Overview of Gamma Knife Radiosurgery

David Schlesinger, Ph.D.

Lars Leksell Gamma Knife Center
University of Virginia
Conflicts of Interest

Elekta, AB: Research Support
Technical Overview

Treatment Planning

Plan Evaluation

“Advanced” Features
Clinically Active Gamma Knife Models

Model C/4C (1999)

- 201 sources (5 annular rings)
- Automatic positioning system + manual trunnion

Model Perfexion (2006)

- 192 sources
- 8 sectors (no helmets)
- Automatic couch positioning system
Gamma Knife Model C

- Shielding doors
- Collimator helmet
- Treatment bed
~20 metric tons to protect you from 20 grams of $^{60}$Co
$^{60}\text{Co}$ decay is a very stable photon source. Sources are usually in pellet-form, double-encapsulated in steel, then placed in an aluminum source bushing.

A single 36 Ci source yields a dose rate of ~480 mSv/hr at 1 meter!

Source: Georgia registry of radioactive sealed sources and devices, 2001
Technical requirement to create many individual small beams led directly to the use of $^{60}$Co.

Spreading the energy out generates the steep dose gradients.

Model C: 201 beams / isocenter

Perfexion: 192 beams / isocenter

Image courtesy of Elekta, AB
The frame defines the coordinate system and immobilizes patient

Coordinate system origin is to the right, superior, posterior of the patient’s head

All coordinates are positive – no sign mistakes

Center of the system is considered to be (100, 100, 100) (mm)
Each helmet has a single-size collimator

Each beam has an identical (400 mm) source to focus distance

Therefore, each beam can be treated identically

Off-axis profiles are 1D functions

Model C has automatic (APS) and manual (trunnion) positioning methods

Shielding is a manual operation
Perfexion – No more helmets!

Roughly conical tungsten collimator

576 (192 x 3) beam channels
Beam channels are not all the same source to focus distance.
Sources are angled relative to the collimators – 2D profiles.

Perfexion collimator system:

- 4mm / 8mm / 16mm and blocked collimator positions
- Also a home position when not in use.
## 15 base beam configurations

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Output factor</th>
<th>Attenuation constant (1/mm)</th>
<th>Scaling distances (mm)</th>
<th>Virtual source-to-focus distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P4_1</td>
<td>0.799</td>
<td>0.00678</td>
<td>377</td>
<td>521</td>
</tr>
<tr>
<td>P4_2</td>
<td>0.815</td>
<td>0.00704</td>
<td>380</td>
<td>546</td>
</tr>
<tr>
<td>P4_3</td>
<td>0.792</td>
<td>0.00690</td>
<td>387</td>
<td>533</td>
</tr>
<tr>
<td>P4_4</td>
<td>0.725</td>
<td>0.00712</td>
<td>398</td>
<td>595</td>
</tr>
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<td>P4_5</td>
<td>0.663</td>
<td>0.00698</td>
<td>420</td>
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</tr>
<tr>
<td>P8_1</td>
<td>0.957</td>
<td>0.00658</td>
<td>374</td>
<td>431</td>
</tr>
<tr>
<td>P8_2</td>
<td>0.946</td>
<td>0.00660</td>
<td>382</td>
<td>437</td>
</tr>
<tr>
<td>P8_3</td>
<td>0.901</td>
<td>0.00681</td>
<td>394</td>
<td>468</td>
</tr>
<tr>
<td>P8_4</td>
<td>0.808</td>
<td>0.00665</td>
<td>408</td>
<td>480</td>
</tr>
<tr>
<td>P8_5</td>
<td>0.730</td>
<td>0.00680</td>
<td>433</td>
<td>522</td>
</tr>
<tr>
<td>P16_1</td>
<td>0.961</td>
<td>0.00694</td>
<td>381</td>
<td>481</td>
</tr>
<tr>
<td>P16_2</td>
<td>1</td>
<td>0.00685</td>
<td>379</td>
<td>459</td>
</tr>
<tr>
<td>P16_3</td>
<td>0.986</td>
<td>0.00675</td>
<td>383</td>
<td>455</td>
</tr>
<tr>
<td>P16_4</td>
<td>0.920</td>
<td>0.00690</td>
<td>389</td>
<td>488</td>
</tr>
<tr>
<td>P16_5</td>
<td>0.851</td>
<td>0.00694</td>
<td>409</td>
<td>519</td>
</tr>
</tbody>
</table>
TMR10 – The basic dose model

\[
\dot{D}_i(P) = \dot{D}_{\text{calibration},16} \times \frac{1}{192} \times \text{of}_i \times e^{-\mu_0(d_i-R_{\text{calibration}})} \times \frac{e^{-\mu_z z}}{(1+\frac{z}{R_{\text{vesf},i}})^2}
\]

A new TMR dose algorithm in Leksell GammaPlan®

The TMR 10 dose algorithm, available in Leksell GammaPlan® 10 and later, is an enhancement of the water-based dose calculation algorithm (here referred to as TMR Classic) in previous software versions. The purpose of this document is to describe the rationale for developing TMR 10, to explain the underlying physics and to review the changes in the predicted dose distributions relative to TMR Classic.
Important approximations

- Treats the brain as a homogeneous ball of water – no inhomogeneity correction
- Ignores build-up region effects
- Uses a poor approximation of the skull shape
- These are all minor issues inside the brain
- FAST – good for Gamma Knife workflow
## Treatment Planning Imaging

### Typical imaging protocols:

<table>
<thead>
<tr>
<th>Solid tumors</th>
<th>AVMs</th>
<th>Skull-base and pituitary</th>
</tr>
</thead>
</table>
| T1-weighted MR + contrast | Biplane DSA  
T1-weighted MR + contrast  
MRA                      | T1-weighted MR + contrast  
T2 CISS or SPACE  
T1-weighted + fat saturation |
Skull Contours

- Used to calculate SSD and depth of each beam
- Also used to determine potential collisions between patient and helmet or side of collimator
Target/Dose Matrix Definition

<table>
<thead>
<tr>
<th>Target</th>
<th>Shots</th>
<th>Prescription dose</th>
<th>Ref point dose</th>
<th>Max dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>C: Ipost f1</td>
<td>1</td>
<td>22.0 Gy at 60% (36.7 Gy at 100%)</td>
<td>36.7 Gy</td>
<td>36.7 Gy</td>
</tr>
<tr>
<td>D: Imedialpostf</td>
<td>1</td>
<td>24.0 Gy at 80% (30.0 Gy at 100%)</td>
<td>30.0 Gy</td>
<td>30.1 Gy</td>
</tr>
<tr>
<td>E: Rfrontalps1</td>
<td>1</td>
<td>20.0 Gy at 50% (40.0 Gy at 100%)</td>
<td>40.0 Gy</td>
<td>40.0 Gy</td>
</tr>
</tbody>
</table>
Single Target vs All Target Modes

Relative Dose Mode:

Single target mode: only shots from current target contribute to isodose lines shown. Dose in % of maximum dose in target.

All target mode: All shots in plan from all targets contribute to isodose lines shown. Dose in units of Gy.

For targets that are close together, there can be significant differences!
Model Perfexion: Basic Isocenter Parameters

Base configurations

Composites and blocking

Weighting

1.0 / 1.0

1.0 / 0.5
Doses are usually prescribed to 50% isodose line.

Defining a Dose Distribution
Gamma Angle

Gamma angle rotates head around x-axis.
Used to avoid collisions
Sometimes to lower dose to critical structures
A plan is a list of locations, collimator configurations, and dwell times. Very similar to HDR treatment planning. Each location is a coordinate to move head so it is at focus of unit. Total # beams = 192 x number of locations (unless sectors are blocked).
Technical Overview

Treatment Planning

Plan Evaluation

“Advanced” Features
Conformity Index

\[ CI = \frac{\text{Volume of target covered by PI}}{\text{Volume of PI}} \times \frac{\text{Volume of target covered by PI}}{\text{Volume of Target}} \]

PI = Prescription Isodose

\( CI = 1.0 \) represents perfect conformity

Paddick, *J Neurosurg* 93 Suppl. 3 (2000), pp. 219–222
Gradient Index

$$GI = \frac{\text{Volume of isodose that is } \frac{1}{2} \text{ of PI}}{\text{Volume of PI}}$$

Measures how quickly dose is dropping outside of target:

Example: If prescription isodose is at 60%, measure volume of 30% / 60%

$GI < 3.0$ is “good” dose falloff

Paddick, et. al., *J Neurosurg* **105** Suppl. 7 (2006), pp. 194-201
Optimizing Dose Falloff

Volume of 50% isodose: 1.7cc
Volume of 25% isodose: 4.7cc
Gradient Index: 2.76

Volume of 50% isodose: 1.7cc
Volume of 25% isodose: 5.4 cc
Gradient Index: 3.18

Same conformity index (0.76) in both cases!
Technical Overview

Treatment Planning

Plan Evaluation

“Advanced” Features
• Combinations of plug patterns are applied to one or more isocenters
• Example: Isocenter #7 has a different optimal plug pattern than isocenter #10
Shielding on Perfexion

- Shielding is achieved by blocking one or more sectors
- Risk structures are used to calculate which sectors to block
- No annular shielding patterns as on model C

Before

After
“Inverse” Planning

- Automatically fills a volume with isocenters
- Optimizes against plan metrics such as coverage, conformity, dose falloff, and beam time
- Dose NOT involve dose/volume constraints
- Plan can be manually adjusted via typical forward-planning techniques
Convolution algorithm

\[ Dose(r) = \iiint TERMA(\rho \cdot r')Kernel(\rho \cdot (r - r'))d^3(r') \]

Allows for tissue inhomogeneity correction

Requires calibrated CT imaging

Fluence profiles, kernel and dose profiles pre-calculated on Elekta in-house Monte-Carlo system based on detailed CAD models of Gamma Knife

Acknowledgements

Thomas Jefferson’s Rotunda at the University of Virginia