Gamma Knife Radiosurgery

Paula L. Petti, Ph.D.

FREMONT, CA

Disclosure: P. Petti is a PFX system-start consultant for Elekta Instrument AB
Lars Leksell, neurosurgeon, introduces idea of stereotactic radiosurgery in 1951

“The stereotactic technique enables the accurate insertion of a needle electrode into any given structure of the brain...

It would therefore be feasible to replace the needle by narrow beams of radiant energy directed at the target in the brain and thereby produce a local destruction of the tissue…”

Leksell Gamma Knife

Model U: (Introduced 1986)

Model C: (Introduced 1999)

Perfexion: (Introduced 2006)
Properties of Leksell Gamma Knife® Radiosurgery

• ~200 $^{60}$Co sources (6000 Ci total initial activity)
• Sources positioned and collimated to focus radiation precisely at isocenter
• Prescription volume shaped to match the target volume by:
  – translating the patient in 3 orthogonal directions between “shot” settings
  – using appropriately sized collimators for each shot
Properties of $^{60}$Co

$^{60}$Co isotope produced by bombarding $^{59}$Co with neutrons in a nuclear reactor $\Rightarrow$ The U.S. Nuclear Regulatory Commission (NRC) oversees its use.

$^{60}$Co decays via beta decay, producing 2 mono-energetic $\gamma$-rays, 1.17 and 1.33 MeV in the process.

The half life of $^{60}$Co is 5.27 yrs.

Depth dose distribution similar to 4 MV photons.
Indications for Gamma Knife Radiosurgery

- **44%** Malignant Tumors
- **35%** Benign Tumors
- **13%** Vascular Disorders
- **8%** Functional Disorders
- **1%** Ocular Vascular Disorders

**Examples:**

**Malignant tumors:** Brain metastases, glial tumors

**Benign tumors:** Meningioma, vestibular schwannoma, pituitary adenoma

**Vascular disorders:** Arteriovenous malformation

**Functional disorders:** Trigeminal neuralgia

*Data from Leksell Gamma Knife Society, worldwide 2009 statistics*
Criteria for Gamma Knife Radiosurgery

Single-fraction GK SRS

• Largest tumor dimension $\leq$ 3 to 4 cm
• Minimum distance to optic apparatus $\geq$ 2 mm
• Max number of lesions that can reasonably be treated in a single session $\sim$ 30
• Can treat very small tumors (e.g. small brain metastases with dimension of the order 2 mm)

Multiple-fraction GK SRS (Extend system)

• Largest tumor dimension $>$ 4 cm
• Tumor “too close” to optic apparatus
• Occasionally, patient preference
Localization Systems for GK

Leksell Stereotactic Frame: attached to patient via 4 pins
Single-fraction radiosurgery

Leksell Extend re-locatable frame system: vacuum bite block
Fractionated radiosurgery

Images from Elekta brochures
GK Model Comparison

<table>
<thead>
<tr>
<th>Models U, C and 4C</th>
<th>Perfexion™</th>
</tr>
</thead>
<tbody>
<tr>
<td>Secondary collimators are external, must be manually changed</td>
<td>All collimation is internal</td>
</tr>
<tr>
<td>Source position fixed</td>
<td>Sources move</td>
</tr>
<tr>
<td>Patient position changed manually or semi-automatically</td>
<td>Patient position changed automatically</td>
</tr>
<tr>
<td></td>
<td>Treatment couch = the patient positioning system</td>
</tr>
</tbody>
</table>
Perfexion™ Collimator

- 3 collimator sizes (4-, 8- and 16-mm)
- 576 collimating channels
- Material is tungsten

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>$^{60}$Co approx. HVL (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tungsten</td>
<td>19300</td>
<td>7.9</td>
</tr>
<tr>
<td>Steel</td>
<td>7800</td>
<td>21</td>
</tr>
</tbody>
</table>

(Images courtesy of Elekta)
Illustration of Sector Positions

5 sector Positions:
- Home
- 8-mm
- Blocked
- 4-mm
- 16-mm

Sectors alternating 16-mm (red) and 8-mm (green) collimators

Note different positions of sectors.
Radiological Accuracy

- Alignment of the radiation focus and the mechanical isocenter

Sources and collimating system defines radiation focus

Patient positioning system defines mechanical isocenter

Critically important since the hallmark of radiosurgery is the ability to deliver focal radiation with sub-millimeter precision
## GK Perfexion™: Selected Technical Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical couch repositioning time</td>
<td>&lt; 3 s</td>
</tr>
<tr>
<td>Couch positioning repeatability</td>
<td>&lt; 0.05 mm</td>
</tr>
<tr>
<td>Maximum patient weight</td>
<td>210 kg (460 lbs)</td>
</tr>
<tr>
<td>Typical collimator size setup time</td>
<td>&lt; 3 s</td>
</tr>
<tr>
<td>Radiological accuracy</td>
<td>&lt; 0.5 mm</td>
</tr>
</tbody>
</table>
Instruments used to check the alignment of patient positioning system with radiation focus for LGK Perfexion:

Master Diode Tool: Service Instrument

New Film Holder: Service and Field Instrument

Old-Style Film Holder: Field Instrument

Diode Tool: Field Instrument
Diode QA Test

- The diode is scanned through the irradiated field in X, Y and Z for the 4-mm collimator. Average deviations are reported.

Calculated Deviation

Instructions

Please save or discard the results.
Example of Results:

Pin-Point Test of Coincidence of PPS and RFP, New Film Holder

\[ \Delta X = 0.02 \text{ mm} \]
# Results of Pin-Point Test at WHHS Averaged over 4 years from 2007 to 2011

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Averaged $\Delta r^*$ over 4-year time period (mm)</th>
<th>Standard Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-mm</td>
<td>0.16</td>
<td>0.07</td>
</tr>
<tr>
<td>8-mm</td>
<td>0.23</td>
<td>0.07</td>
</tr>
<tr>
<td>16-mm</td>
<td>0.27</td>
<td>0.08</td>
</tr>
</tbody>
</table>

\[ *\Delta r = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \]

- $\Delta r$ = deviation of radiation focal point from center of patient positioning system
- Results within the specified 0.5 mm radiological accuracy of the Perfexion positioning system
End-to-End Tests

• Tests described on previous slides assess the precision with which the radiation focal point is aligned to the mechanical isocenter
• They do not test the accuracy of the entire GK procedure
• End-to-end tests are not done routinely for GK
• A few studies have been reported
End-to-End Experiments

- Attached LGK SRS frame to phantom
- Obtained CT scan
- Inserted film in phantom
- Irradiated film for 6 representative treatment plans
Results from L. Ma Study

TABLE I. Summary of film measurement results as compared with the Leksell Gamma Plan dose calculations at different levels of the isodose lines, i.e., 25%, 50%, and 75% and 90% in distance-to-agreement ($\Delta$): the maximum, the average and the standard deviation (Std) values are given.

<table>
<thead>
<tr>
<th>Case No.</th>
<th>No. of shots</th>
<th>$\Delta_{25%}$ (mm)</th>
<th>Mean ± Std $\Delta_{25%}$ (mm)</th>
<th>Max $\Delta_{30%}$ (mm)</th>
<th>Mean ± Std $\Delta_{30%}$ (mm)</th>
<th>Max $\Delta_{75%}$ (mm)</th>
<th>Mean ± Std $\Delta_{75%}$ (mm)</th>
<th>Max $\Delta_{90%}$ (mm)</th>
<th>Mean ± Std $\Delta_{90%}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.8</td>
<td>0.4 ± 0.28</td>
<td>0.5</td>
<td>0.2 ± 0.15</td>
<td>0.3</td>
<td>0.1 ± 0.12</td>
<td>2.0</td>
<td>1.2 ± 0.76</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1.0</td>
<td>0.6 ± 0.31</td>
<td>0.5</td>
<td>0.3 ± 0.16</td>
<td>1.0</td>
<td>0.6 ± 0.32</td>
<td>0.8</td>
<td>0.6 ± 0.19</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>2.0</td>
<td>1.2 ± 0.50</td>
<td>1.8</td>
<td>1.1 ± 0.49</td>
<td>1.8</td>
<td>1.2 ± 0.39</td>
<td>2.0</td>
<td>1.0 ± 0.65</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>2.1</td>
<td>1.5 ± 0.49</td>
<td>1.5</td>
<td>0.9 ± 0.36</td>
<td>1.8</td>
<td>1.1 ± 0.49</td>
<td>2.0</td>
<td>1.3 ± 0.58</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>2.0</td>
<td>1.6 ± 0.35</td>
<td>1.0</td>
<td>0.5 ± 0.46</td>
<td>1.7</td>
<td>1.2 ± 0.46</td>
<td>1.5</td>
<td>0.8 ± 0.48</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>2.0</td>
<td>1.4 ± 0.59</td>
<td>2.1</td>
<td>1.2 ± 0.71</td>
<td>1.6</td>
<td>0.9 ± 0.58</td>
<td>0.8</td>
<td>0.4 ± 0.37</td>
</tr>
</tbody>
</table>

- E.g., for 50% isodose line, average DTA was $1.02 \pm 0.18$ mm
- Considering all isodose levels, no statistically significant difference in uncertainty with increasing number of shots
Uncertainties in Extend System

• Data reported at AAPM 2012 meeting:
  – SU-E-T-405: UCSF
  – SU-C-BRCD-2: D. Schlesinger et al. UVA
  – SU-E-T-398: N. Gopishankar et al., All India Inst. of Med. Sciences
For the Leksell Gamma Knife, measurements of the alignment between patient-positioning system (PPS) and the radiation focal point (RFP) are typically \( \leq ____ \) mm, and the manufacturer’s specification is that the alignment be \( \leq ____ \) mm.

| 0% | 1. | 0.1, | 0.3 |
| 0% | 2. | 0.3, | 0.5 |
| 0% | 3. | 0.6, | 1.0 |
| 0% | 4. | 1.0, | 1.5 |
| 0% | 5. | 1.5, | 2.0 |
For the Leksell Gamma Knife, measurements of the alignment between patient-positioning system (PPS) and the radiation focal point (RFP) are typically ≤ ____ mm, and the manufacturer’s specification is that the alignment be ≤ ____ mm.

**Answer:** 2: M. Schell et al., AAPM Report No. 54, “Stereotactic Radiosurgery,” p. 65 (1999). Also, note that the values listed on slide 18 are ≤ 0.3 mm. Specifications for the radiological accuracy of the Perfexion system are stated in Elekta’s documentation, “LGK Perfexion, System Description.”

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Averaged $\Delta r$* over 4-year time period (mm)</th>
<th>Standard Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-mm</td>
<td>0.16</td>
<td>0.07</td>
</tr>
<tr>
<td>8-mm</td>
<td>0.23</td>
<td>0.07</td>
</tr>
<tr>
<td>16-mm</td>
<td>0.27</td>
<td>0.08</td>
</tr>
</tbody>
</table>
Based on reports in the literature, the distance-to-agreement (DTA) for the 50% isodose level in a multi-shot GK treatment is approx. ___ mm

0%  1.  0.1
0%  2.  0.5
0%  3.  1.0
0%  4.  1.8
0%  5.  2.5
Based on reports in the literature, the distance-to-agreement (DTA) for the 50% isodose level in a multi-shot GK treatment is approx. ___ mm

Workflow for Frame-Based GK SRS

- Neurosurgeon attaches stereotactic frame
- Skull and frame measurements obtained
- MR and/or CT images acquired
- Treatment planning performed (by either physicists or MDs)
- Treatment plan approved
- Treatment delivered

All steps completed in one day

Several patients can be treated per day depending on complexity of cases and staffing
Frame attachment, Skull Measurements

Stereotactic Frame defines LGK coordinate system

Surface of the head determined by skull scaling instrument ("bubble")

Everything inside skull, as determined by bubble, is assumed to be unit density
Skull Definition from CT

- Relatively new feature:
  - Determine skull outline from CT scan
  - Use CT to make tissue heterogeneity correction via convolution dose calculation algorithm

- Pros: More accurate dose calc
- Cons:
  - Requires CT as well as MR for treatment planning
  - Existing data for dose prescriptions based on unit-density approximation
MRI Fiducial Boxes

Image Definition

Copper Sulfate channels
Distortions in MRI Images

• Sources of distortion in MR images:
  – Different pulse sequences
  – Different magnetic susceptibilities of individual patients
  – The presence of magnetic objects such as surgical clips

• Investigators* have documented distortions in MRI images used for GK SRS to be of the order of 1 mm or less

*e.g., A. Ertl et al., Med Phys. 28, 166-170, (1999)
Assessing Distortion in MR Images

• Consider obtaining CT scans in patients for whom a 1 mm shift in targeting could be critical
  – Fuse the CT with the MR (i.e., overlay corresponding pixels of defined images)
  – Or, simply assess targeted area on CT scan
• Perform phantom measurements to assess distortions on MR as part of regular QA
To reduce geometric uncertainty for cases where shot placement is critical (e.g., single-shot treatment for TN), consider acquiring CT as well as MR.
An Example of a QA Phantom from CIRS

- Phantom filled with a proprietary water-based polymer that images well on MR and CT. The skull is made from an epoxy-based tissue substitute.
- Rods running in orthogonal directions inside the phantom are used to assess distortions.
- Can attach the Leksell frame to phantom.
Qualitative Assessment of Distortions in MR Images

Can visually assess spatial agreement between images by examining overlap of fiducials.
Quantitative Assessment of Distortions in MR Images

- Identify corresponding points on CT and MR
- Use measuring tool in LGP to assess differences

Typically, I have found RMS differences of about 0.5 mm
Tumor Definition for GK

• T1 MR sequences
• T2 MR useful for benign lesions (e.g. meningioma and vestibular schwannoma)
• CT useful for skull-base lesions
• Margins are generally not added to the Gross Tumor Volume
Tumor and Critical Structure Definition
T1-, T2- MR and CT to Visualize Acoustic Tumor and Cochlea

Cochlea most easily identified on T2 MR or CT images

All three image sets used to identify tumor within auditory canal
Treatment Planning Basics

Different size “shots” of radiation delivered to target

- Treatment planning consists of determining:
  - the positions for each focus of radiation
  - the collimator size for each focus
  - the tilt of the patients head (gamma angle) for each focus

Until recently, all GK was forward planned, inverse planning is now an option.
GK Treatment Planning Basics

Placement of first shot

Placement of second shot
A GK shot-placing strategy for GK: large shots placed centrally, smaller shots used to “fill in” with smaller collimators “near” the critical structures.

Cavernous sinus meningioma, $V_P = 15 \text{ Gy}$

Max dose to pituitary stalk is 6.5 Gy

Max dose to optic structures is 4 Gy

16mm$^3$ of brainstem receives > 12 Gy
Plan for Small Vestibular Schwannoma

Three 4-mm isocenters, each with some sector blocking so that the cochlea receives ≤ 4Gy
Treatment Plan Evaluation: Some Definitions:

\[ V_T = \text{Target Volume} \]
\[ D = \text{Prescription dose} \]
\[ V_D = \text{Volume receiving dose } D \]
(i.e., the prescription volume)

Target Coverage
\[ C = \frac{V_D \cap V_T}{V_T} \]

Plan Selectivity
\[ S = \frac{V_D \cap V_T}{V_D} \]
Coverage versus Selectivity

- Excellent target coverage, poor selectivity
- Excellent selectivity, poor target coverage
Conformity Indices

RTOG conformity index*:

\[ C_S = \frac{V_D}{V_T} = \frac{C}{S} \]

Usually \( \geq 1 \), but can be \(< 1 \) if coverage is sub-optimal.

Paddick conformity index**:

\[ C_P = c \times S \]

Always \( \leq 1 \)

\( C_P = 1 \) represents perfect conformity

---


Relationship between Shaw (RTOG) and Paddick Conformity Indices

\[ C_P = \frac{c^2}{C_S} \]

- \( C_P \) is inversely proportional to \( C_S \), with proportionality constant equal to the square of the target coverage.
- \( C_P = 1/C_S \) if the target coverage is 100% (i.e., \( c = 1 \)).
- In GK SRS we seem to be moving towards using \( C_P \).
To understand the meaning and implication of conformity index, consider the dose plans shown on the next three slides.....
Brain Met: $V_T = 0.15$ cc
Meningioma: $V_T = 1.2 \text{ cc}$
Meningioma: VT = 5.5 cc
Considering the 3 plans shown on the preceding slides, which of the following statements regarding their Paddick conformity indices is true?

0% 1. \( C_P \text{ (sm met) } > C_P \text{ (sm meningioma) } > C_P \text{ (lg mening) } \)

0% 2. \( C_P \text{ (sm met) } < C_P \text{ (sm meningioma) } < C_P \text{ (lg mening) } \)

0% 3. \( C_P \text{ (sm met) } = C_P \text{ (sm meningioma) } > C_P \text{ (lg mening) } \)

0% 4. \( C_P \text{ (sm met) } > C_P \text{ (sm meningioma) } = C_P \text{ (lg mening) } \)

0% 5. \( C_P \text{ (sm met) } = C_P \text{ (sm meningioma) } = C_P \text{ (lg mening) } \)
Considering the 3 plans shown on the preceding slides, which of the following statements regarding their Paddick conformity indices is true?

**Answer:** 5:

\[
C_P \text{ (small met)} = C_P \text{ (small meningioma)} = C_P \text{ (large meningioma)}
\]

All 3 plans have the same Paddick conformity index.

*(Recall that larger values of \( C_P \) correspond to better conformity and that \( C_P = 1.0 \) represents “perfect” conformity.)*

For all 3 plans:

Target Coverage = 1.0

Plan selectivity = 0.58

\[ \therefore C_P = 0.58, \quad C_S = 1.72 \]

However, the volume of non-target tissue receiving the prescription dose is:

Small met: 0.1 cc

Small Meningioma: 0.9 cc

Large Meningioma: 3.9 cc
Actual Plan for Large Meningioma

C_p = 0.80, C_S = 1.25

Volume of non-target tissue receiving 15 Gy (prescription dose) = 1.3 cc

- 1181 evaluable lesions treated between 1993 and 1998
- Symptomatic radiation toxicity associated with larger:
  - Target volume ($V_T$)
  - Prescription volumes ($V_P$)
  - Larger volume of non-target tissue receiving the prescription dose
- But not with:
  - Worsening conformity index ($V_P/V_T$)
The moral of the story…

• Conformity index is simply a ratio of volumes
• Does not tell us the absolute volume of normal tissue irradiated
• Larger targets are likely to require better conformity
  – (probably > 0.75 for $V_T > 3 \text{ cm}^3$)*

QA and Radiation Safety for Gamma Knife

- Large doses delivered in a single fraction
- Imaging, planning and treatment performed in a single day
- Often, multiple patients treated in a single day

- GK team members are often under stress to compete steps involved for GK treatment
  
  + distractions including the occasional necessity to “multi-task”
Potential for Human Error

• Types of errors that have occurred
  – Left/Right inversion errors
  – Delivering the wrong treatment plan to a patient
  – Entering incorrect prescription dose
  – For older model GKs, setting coordinates incorrectly
Gamma Knife users must adhere to recommendations put forth by the

1. U.S. Food and Drug Administration
2. U.S. Environmental Protection Agency
3. National Institute of Health
4. U.S. Nuclear Regulatory Commission
5. National Institute of Standards and Technology
Gamma Knife users must adhere to recommendations put forth by the…

**Answer: 4:** The US Nuclear Regulatory Commission*

Unlike other forms of radiosurgery, GK SRS falls under the jurisdiction of the NRC (because Co-60 is reactor bi-product material)

NRC Requirements for PFX

- Training of AUs and AMPs, and documentation of training
- Preparation and use of “written directive”
- Routine QA

Purpose of both the NRC requirements and of many of the technological developments in hardware and software for the Gamma Knife over the years has been to reduce the likelihood of human error

Thank you for your attention!