Uncertainties in SRS: Definitions and Gamma Knife

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Conflicts of interest

Elekta, AB: Research Support
Educational objectives

Review definitions and concepts of uncertainty as they apply to total treatment uncertainty for SRS

Understand the primary sources of uncertainty that must be considered for Gamma Knife SRS procedures

Learn some techniques for evaluating total uncertainty and working in spite of procedural uncertainty.
Not interchangeable!

**Error:** Difference between the measurement and the true value

**Accurate, but not precise**

**Precise, but not accurate**

Images: http://en.wikipedia.org/wiki/Accuracy_and_precision
Precision ≠ Resolution

Resolution: The range in stimulus that will produce the same indicated output.

http://www.istl.nist.gov
Repeatability: Closeness of measurements when measured under identical conditions

Reproducibility: Closeness of measurements when measured under changing conditions

Both are part of the concept of precision.
Uncertainty: Parameter that characterizes the dispersion of the values that could reasonably be attributed to the measurand.
# Uncertainty budgets

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Standard Uncertainty (1 standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>resolution</td>
<td>0.050 mm</td>
</tr>
<tr>
<td>alignment</td>
<td>0.050 mm</td>
</tr>
<tr>
<td>temperature</td>
<td>0.010 mm</td>
</tr>
<tr>
<td>repeatability</td>
<td>0.020 mm</td>
</tr>
<tr>
<td>ruler calibration</td>
<td>0.010 mm</td>
</tr>
<tr>
<td><strong>Combined standard uncertainty</strong></td>
<td><strong>0.075 mm</strong></td>
</tr>
<tr>
<td><strong>Expanded uncertainty (k=2, 95% confidence)</strong></td>
<td><strong>0.150 mm</strong></td>
</tr>
</tbody>
</table>

Adapted from: http://www.muelaner.com/uncertainty-budget/
Basic Principles

Gamma Knife Delivery Uncertainty

Other Radiosurgery Uncertainty

Management Strategies
Why is understanding uncertainty important for Gamma Knife SRS?

<table>
<thead>
<tr>
<th>Collimator</th>
<th>Distance from 50% to 25% isodose line (axial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16mm</td>
<td>4.6mm</td>
</tr>
<tr>
<td>8mm</td>
<td>2.0 mm</td>
</tr>
<tr>
<td>4mm</td>
<td>1.3 mm</td>
</tr>
</tbody>
</table>

Gamma Knife 4mm isocenter

Source: Leksell GammaPlan version 10.1
Gamma Knife Perfexion

- Patient Positioning System
- Shielding doors
- Shielding
- $^{60}$Co sources
- Collimator body
- Sector drives
Treatment machines are really manufacturing machines

Linear encoders
Resolution: 0.01 μm
Accuracy over entire length of scale: ± 5 μm

Rotational encoders
2000 pulses per rotation
Pitch on sector screws is 1mm
Resolution: 0.5 μm
Outer 4mm beam channels mechanically aligned with holes in sector

Linear and rotational encoders both monitor sector position

Procedure is performed for every beam channel for every sector, at the factory
PPS Calibration

Mechanical calibration of orthogonality of movements

Creation of compensation curves for orthogonality

Laser interferometer verifies calibration of absolute positioning (<0.01mm absolute accuracy)
“Master” diode calibrated at “reference” unit at Timone Hospital, Marseille

Center diode < 0.08 mm repeatability at installation

Site-diode tool (Focus Precision Tool) calibrated offset to master

Manufacturer tolerance for monthly test < 0.5 mm radial

How is this validated?
<table>
<thead>
<tr>
<th>Specification</th>
<th>Tolerance</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>RFP vs PPS (master diode, center target, 4mm isocenter)</td>
<td>&lt;0.15mm (0.08 at installation)</td>
<td>Preventive maintenance procedures</td>
</tr>
<tr>
<td>RFP vs PPS (master diode, center target, 8/16 mm isocenter)</td>
<td>&lt;0.2mm</td>
<td>Preventive maintenance procedures</td>
</tr>
<tr>
<td>RFP vs PPS (master diode, off-center target, 4mm isocenter)</td>
<td>&lt;0.4mm</td>
<td>Preventive maintenance procedures</td>
</tr>
<tr>
<td>RFP vs PPS (site diode)</td>
<td>&lt;0.5mm</td>
<td>Perfexion user’s manual</td>
</tr>
<tr>
<td>Film RFP vs PPS</td>
<td>&lt;0.3mm per axis, &lt;0.4mm radial, at 50% line</td>
<td>Acceptance procedures</td>
</tr>
<tr>
<td>Sector positions</td>
<td>&lt;0.1mm, all sectors/sector positions</td>
<td>Preventive maintenance procedures</td>
</tr>
</tbody>
</table>
What do we achieve in practice?

Control chart: Monthly focus precision results
Radial difference from calibration position

Control limit (3σ) determined from first 5 measurements
Output Calibration Uncertainty

NO calibration standard!

Various centers use TG-21, TG-51, IAEA TRS-277, IAEA TRS 398

Elekta-provide polystyrene(?) phantom, solid water phantom, custom phantom

Various ion chambers

SU-GG-T-279: Current Practice in Small Radiosurgery Field Dosimetry — Preliminary Results from 21 Centers Participating in the International Leksell Gamma Knife Calibration Survey

J Novotny, Jr., M Desrosiers, J Bhatnagar, et. al.

Med Phys 37(6), 2010
UVA Monthly output check

Protocol: TG-51*
Chamber: PR-05P
Phantom: Elekta spherical (polystyrene)

IROC TLD Ratio:
2012: 0.99
2013: 1.01
2014: 1.00

*with modified assumptions
Frame and Docking Uncertainty

Frame mechanical uncertainty: 0.2-0.7 mm (mostly in pin fixation)
Frame adapter x play: <0.15 mm
Frame adapter angle play: <60 μm
Frame adapter deflection: 0.15-0.20 mm

Leksell Gamma Knife Perfexion Planned Maintenance Manual
Worst-case image registration error – mean (max): 0.1mm (1.4mm)
Resulting localization error – mean (max): 0.0 mm (0.2 mm)

A clinical comparison of patient setup and intra-fraction motion using frame-based radiosurgery vs a frameless image-guided radiosurgery system for intracranial lesions

N. Ramakrishna, et al., Radiotherapy and Oncology, 95(1), 2010

**Immobilization Uncertainty**

Study includes both mechanics and imaging

Frame has a slightly lower mean and SD

Headframe vs Mask immobilization

Mean mask: 0.7mm (SD = 0.5mm)
Mean frame: 0.4mm (SD = 0.3mm)
Small-Field Uncertainty

Determination of the 4 mm Gamma Knife helmet relative output factor using a variety of detectors

B. Heck, A. Jess-Hempen, H. Kreiner, H. Schöpgens, A. Mack
Med Phys 37(6), 2010
TMR Dose Algorithm Uncertainty

Planning system over-predicts dose adjacent to interface due to loss of electronic equilibrium.

Planning system under-predicts dose away from cavity because it over-attenuates beams in air region.

In most cases, this isn’t an issue.

But….now there is a convolution option!

Skull Contour Uncertainty

Effect of skull shape approximations in Gamma Knife dose calculations
A. Berndt, J. Beck
J. Appl Clin Med Phys 8(3)

Peripherally-located targets most effected
Shot time differences of up to 4% (most less than 1%)
Basic Principles

Gamma Knife Delivery Uncertainty

Other Radiosurgery Uncertainty

Management Strategies
Timing of contrast injection can have significant effects on GTV definition.

<table>
<thead>
<tr>
<th>Lesion</th>
<th>Immediate scan Mean volume (SD) (mm³)</th>
<th>Delayed scan Mean volume (SD) (mm³)</th>
<th>% change in volume</th>
<th>3D shift in isocentre (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>279 (79)</td>
<td>474 (59)</td>
<td>70</td>
<td>1.4</td>
</tr>
<tr>
<td>A2</td>
<td>not analysed</td>
<td>325 (63)</td>
<td>12</td>
<td>1.0</td>
</tr>
<tr>
<td>B1</td>
<td>290 (87)</td>
<td>1134 (103)</td>
<td>28</td>
<td>0.7</td>
</tr>
<tr>
<td>B2</td>
<td>879 (114)</td>
<td>492 (21)</td>
<td>3</td>
<td>0.9</td>
</tr>
<tr>
<td>C</td>
<td>477 (15)</td>
<td>1798 (22)</td>
<td>21</td>
<td>1.3</td>
</tr>
<tr>
<td>D1</td>
<td>1479 (32)</td>
<td>1767 (35)</td>
<td>−1</td>
<td>0.4</td>
</tr>
<tr>
<td>D2</td>
<td>1780 (33)</td>
<td>2093 (101)</td>
<td>22</td>
<td>0.6</td>
</tr>
<tr>
<td>E</td>
<td>1708 (33)</td>
<td>2731 (39)</td>
<td>51</td>
<td>0.5</td>
</tr>
<tr>
<td>F1</td>
<td>1807 (21)</td>
<td>3179 (45)</td>
<td>36</td>
<td>1.5</td>
</tr>
<tr>
<td>F2</td>
<td>2326 (23)</td>
<td>2871 (559)</td>
<td>46</td>
<td>0.2</td>
</tr>
<tr>
<td>G1</td>
<td>1961 (161)</td>
<td>5952 (188)</td>
<td>58</td>
<td>1.4</td>
</tr>
<tr>
<td>G2</td>
<td>3764 (234)</td>
<td>6434 (166)</td>
<td>20</td>
<td>2.4</td>
</tr>
<tr>
<td>H1</td>
<td>5333 (138)</td>
<td>13047 (115)</td>
<td>14</td>
<td>4.6</td>
</tr>
<tr>
<td>H2</td>
<td>not analysed</td>
<td>16688 (5009)</td>
<td>−16</td>
<td>not planned</td>
</tr>
</tbody>
</table>

Mean delay: 65 min
92% would select larger collimator sizes

Br J Radiol. 77, 2004
Delineation of brain metastases on CT images for planning radiosurgery: concerns regarding accuracy
K. Sidhu, P Cooper, R. Ramani, et. al.
Biological Uncertainty

Radiation necrosis

Pre-SRS

16 months post

Basic Principles

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Management Strategies
Quality assurance in stereotactic space: A system test for verifying the accuracy of aim in radiosurgery

A. Mack, H. Czempiel, H-J Kreiner, et. al.
Med Phys 29(4), 2002
Doing it yourself – keep it simple!

Two separate exposures
Approximately orthogonal film placement
Two profiles per film
End of copper wire used to localize target

Last time for us - mean radial offset: 0.37mm

Don’t forget IROC!
<table>
<thead>
<tr>
<th>Case</th>
<th># shots</th>
<th>Δ25%</th>
<th>Δ50%</th>
<th>Δ90%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0.4±0.28</td>
<td>0.2±0.15</td>
<td>1.2±0.76</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0.6±0.31</td>
<td>0.3±0.16</td>
<td>0.6±0.19</td>
</tr>
<tr>
<td>3</td>
<td>9</td>
<td>1.2±0.5</td>
<td>1.1±0.49</td>
<td>1.0±0.65</td>
</tr>
<tr>
<td>4</td>
<td>12</td>
<td>1.5±0.49</td>
<td>0.9±0.36</td>
<td>1.3±0.58</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>1.6±0.39</td>
<td>0.5±0.46</td>
<td>0.8±0.48</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>1.4±0.59</td>
<td>1.2±0.71</td>
<td>0.4±0.37</td>
</tr>
</tbody>
</table>

Whole procedure clinical accuracy of Gamma Knife treatments of large lesions

L. Ma, C. Chuang, M. Descovich, et al.  
Med Phys 35(11), 2008
Scope and terminology are critical considerations when describing treatment uncertainty.

There are MANY potential sources of uncertainty in any SRS procedure (Gamma Knife or other).

One consequence of summing in quadrature is smaller sources of uncertainty drop out:

$$\sqrt{(0.1)^2 + (0.1)^2 + (1.0)^2} = 1.01$$

Understand your largest sources of uncertainty!
Acknowledgements

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