Delivery Systems I

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Disclosures

- Ownership: VeriDos Solutions, LLC
Learning Objectives

• Understand the influence of Gamma Knife on development of linac-based SRS

• Understand the founding principles of conventional linac-based stereotactic delivery and the rationale for the incorporation of upgrade modifications to linacs

• Understand the impact of add-on equipment to conventional linear accelerators and how it improves accuracy and precision in SRT
Outline of Presentation

• Basic stereotactic principles
• Early era of linac-based SRS
  – Mechanical stability & localization improvements
• Beam modifiers
• “Early era” image guidance
• 6D robotic couches
Origin of Stereotaxis

- Method of locating points within the brain using an external, 3D frame of reference in order to perform a neurological procedure

*Solberg TD., SBRT, Medical Radiology. 2012*
Linac Stereotactic Localization

Lesion ↔ frame

Frame ↔ linac

Lesion ↔ frame ↔ linac
“Key” Physical Stereotactic RT Principles

• Core components
  – Robust immobilization
  – Accurate spatial localization
  – Precise, focused dose distribution
  – Accurate dose calculation
  – Ablative “radiosurgical” doses (≥ 8 Gy)
Immobilization & Localization

- Frameless IG-SRS
- Ease of workflow
- Setup accuracy studies
  - BrainLAB: 0.76 ± 0.46mm*
- SIG-SRS
- Initial study show comparable clinical outcomes for brain mets#
- Improved patient comfort

Focused dose distributions

- Large # of beams
- Non-coplanar
- Beam shapers - precision
Linac-based Radiosurgery?

“If radiation surgery will reach a position as a standard procedure, improved electron accelerators for roentgen production, adapted for the purpose, would seem a most attractive alternative” - Larsson et al. 1974
“Cyclothrone”

• Chair designed since couch weakest mechanical link
  – Betti chair (Osvaldo Betti - neurosurgeon)
• Varian Clinac 18
• Frame-based system: Talairach
  – Attached to chair
• Convergent beam delivery via gantry and chair rotations
Early Linac-based SRS Limitations

- Major impediments to linac SRT
  - Mechanical uncertainty (~ 3mm)
    - Couch
    - Gantry
  - Dosimetric
    - Dose rate (<400MU/min)
    - Small output factors → Long tx times
Late 80’s - Developments

• Significant pioneering efforts
• Floor stand development – Wendell Lutz
  – Immobilize and precisely position w/o room lasers
• Floor stand further refined by Siddon and Barth
  – Orthogonal radiograph

Lutz W, et al. IJROBP 10(suppl 2) 189. 1984
Overall Geometrical Accuracy

1.0 mm
• Test MECHANICAL isocentricity of linac
• Align sphere to mechanical isocenter w crosshairs
  • Cone
  • MLC
• Irradiate at various couch, collimator & gantry angles
  • Film
  • EPID
• Tolerances*
  • Mean deviation: ≤ 0.75mm
  • Max ≤ 1.0mm

The classic Winston-Lutz test is used to evaluate which of the following:

1. Radiation isocenter stability
2. Mechanical isocenter stability
3. Imaging isocenter stability
4. Radiation & imaging isocenter stability

Answer: 2. Mechanical isocenter stability

Isocentric arm system

- Precision bearings to control patient and accelerator movements
- Accuracy: 0.2 ± 0.1mm

First Commercial System

- SRS 200 (Philips Medical)
  - 1989
  - Complete package system
  - U of Florida gimble-type bearing stand
  - CT-based TPS
  - BRW stereotactic frame
  - Circular collimators (10-32mm)
Dedicated Commercial SRS Linac

Varian 600SR (1994)

Varian 600SR

• Stereotactic – specific features
  • Single energy (6MV)
  • Redesigned flattening filter => 800MU/min
  • Primary collimator: 10cm in dia.
  • Secondary: cylindrical shield
  • Tertiary: cones
  • Rotational considerations: range in MU/degree: 0.3-20

• Mechanical improvements
  • Lighter treatment head/reduced counter weight
  • Varian ETR couch
  • Mechanical isocentricity (WL) < 0.9mm
Novalis SRS Platform

- 10x10 cm² FS
- 3 – 5.5mm leaves
- Small penumbra
- Low leakage/transmission
- Circular collimators
  - 3-40mm
Development of microMLCs

- Lesions not spherical
- Irregular shapes require multiple isocenters / cones
  - GK “technique”
- Treatment time long
- Heterogeneous dose distributions
  - Lower ISL prescriptions
Cone Collimators

- Spherical lesions
- Small treatment volumes
  - Small brain metastases (<10mm)
  - Trigeminal neuralgia
- Improved geometric penumbra
- Faster dose fall off
  - Reduced brain V\textsubscript{12Gy}
• 1992 - First mMLC collimators for SRS developed in DKFZ (Heidelberg)
  - 3mm wide leaves
  - Motorized

• 1997 – XKnife system
  - 15 pairs
  - 4mm (max field size: 6x6cm²)
  - v2.0: 27 leaf pair (13.4x10.8cm²)

• 1997 – BrainLAB
  - 52 leaf
  - 3mm (14 pairs) / 4.5mm (6pairs)

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microMLCs integrated

• Varian HD120 MLC
  – 40 x 22cm²
  – 60 leaf pairs
  – 2.5mm (32 pairs)
  – 5.0mm (28 pairs)
  – Transmission
    • 1.20% (6x)
    • 1.35% (15x)

mMLC-based Delivery

5 isocenters / 20 arcs

1 isocenter / 5 arcs
mMLC SRS Dosimetric Parameters

mMLC SRS Dosimetric Parameters

(a) Conformity Index vs Homogeneity Index for retrospective and treated plans.

(b) Conformity Index vs Homogeneity Index for different tumor sizes.

mMLC SRS Dosimetric Parameters

(b) NTV$_{100}$/PTV vs Homogeneity Index

(e) NTV$_{50}$/PTV vs Homogeneity Index

mMLC - SBRT Planning

- Lung\Liver SBRT (n=29)
  - Dif. MLC
    - M120
    - HD120
  - Dif. technique
    - 3DCRT – FF
    - IMRT - FF
    - DCA
- Results
  - Small differences b/w MLCs
  - Lesion volume size and shape complexity dependent

Table 3: Mean (top) and max (bottom) percent improvement or worsening of HD120 MLC plans over M120 MLC plans.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Improvement (%)</th>
<th>Worsening (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cl</td>
<td>V_{HS}</td>
</tr>
<tr>
<td>IMRT</td>
<td>3.9</td>
<td>4.6</td>
</tr>
<tr>
<td>3DCRT</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>DCA</td>
<td>2.4</td>
<td>2.2</td>
</tr>
<tr>
<td>IMRT</td>
<td>18.5</td>
<td>20.4</td>
</tr>
<tr>
<td>3DCRT</td>
<td>9.5</td>
<td>9.8</td>
</tr>
<tr>
<td>DCA</td>
<td>8.1</td>
<td>6.4</td>
</tr>
</tbody>
</table>

mMLC - SBRT Planning

- Spine lesions
  - Dif. MLC
    - 5.0mm
    - 2.5mm
  - Dif. technique
    - IMRT - FF
    - VMAT

- Results
  - TC (5.7%) & GI (6.3%) improved
  - Larger effect on IMRT over VMAT

mMLC Overall Advantages

• 3D conformal
  – Single isocenter
  – No need for collimator changes
  – Increase delivery efficiency
  – Higher prescription isodose line normalization (~75%)

• IMRT delivery capabilities
As compared to multiple isocenter, cone-based SRS for treatment of an irregular lesion, the use of microMLC (mMLC) for collimation employing dynamic arc delivery technique will:

1. Decrease delivery time
2. Reduces target volume dose inhomogeneity
3. Reduces dose to surrounding normal tissue
4. All of the above
5. None of the above

Answer: 4. All of the above

When treating a small, spherical cranial lesion, (<10mm in max diameter) with a linac, the key advantage of using cone collimation (used as a tertiary collimator) instead of mMLC collimation is:

1. Reduced transmission penumbra
2. Improved field flatness by side scatter from cone walls
3. Reduced geometric penumbra
4. Assure accuracy of beam alignment
5. Reduced scatter penumbra

Answer: 3. Reduced geometric penumbra

Fractionated SRT: Initial Work

Overall accuracy: ~3-4.0mm
**TALON - SRT: Invasive**

Fig. 2. Patient with TALON attached to titanium base screws, docked to Nomogrip in CT suite.

Accuracy: $0.99 \pm 0.28\text{mm}$

TALON - SRT: Invasive


- n=9 patients
- 6 wks fractionated radiotherapy
- 6DOF correction
SRT: Frameless Localization System

- Infrared LED-based monitoring
  - Res: 0.1mm
  - 100fps
- Cranial FSRT
- Bite-block based
- Real-time correction display

SRT: Frameless Localization System

- Frameless system
- Thermal plastic mask
- Fast localization
- 5DOF
- \( n = 20 \) patients
- Accuracy
  - \( 0.5 \pm 0.3 \) mm

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**Fig. 4.** The immobilization system holder attached to the stereotactic head mold and mask are positioned.

**Table 3.** Mean repositioning error for the first 11 patients treated:

<table>
<thead>
<tr>
<th>Patient number</th>
<th>Mean error ± standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.20 ± 0.13</td>
</tr>
<tr>
<td>2</td>
<td>0.13 ± 0.12</td>
</tr>
<tr>
<td>3</td>
<td>0.07 ± 0.04</td>
</tr>
<tr>
<td>4</td>
<td>0.18 ± 0.11</td>
</tr>
<tr>
<td>5</td>
<td>0.26 ± 0.20</td>
</tr>
<tr>
<td>6</td>
<td>0.13 ± 0.12</td>
</tr>
<tr>
<td>7</td>
<td>0.27 ± 0.14</td>
</tr>
<tr>
<td>8</td>
<td>0.12 ± 0.05</td>
</tr>
<tr>
<td>9</td>
<td>0.40 ± 0.19</td>
</tr>
<tr>
<td>10</td>
<td>0.08 ± 0.05</td>
</tr>
<tr>
<td>11</td>
<td>0.38 ± 0.17</td>
</tr>
<tr>
<td>Mean for all patients</td>
<td>0.20 ± 0.12</td>
</tr>
</tbody>
</table>

*The first 11 patients each had 10 initial readings for bite plate position and had the average of the first five readings compared with each of the next five readings. The average difference in these readings is the standard deviation shown.*

**SRT: Frameless, Planar kV Loc.**

- **ExacTrac System**
  - Two kV x-rays
  - Two aSi flat panel detectors (20.5cm square)
  - Optical infrared tracking system

- **Geometrical accuracy**
  - Isocenter accuracy: 0.35mm*
  - 6D positional accuracy: 0.07 ± 0.22mm*

*Takakura T et al. PMB. 2010.*
SRT: Frameless, Planar kV Loc.

- CyberKnife Imaging System
  - Two ceiling-mounted kV x-rays tubes
  - Two floor-mounted aSi flat panel detectors (25cm square)
  - Orthogonal view geometry
  - Optical infrared tracking system
- Geometrical accuracy
  - Positional accuracy: $0.7 \pm 0.3\text{mm}$

**Isocenter localization errors**

- X: 0.5 ± 0.7mm
- Y: 0.6 ± 0.5mm
- Z: 0.0 ± 0.5mm


Initial 6DOF Corrections

- Rotation corrections – cranial mounts
- Adoption of extra-cranial IG localization necessitates 6D correction
  - Translations
  - Rotations
- Reduced residual localization errors
6 DOF Couch - ProTura™

- Aftermarket robotic couch
- Civco Medical Solutions
- Rotations about machine isocenter
- Correction limits
  - 3° pitch, roll, & yaw
  - ±50mm lat. & long.
  - ±25mm vert.
6 DOF correction – SRS Implications

- Protura™ accuracy
  - Lat: 0.2mm
  - Vert: 0.3mm
  - Long: 0.4mm
  - Pitch: 0.1°
  - Roll: 0.2°
  - Yaw: 0.1°
- n=28 pts (63fxs)
6 DOF correction - SRS Implications

- Protura™ w NovalisTx (frameless SRS)
- N=113 pts (160 targets)
- Initial CBCT
  - $1.03^\circ \pm 0.8$ (yaw), $1.16^\circ \pm 0.9$ (roll) and $0.9^\circ \pm 0.7$ (pitch)
- Verification CBCT
  - $0.37^\circ \pm 0.6$ (yaw), $0.27^\circ \pm 0.28$ (roll) and $0.24^\circ \pm 0.29$ (pitch)
- Reduce residual errors
  - $\leq 0.4^\circ$ rotational
  - $\leq 0.7$mm translational
6 DOF Couch - HexaPOD

- Elekta Solution
- Correction limits
  - 3° pitch, roll, & yaw
  - ±30mm lat. & long.
  - ±40mm vert.
6 DOF correction – Accuracy

- HexaPOD™ accuracy

Table 5. Summarized repositioning errors resulting from multiple translations and multiple rotations

<table>
<thead>
<tr>
<th>Bone</th>
<th>Translational errors [mm] (x,y,z)</th>
<th>Rotational errors [°] (u,v,w)</th>
<th>Translational errors [mm] (x,y,z)</th>
<th>Rotational errors [°] (u,v,w)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.04</td>
<td>0.01</td>
<td>0.08</td>
<td>−0.05</td>
</tr>
<tr>
<td>SD</td>
<td>0.13</td>
<td>0.40</td>
<td>0.10</td>
<td>0.16</td>
</tr>
<tr>
<td>Max ABS</td>
<td>0.30</td>
<td>0.90</td>
<td>0.20</td>
<td>0.30</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.11</td>
<td>0.29</td>
<td>0.11</td>
<td>0.12</td>
</tr>
</tbody>
</table>

6 DOF Couch – ExaTrac Couch

• BrainLAB Solution
• Accuracy
  – Lat: 0.06±0.15mm
  – Vert: 0.06±0.12mm
  – Long: 0.06±0.10mm
  – Roll: -0.05±0.14°
  – Pitch: 0.02±0.10°
  – Yaw: -0.01±0.07°

Takakura T et al. PMB. 2010.
6 DOF Couch – Perfect Pitch

- Varian Solution
- Correction limits
  - $\pm 3^\circ$ pitch, roll, & yaw
  - $\pm 50$mm lat. & long.
  - $\pm 25$mm vert.
The integration of a 6 degree-of-freedom treatment couch as compared to a 3 degree-of-freedom treatment couch in modern image-guided SRT delivery systems will:

1. Improve mechanical stability of couch
2. Reduce mechanical accuracy of couch
3. Reduce residual setup errors
4. Allow for faster patient repositioning

Answer: 3. Reduce residual setup errors

Summary/Conclusion

• Linac-based stereotactic techniques have evolved over time to improve accuracy and precision of radiation delivery

• Additive development of improved components have enabled the creation of robust, dedicated stereotactic delivery systems
Thank you for your time and attention.