Strategies and Technologies for Cranial Radiosurgery Planning

MLC-based Linac Radiosurgery

Grace Gwe-Ya Kim, Ph.D. DABR
Disclosure

• No conflict of interests to disclose.
Learning Objectives

• Introduce the overview of MLC-based Linac radiosurgery.

• Demonstrate basic treatment planning techniques for MLC based radiosurgery

• Discuss metrics for evaluating SRS treatment plan quality.
Overview

BrainLAB m3

Varian Trilogy

Elekta Axesse

Novalis

Varian Edge

Elekta VersaHD
Evolution of technology

Hardware
- Micro-MLC
- IMRS (Dynamic MLC)
- IGRT
- Frame-less monitoring
- VMAT
- High-Intensity Beam

Software
- Better image quality
- Registration algorithm
- Faster compute power
- Improvement of optimization algorithm
- Small field dosimetry
MLC based Linac SRS

- Better conformity for irregular target
- Improved dose homogeneity inside the target
- Comparable dose fall-off outside the target
- Less time-consuming treatment planning
- Shorter treatment time
- Linac is not limited for cranial treatment
What is one advantage of MLC-based Linac radiosurgery over other machines?

1. Relatively fast treatment delivery (79%)
2. Easy to treat heterogeneous tissues (10%)
3. Multiple choices of different cone sizes (2%)
4. More accurate delivery (3%)
5. Easy forward planning (5%)
What is one advantage of MLC-based Linac radiosurgery over other machines?

Answer: 1. Relatively fast treatment delivery

Ref: L Ma et al., Variable dose interplay effects across radiosurgical apparatus in treating multiple brain metastases, Int. J CARS, 20 April 2014
Mechanical Stability

- **Linac (TG-142)**
  - Coincidence of Radiation & Mechanical ISO
    - ±1 mm from baseline
  - Couch position indication tolerance
    - 1 mm/0.5 degree

- **IGRT (TG-142)**
  - KV, MV, CBCT, monitoring image system coincidence
    - ≤ 1 mm
  - Positioning/repositioning
    - ≤ 1 mm
Multiple Metastases

Beam Configuration for Small Field

• Small Field Dosimetry
  • Machine-specific-reference field (msr)
  • Plan-class specific reference field (pcsr)

• Beam Configuration
  • Dosimetry leaf gap
  • Transmission
  • Target Spot Size

Table 14 Example Values for Target Spot Size Parameters

<table>
<thead>
<tr>
<th>Algorithm / Treatment Unit</th>
<th>Spot Size X-direction [mm]</th>
<th>Spot Size Y-direction [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAA / Varian treatment unit</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>1.0 if MLC in field</td>
<td>0.0 if MLC in field</td>
</tr>
<tr>
<td>Acuros XB / Varian treatment unit</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.5 if MLC in field</td>
<td>0.0 if MLC in field</td>
</tr>
<tr>
<td>AAA / Elekta Beam Modulator</td>
<td>2.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Acuros XB / Elekta Beam Modulator</td>
<td>2.5</td>
<td>0.0</td>
</tr>
<tr>
<td>AAA / Other Elekta treatment units</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>1.0 if MLC in field</td>
<td>0.0 if MLC in field</td>
</tr>
<tr>
<td>Acuros XB / Other Elekta treatment units</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.5 if MLC in field</td>
<td>0.0 if MLC in field</td>
</tr>
<tr>
<td>AAA / Siemens treatment units</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Acuros XB / Siemens treatment units</td>
<td>2.5</td>
<td>2.5</td>
</tr>
</tbody>
</table>

In all cases, fine-tuning of the spot size parameter values can be performed based on matching measurements and calculations.

Treatment Planning

- Imaging
- Registration
- Contouring
- Prescription
- Setting up the fields
- Optimization
- Plan Evaluation
Metastatic

- MRI with Gadolinium
  - T1 post contrast (thin slice)
  - Small non-enhancing lesions may be seen on T2
  - T2 Flair showed peritumoral edema

- CT Head with contrast
  - If MRI unavailable
  - Combine target delineation

AVM

- CTA, DSA, MRA

Trigeminal Neuralgia

- T1 post, FIESTA
**TG-54**

“MRI contains distortions which impede direct correlation with CT data at the level required for SRS”

**TG-117**

Use of MRI data in Treatment Planning and Stereotactic Procedures – Spatial Accuracy and Quality Control Procedures

---

Gradient nonlinearity distortion, Siebert et al, ASTRO 2014

Planning CT

- Slice Size (< 1.5 mm)
  - Spatial resolution of Z axis
  - Thick slices: more partial volume averaging.
- FOV (Pixel = FOV/matrix)
  - Smaller is better
- Body
- Immobilizer / Registration
- Target localization
# Uncertainty – TG54

<table>
<thead>
<tr>
<th>TABLE II. Achievable Uncertainties in SRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereotactic Frame</td>
</tr>
<tr>
<td>Isocentric Alignment</td>
</tr>
<tr>
<td>CT Image Resolution</td>
</tr>
<tr>
<td>Tissue Motion</td>
</tr>
<tr>
<td>Angio (Point Identification)</td>
</tr>
<tr>
<td>Standard Deviation of Position Uncertainty (by Quadrature)</td>
</tr>
</tbody>
</table>
Planning CT - IGRT

Bellon et al., J. Radiosurgery and SBRT, 3, (2014)

What is the most appropriate imaging modality for target delineation of brain metastases?

<table>
<thead>
<tr>
<th></th>
<th>Option</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>Digital subtraction angiography (DSA)</td>
<td>1%</td>
</tr>
<tr>
<td>14%</td>
<td>MRI T2 weighted FLAIR</td>
<td>14%</td>
</tr>
<tr>
<td>83%</td>
<td>MRI T1 weighted + Contrast</td>
<td>83%</td>
</tr>
<tr>
<td>0%</td>
<td>Scout image</td>
<td>0%</td>
</tr>
<tr>
<td>2%</td>
<td>Computed tomography</td>
<td>2%</td>
</tr>
</tbody>
</table>
What is the most appropriate imaging modality for target delineation of brain metastases?

Answer: 3. – MRI T1 FS + Contrast

Registration

CT/CT registration

CT/MR registration

- Benchmark Test for Cranial CT/MR Registration
  - 45 Institutions and 11 software systems
  - Average error: 1.8 mm
  - MR 2.0 mm Thickness, CT 2.5 mm Thickness
  - Manual registration: significant better result
Registration

- FMEA study of surface image guided radiosurgery (SIG-RS)

<table>
<thead>
<tr>
<th>Rank</th>
<th>Step</th>
<th>Potential failure modes</th>
<th>Potential cause of failure</th>
<th>Potential effects of failure</th>
<th>O</th>
<th>S</th>
<th>D</th>
<th>RPN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>31. Contour critical structures</td>
<td>Inaccurate contours</td>
<td>Poor image quality</td>
<td>Excessive dose to critical structure</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>288</td>
</tr>
<tr>
<td>1</td>
<td>79. Apply CBCT couch shifts</td>
<td>Inaccurate CBCT–CT registration</td>
<td>Poor image quality</td>
<td>Geometric miss</td>
<td>6</td>
<td>8</td>
<td>6</td>
<td>288</td>
</tr>
<tr>
<td>3</td>
<td>29. Previous tx CT registered to planning CT</td>
<td>Inaccurate CT–CT registration</td>
<td>Failed to save registration. Registration error</td>
<td>Retreat previous target.</td>
<td>5</td>
<td>8</td>
<td>7</td>
<td>280</td>
</tr>
<tr>
<td>4</td>
<td>39. Review OAR statistics</td>
<td>Critical structure doses not checked</td>
<td>Inattention</td>
<td>Excessive dose to critical structure</td>
<td>5</td>
<td>8</td>
<td>6</td>
<td>240</td>
</tr>
<tr>
<td>4</td>
<td>29. Previous tx CT registered to planning CT</td>
<td>Not done</td>
<td>Inattention</td>
<td>Retreat previous target</td>
<td>5</td>
<td>8</td>
<td>6</td>
<td>240</td>
</tr>
<tr>
<td>4</td>
<td>33. Insert Rx and contour target volumes</td>
<td>Contours accidentally changed by planner</td>
<td>Contours not locked</td>
<td>Underdosing of target volume</td>
<td>6</td>
<td>8</td>
<td>5</td>
<td>240</td>
</tr>
<tr>
<td>7</td>
<td>23. Images labeled with acquisition date and technique</td>
<td>Incorrect date label</td>
<td>Transcription error</td>
<td>May cause confusion and/or affect MD decision making</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>210</td>
</tr>
<tr>
<td>8</td>
<td>84. Monitor SIG indicated offsets to ensure patient position is within tolerance</td>
<td>SIG system fails to detect patient movement</td>
<td>SIG system failure</td>
<td>Geometric miss</td>
<td>3</td>
<td>8</td>
<td>8</td>
<td>192</td>
</tr>
<tr>
<td>9</td>
<td>59. Ensure SRS QA has been completed (Winston–Lutz, etc.) (P)</td>
<td>SRS QA not checked</td>
<td>Inattention</td>
<td>System out of tolerance</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>180</td>
</tr>
<tr>
<td>9</td>
<td>60. Ensure daily integrated IGRT QA has been performed (P)</td>
<td>IGRT QA not checked</td>
<td>Inattention</td>
<td>System out of tolerance</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>180</td>
</tr>
</tbody>
</table>

Manger et al., Medical Physics, **42** (5), 2449-2461 (2015)
Tested 6 SRS TPS platforms

Phantom study shows -3.6-22% vol. variation

Most of platforms & algorithm overestimated

Large variation: small target < 0.4 cc, near the end slice
• Randomized Trial to 1-mm versus 3-mm expansion with IG-SRS
• The local recurrence rate was low for both arms (<10% 12 months after SRS)
• Biopsy-proven radionecrosis was more frequently observed in the 3-mm arm
• Suggest a 1-mm margin is appropriate for IG-SRS
Prescription

- Treatment regimens
  - Target volume (RTOG 90-05)
  - Target location
  - Pre-existing edema
  - Pre-existing neurologic deficit
  - Pathology
  - Previous treatment
Beam Geometry

- Static, DCA, IMRS, VMAT approach
- Similar solid angle
- Avoid collision
- Reasonable number of beams
- BEV play
- Select isocenter

Multi-met Planning Strategy

Multi-iso approach

- Relatively easier to achieve good plan quality
- Less influenced by setup uncertainty
- Hard to control sum dose

- Contribution dose can be considered during the optimization
- Worse plan quality indices as an individual plan
- Need better understanding for planning tools
- Requires accurate patient positioning / monitoring method
Multi-met Planning Strategy

**Base plan approach**

- Contribution dose can be considered during the optimization
- Worse plan quality indices as an individual plan
Multi-met Planning Strategy

**Single-iso approach**

- Need better understanding of planning tools
- Requires accurate patient positioning / monitoring method
IMRS vs. VMAT

JZ Wang et al, Medical Dosimetry 37, 31-36, (2012)
Multiple Metastases

< Island blocking problem>

Fig. 1. Schematic beam-eye-view illustration of MLC blocking for an example case with three lesions. The lesions are projected onto the beam Y-axis vector. The MLC is unable to block the square region.

< Shadow>

Fig. 2. The sinogram for the three-lesion case. The shadowed region shows the area where two lesions overlap and an island blocking problem is present. The dashed line represents the gantry angle 140°, where the projections of lesion2 and lesion3 have overlap region.

Kang et al., Medical Physics, 37 (8), 4146-4154 (2010)
Plan optimization

- Constraints (GTV, CTV, PTV, OARs)
- NTO or Tuning Structures
- MU constraint
- Optimization resolution
- Calc. grid size
## Constraints

• **TG-101**

<table>
<thead>
<tr>
<th>Serial Tissue</th>
<th>Max vol. (cc)</th>
<th>One fraction</th>
<th>Three fraction</th>
<th>Five fraction</th>
<th>End point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Threshold dose (Gy)</td>
<td>Max point dose (Gy)</td>
<td>Threshold dose (Gy)</td>
<td>Max point dose (Gy)</td>
</tr>
<tr>
<td>Optic pathway</td>
<td>&lt;0.2</td>
<td>8</td>
<td>10</td>
<td>15.3</td>
<td>17.4</td>
</tr>
<tr>
<td>Cochlea</td>
<td></td>
<td>9</td>
<td>17.1</td>
<td>25</td>
<td>Hearing loss</td>
</tr>
<tr>
<td>Brainstem (not medulla)</td>
<td>&lt;0.5</td>
<td>10</td>
<td>15</td>
<td>18</td>
<td>23.1</td>
</tr>
<tr>
<td>Spinal cord and medulla</td>
<td>&lt;0.35</td>
<td>10</td>
<td>14</td>
<td>18</td>
<td>21.9</td>
</tr>
<tr>
<td></td>
<td>&lt;1.2</td>
<td>7</td>
<td>14</td>
<td>12.3</td>
<td>14.5</td>
</tr>
</tbody>
</table>

- **Lens** Max. dose <10 Gy (1 fx)
- **Normal Brain** V10 < 12 cc or V12 < 10 cc
- **Cranial Nerves** (fifth, seventh and eighth CN) 12.5-15 Gy (Flicker et al., IJROBP 2004)
Plan optimization – MU

Plan A

Plan B

<table>
<thead>
<tr>
<th>Field</th>
<th>Arc 1</th>
<th>Arc 2</th>
<th>Arc 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plan A</td>
<td>4116</td>
<td>2105</td>
<td>2105</td>
</tr>
<tr>
<td>Plan B</td>
<td>3488 (18% ↓)</td>
<td>1794 (17% ↓)</td>
<td>1794 (17% ↓)</td>
</tr>
</tbody>
</table>
Normal brain dose

Stereotactic radiosurgery for brain metastases: analysis of outcome and risk of brain radionecrosis

Giuseppe Minniti, Enrico Clarke, Gaetano Lanzetta, Mattia Falchetto Osti, Guido Trasimeni, Alessandro Bozzao, Andrea Romano and Riccardo Maurizi.

- V10 and V12 volumes greater than 4.5-7.7 and 6.0-10.9 cc carry >10% risk of symptomatic radiation necrosis, respectively.

G Minniti et al, Radiation Oncology 2011, 6:48
Multi-met optimization

- Optimize individual target
- Single ISO, multiple prescription targets
Tuning Structures

- Individual target(s) (not the composite PTV_total): lower = 100% of the target to receive 102% of prescription, no upper constraint
  - Inner control max dose = 98% of prescription dose
  - Middle control max dose = 50% of prescription
  - Outer control max dose = 40% of prescription

---

**Table 3** Dosimetric indices (15 patients with 1-5 targets)

<table>
<thead>
<tr>
<th>Patient</th>
<th>Target(s)</th>
<th>Target volume (cm³)</th>
<th>Conformity index</th>
<th>Homogeneity index</th>
<th>Gradient index a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>13.17</td>
<td>1.12</td>
<td>1.44</td>
<td>3.34</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>13.81</td>
<td>0.13</td>
<td>0.11</td>
<td>0.42</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>0.43-44.68</td>
<td>0.99-1.49</td>
<td>1.19-1.65</td>
<td>2.53-4.13</td>
<td></td>
</tr>
</tbody>
</table>

a Gradient index (GI) is calculated on per-plan basis, with GI = volume of 50% isodose line divided by the volume of the 100% isodose line.

---

Calculation Grid Size

Calculation Grid Size

• Expected effects for SRS case

• Calculation accuracy
• Max dose
• Conformity Index
• Gradient
• DVH
Plan Evaluation

• Target coverage
  • DVH evaluation
  • Location of hot and cold spots

• Dose to Organ at Risk (OAR)
  • DVH evaluation

• Conformity, Gradient, Homogeneity

• Normal tissue irradiated

• Delivery efficiency

• Number of MU
Paddick GI = $PV_{50\%} / PV$

$PV_{50\%}$ is the volume that received 50% of the effective prescribed dose, and $PV$ the prescribed dose.

- G. Clark et al. GI = $3.34 \pm 0.42$ (15 multi-met patients)

**Gradient Measurement (GM)**

Difference between the equivalent sphere radius of the prescription and half-prescription

→ Normal Brain Dose, V12 or V10
Conformity

RTOG CI = PV / TV

PV = The prescription volume
TV = The target volume

Paddick CI = (TV_{PV})^2 / TV \times PV

TV = Target volume
PV = prescription volume
TV_{PV} = Target volume within the prescribed isodose cloud

- G. Clark et al : CI = 1.12 ± 0.13 (15 multi-met patients)
- G. Kim et al : CI = 1.14 ± 0.18 (55 multi-met patients)
SAM Question 3.

What should not be used when treatment planning for small size multi-metastases?

<table>
<thead>
<tr>
<th>Percentage</th>
<th>Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>1. High resolution MRI</td>
</tr>
<tr>
<td>65%</td>
<td>2. Co-planar beams</td>
</tr>
<tr>
<td>31%</td>
<td>3. Individual PTV optimization</td>
</tr>
<tr>
<td>2%</td>
<td>4. Smaller calculation grid size</td>
</tr>
<tr>
<td>1%</td>
<td>5. Thin slice planning CT</td>
</tr>
</tbody>
</table>
What should not be used when treatment planning for small size multi-metastases?

Answer: 2. Use co-planar beams

Ref: Audet et al., Evaluation of volumetric modulated arc therapy for cranial radiosurgery using multiple noncoplanar arcs, Medical Physics, Vol. 38, No. 11, November 2011
Acknowledgements

• Todd Pawlicki, PhD
• Mariel Conell, CMD
• Jane Uhl, CMD
• Ryan Manger, PhD
• Adam York, PhD
• Kevin Murphy, MD
• Jona Hattangadi, MD
• Parag Sanghvi, MD
• Clark Chen MD PhD