo (thoracic)
       Pencil Beam (lumbar)

TrueBeam: 2 RapidArcs
          AAA Algorithm
          Repeat for flattened and FFF

CyberKnife: 3 fixed cones (10, 15, 25 mm)
            Ray Tracing
IGRT used for phantom setup

Thoracic targets and cord verified using ion chamber - Exradin A16
0.007 cc

Thoracic targets verified using laser cut GafChromic EBT film

For Plan C, the IC is not within the target, so measurements have significant uncertainty and were not reported
**Table 2.** Lumbar measurements with GAFCHROMIC EBT3 film with gamma analysis utilizing the dose criterion relative to the global maximum dose method.

<table>
<thead>
<tr>
<th>Treatment Plan</th>
<th>3%/3 mm</th>
<th>2%/2 mm</th>
<th>1%/1 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan A</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>99.7</td>
<td>97.9</td>
</tr>
<tr>
<td></td>
<td>81.3</td>
<td>61.8</td>
<td>77.6</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>84.3</td>
<td>95.4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Treatment Plan</th>
<th>3%/3 mm</th>
<th>2%/2 mm</th>
<th>1%/1 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan B</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>99.9</td>
<td>98.7</td>
<td>98.5</td>
</tr>
<tr>
<td></td>
<td>93.9</td>
<td>62.3</td>
<td>81.5</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>87.3</td>
<td>85.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Treatment Plan</th>
<th>3%/3 mm</th>
<th>2%/2 mm</th>
<th>1%/1 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan C</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>99.9</td>
<td>98.7</td>
<td>98.5</td>
</tr>
<tr>
<td></td>
<td>93.0</td>
<td>65.2</td>
<td>86.3</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>87.3</td>
<td>85.5</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Treatment Plan</th>
<th>3%/3 mm</th>
<th>2%/2 mm</th>
<th>1%/1 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan D</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>99.7</td>
<td>100.0</td>
<td>96.9</td>
</tr>
<tr>
<td></td>
<td>99.7</td>
<td>96.9</td>
<td>99.8</td>
</tr>
<tr>
<td></td>
<td>87.3</td>
<td>89.1</td>
<td>90.5</td>
</tr>
<tr>
<td></td>
<td>90.0</td>
<td>90.4</td>
<td></td>
</tr>
</tbody>
</table>

**Table 3.** Lumbar measurements with GAFCHROMIC EBT3 film with gamma analysis utilizing the dose criterion relative to the pixel under analysis method.

<table>
<thead>
<tr>
<th>Treatment Plan</th>
<th>3%/3 mm</th>
<th>2%/2 mm</th>
<th>1%/1 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan A</td>
<td>100.0</td>
<td>99.9</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>99.9</td>
<td>100.0</td>
</tr>
<tr>
<td></td>
<td>71.7</td>
<td>49.8</td>
<td>64.7</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>100.0</td>
<td>96.1</td>
</tr>
<tr>
<td></td>
<td>85.5</td>
<td>51.3</td>
<td>71.7</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>100.0</td>
<td>99.2</td>
</tr>
<tr>
<td></td>
<td>77.1</td>
<td>47.2</td>
<td>81.3</td>
</tr>
<tr>
<td></td>
<td>100.0</td>
<td>100.0</td>
<td>97.5</td>
</tr>
<tr>
<td></td>
<td>80.7</td>
<td>75.5</td>
<td>81.8</td>
</tr>
<tr>
<td></td>
<td>97.5</td>
<td>95.1</td>
<td>95.1</td>
</tr>
</tbody>
</table>
CK would be faster with IRIS collimator

### Table 4. Treatment beam-on delivery times for various treatment platforms and target regions.

<table>
<thead>
<tr>
<th>Treatment Machine</th>
<th>Treatment Region</th>
<th>Plan &amp; Delivery Time (min)</th>
<th>Average (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>TomoTherapy</td>
<td>Thorax</td>
<td>21.1</td>
<td>35.3</td>
</tr>
<tr>
<td></td>
<td>Lumbar</td>
<td>24.8</td>
<td>20.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vero</td>
<td>Thorax</td>
<td>15.0</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td>Lumbar</td>
<td>16.8</td>
<td>24.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TrueBeam (Flattened)</td>
<td>Thorax</td>
<td>9.6</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>Lumbar</td>
<td>11.2</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TrueBeam (FFF)</td>
<td>Thorax</td>
<td>4.3</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>Lumbar</td>
<td>4.9</td>
<td>4.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CyberKnife</td>
<td>Thorax</td>
<td>50.0</td>
<td>44.4</td>
</tr>
<tr>
<td></td>
<td>Lumbar</td>
<td>43.9</td>
<td>46.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Adrian Nalichowski1,2 | Isaac Kaufman3 | John Gallo3 | Todd Rossenberger4 | Tim Solberg5 | Ezequiel Ramirez2 | Yulong Yan3 | Julie Friedrick4 | Tewfik Bichay5 | Alan Maxville5 | Jay Burmeister1,2

Single fraction SBRT plans designed for 4 targets for 4treatment modalities: RapidArc, Tomotherapy, CyberKnife, Vero

Plans prescribed to 16 Gy to cover 90% of the target volume using constraints from RTOG 0631

Revisited for thoracic and lumber levels
Lowest cord doses and sharpest falloff in CyberKnife and Vero plans, particularly for small targets.
Clinical Results

- 93 patients and 103 spinal mets
- Solid Malignancy, No prior surgery, No compression, No instability, No prior XRT
- Single fraction 18 – 24 Gy, Cord limited to 14 Gy
- Actuarial local control rate 90% (median follow up of 15 months)
- **No Myelopathy**

Yamada et al, IJROBP 2008; 71(2):484-90
Yenice et al, IJROBP 2003; 55(3):583-93

- 230 mets in 177 patients
- 1-2 contiguous levels, ≤ 3 sites, no prior XRT, varying histology and spinal levels
- Single fraction 8 Gy - 18 Gy prescribed to 90% isodose line
- Median follow up 6.4 mo (range 0.5 – 49)
- **1 case of cord injury at 13 months**


- Estimated that 10 Gy to 10% of the cord as defined 6mm above and below the target is safe

---

Dose Response to Spine SRS

91 lesions in 79 patients
Prescribed 18-24 Gy
Cord constrained to 14 Gy

---

CORRELATION OF LOCAL FAILURE WITH MEASURES OF DOSE INSUFFICIENCY IN THE HIGH-DOSE SINGLE-FRACTION TREATMENT OF BONY METASTASES

D. Michael Loyelock, Ph.D.,† Zhigang Zheng, Ph.D.,† Andrew Jackson, Ph.D.,‡ Jennifer Keam, M.D.,§ Justin Beikman, M.D.,§ Mark Blesky, M.D.,§ Eric Lis, M.D.,§ and Yoshiya Yamada, M.D.
Spinal SRS Complications
5 reported cases of myelopathy in de novo SRS cases

<table>
<thead>
<tr>
<th>#</th>
<th>Max Fractions</th>
<th>Cord Dose</th>
<th>Dose (0.1 cc)</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.6 Gy</td>
<td>8.5 Gy</td>
<td>Gerszten et al, Neurosurg, 2008</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>13.1 Gy</td>
<td>6.9 Gy</td>
<td>Gerszten et al, Neurosurg, 2008</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14.6 Gy</td>
<td>13.7 Gy</td>
<td>Ryu et al, Cancer, 2007</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>25.6 Gy</td>
<td>24.7 Gy</td>
<td>Gibbs et al, Radiother Onc, 2007</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>30.9 Gy</td>
<td>27.8 Gy</td>
<td>Dodd et al, Neurosurg, 2006</td>
<td></td>
</tr>
</tbody>
</table>

Spinal SRS Complications
5 reported cases of myelopathy in patients with prior irradiation

<table>
<thead>
<tr>
<th>Spine tumor location and target volume</th>
<th>Prior EBRT thacal sac dose (Gy/FR) (BED)</th>
<th>SBRT Retreatment tumor dose (Gy/FR) prescription isodose (%)</th>
<th>Time interval to SBRT (months)</th>
<th>Time to RM after reatration (months)</th>
<th>Follow-up Post SBRT (months)</th>
<th>Status last follow-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>T5 (19.7)</td>
<td>40/22 (76 Gy) (38 GyFR)</td>
<td>20/290 (20 Gy) (14 GyFR)</td>
<td>81</td>
<td>6</td>
<td>55</td>
<td>Alive/ Para-plagia</td>
</tr>
<tr>
<td>T1 (18.8)</td>
<td>25/228 (50 Gy) (33 GyFR)</td>
<td>21/289 (35 Gy) (25 GyFR)</td>
<td>70</td>
<td>5</td>
<td>29</td>
<td>Alive/ Chair bound</td>
</tr>
<tr>
<td>T11-T12 (13.9)</td>
<td>21.25 (48 Gy) (35 GyFR)</td>
<td>14/100 (20 Gy) (15 GyFR)</td>
<td>11</td>
<td>3</td>
<td>17</td>
<td>Alive/ Para-plagia</td>
</tr>
<tr>
<td>C1/C2 (31.5)</td>
<td>51.928 (60 Gy) (40 GyFR)</td>
<td>30/983 (35 Gy) (25 GyFR)</td>
<td>18</td>
<td>8</td>
<td>11</td>
<td>Alive/ Sensory deficit</td>
</tr>
<tr>
<td>T1 (40.4)</td>
<td>43.205 (55 Gy) (45 GyFR)</td>
<td>16/188 (35 Gy) (22 GyFR)</td>
<td>12</td>
<td>3</td>
<td>3</td>
<td>Dead</td>
</tr>
</tbody>
</table>

REIRRADIATION HUMAN SPINAL CORD TOLERANCE FOR STEREOTACTIC BODY RADIOTHERAPY
Arun Sagar, M.D.,*, Liun Ma, Ph.D.,† Vivian Weiner, Ph.D.,‡ Iris C. Gibbs, M.D.,§ Sam Chou, M.D.,∥ Jong-Kyu Chang, M.D.,∥ Maria Weiner-Warnc, M.D.,∥∥ Lemon A. Angeloni, M.D.,∥ Eric L. Chao, M.D.,∥∥ Moon-Jin Ko, M.D.,∥∥ Scott G. Sooy, M.D.,∥∥ Daniel Letourneau, Ph.D.,∥∥ Sam Ryu, M.D.,∥∥ Peter C. Gerszten, M.D.,∥∥ Jack Fowler, Ph.D.,∥∥∥∥ C. Shun Wong,∥∥∥∥ and David A. Larson,∥∥∥∥
Swine SRS Spinal Cord Study – 25 animals per arm

Arm #1
- External Beam (10 times 3 Gy)
- Wait 1 year
- SRS Hemi-cord (5 Dose Groups)
- MRI and Eval. (1 year)
- Pathological Examination

Arm #2
- SRS Hemi-cord (5 Dose Groups)
- MRI and Eval. (1 year)
- Pathological Examination

Arm #3
- SRS Whole-Cord (5 Dose Groups)
- Wait 1 year
- Pathological Examination

Spinal Cord Tolerance

Copyright © 2011 Elsevier Inc.
Printed in the USA. All rights reserved
0360-3016/5 - see front matter

BIOLOGY CONTRIBUTION

SPINAL CORD TOLERANCE TO SINGLE-FRACTION PARTIAL-VOLUME IRRADIATION: A SWINE MODEL

Paul M. Medina, Ph.D., Ryan D. Foster, Ph.D., Albert J. van der Kogel, Ph.D.,
James W. Sayre, Ph.D., William H. McBrede, D.Sc., and Timothy D. Solberg, Ph.D.
What about prior irradiation?

**Biology Contribution**

Spinal Cord Tolerance to Reirradiation With Single-Fraction Radiosurgery: A Swine Model

Paul M. Medlin, Ph.D., Ryan D. Foster, Ph.D., Albert J. van der Kogel, Ph.D., James W. Sayre, Ph.D., William H. McBride, D.Sc., and Timothy D. Salberg, Ph.D.


---

**Arm #1**

- External Beam (10 times 3 Gy)
- Wait 1 year
- SRS Hemi-cord (5 Dose Groups)
- MRI and Eval. (1 year)
- Pathological Examination

---

1. **RTOG 0631:**
   a) Permits treatment of three contiguous vertebral bodies
   b) Randomizes patients to one or three fractions
   c) Has a primary endpoint of local control
   d) Always requires treatment of the entire vertebral body
   e) Specifies a maximum cord dose of 14 Gy

Answer: Specifies a maximum cord dose of 14 Gy

Refs: RTOG 0631
2. Spinal SRS ....

a) Has never been performed without image guidance
b) Is only delivered in a single fraction
c) Should never be performed if the patient has received prior irradiation
d) Is delivered the fastest on a Tomotherapy unit
e) Is delivered the slowest on a CyberKnife unit

Answer: CyberKnife delivery is significantly longer than that on conventional linacs or Tomotherapy systems

Ref: Nalichowski et al, JACMP, 2016

Thank You