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.

Basic Principles

Gamma Knife Delivery Uncertainty

Other Radiosurgery Uncertainty

Management Strategies

Error, accuracy and precision

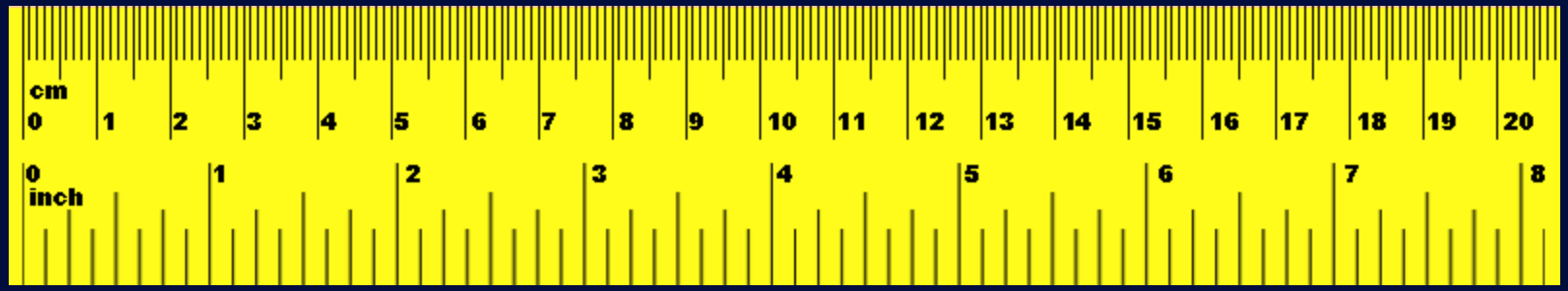
Error: Difference between the measurement and the true value

Accurate, but not precise

Precise, but not accurate

NOT interchangeable!

Images: http://en.wikipedia.org/wiki/Accuracy_and_precision



Precision ≠ Resolution

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

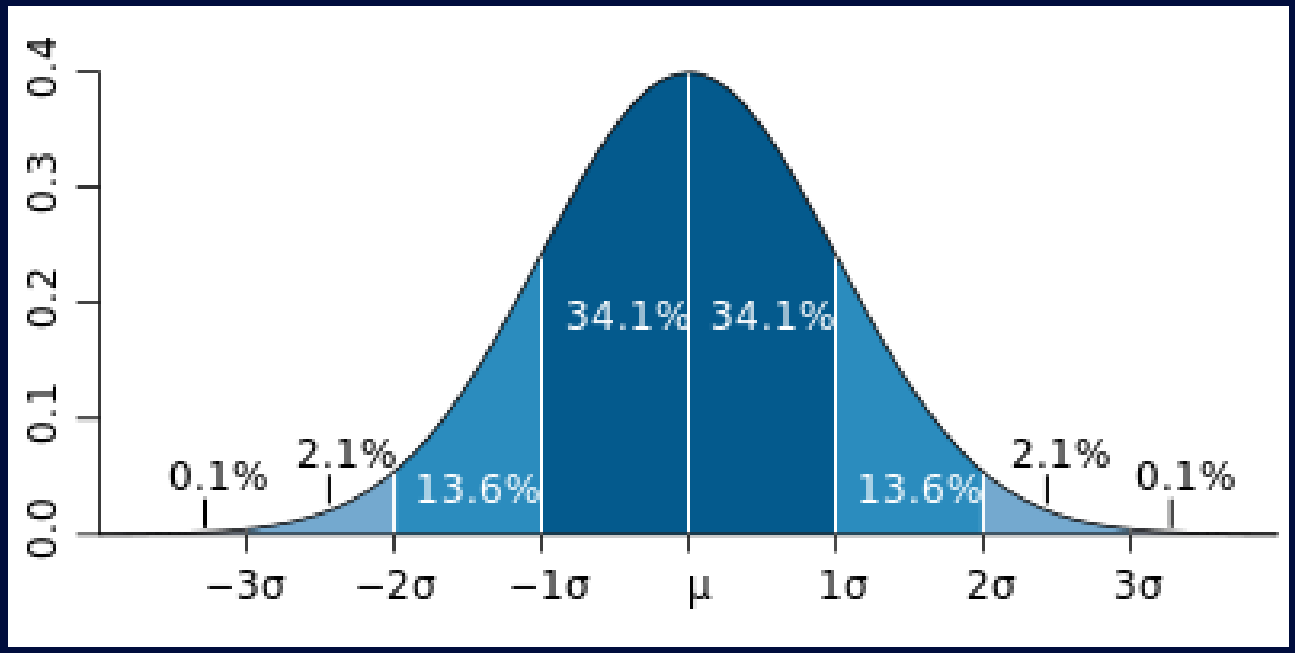
http://www.istl.nist.gov

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.



http://physics.nist.gov

Uncertainty budgets

Source of Uncertainty	Standard Uncertainty (1 standard deviation)
resolution	0.050 mm
alignment	0.050 mm
temperature	0.010 mm
repeatability	0.020 mm
ruler calibration	0.010 mm
Combined standard uncertainty	**0.075 mm**
Expanded uncertainty (k=2, 95% confidence)	**0.150 mm**

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

Basic Principles

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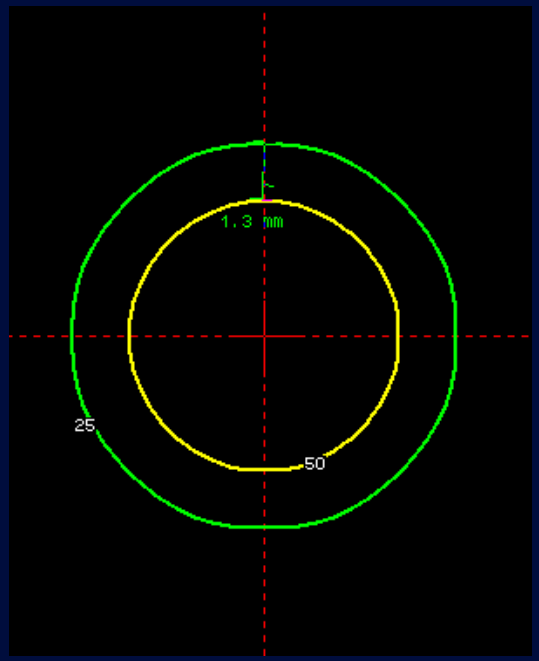
Management Strategies

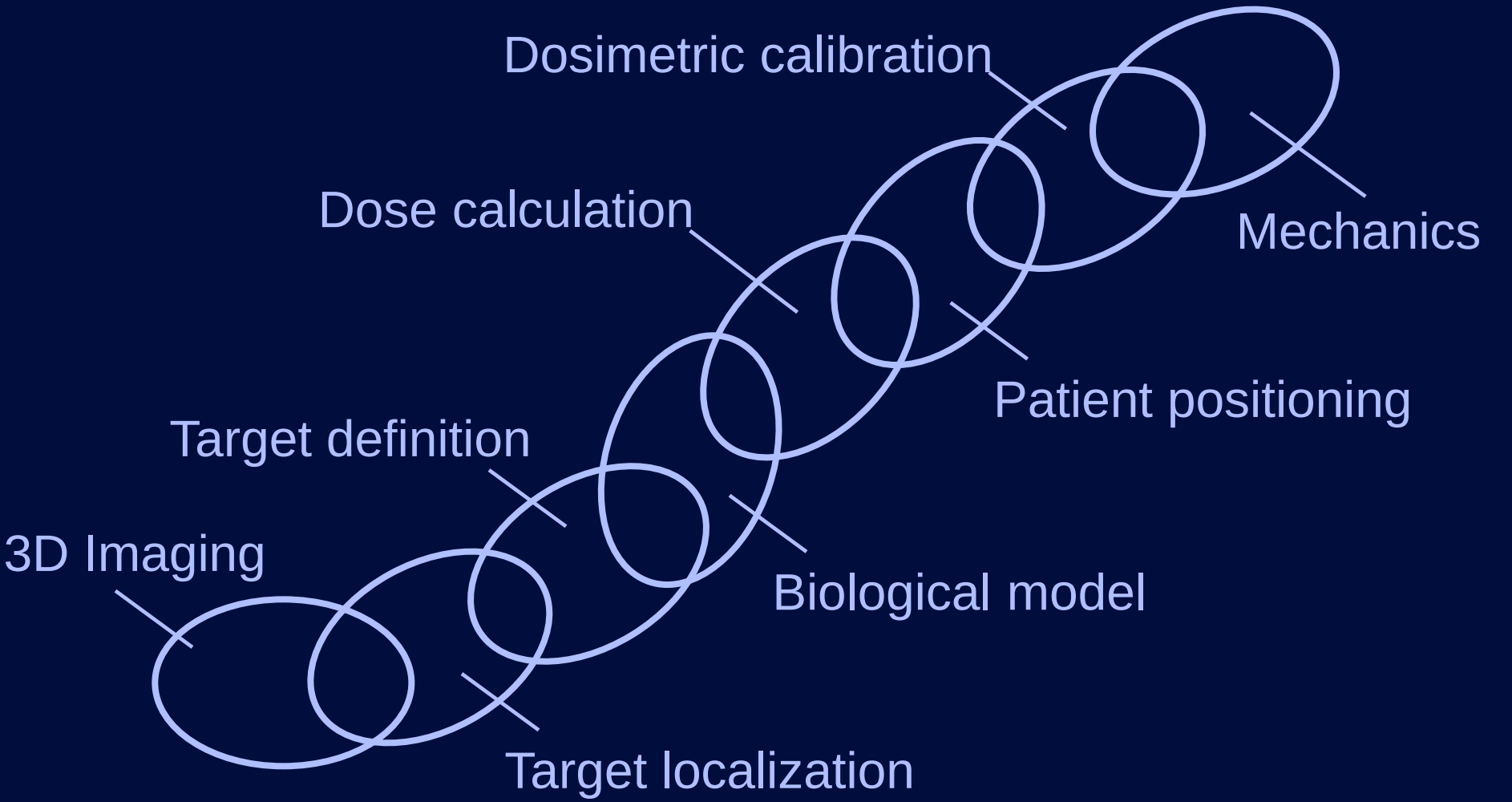
Why is understanding uncertainty important for Gamma Knife SRS?



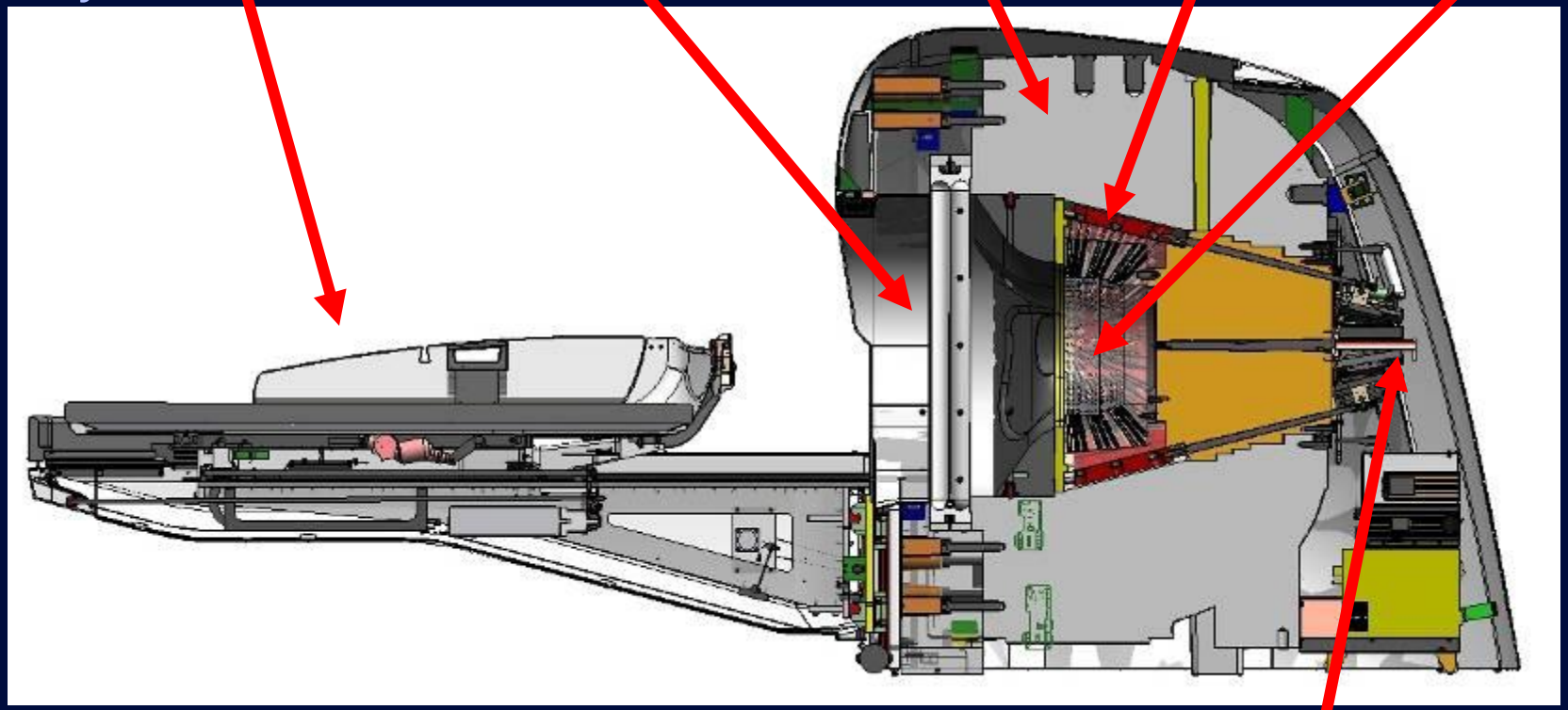
Gamma Knife 4mm isocenter

Collimator	Distance from 50% to 25% isodose line (axial)
16mm	4.6mm
8mm	2.0 mm
4mm	1.3 mm

Radiosurgery chain of uncertainty



Gamma Knife Perfexion



Treatment machines are really manufacturing machines

Linear encoders

Resolution: 0.01 µm

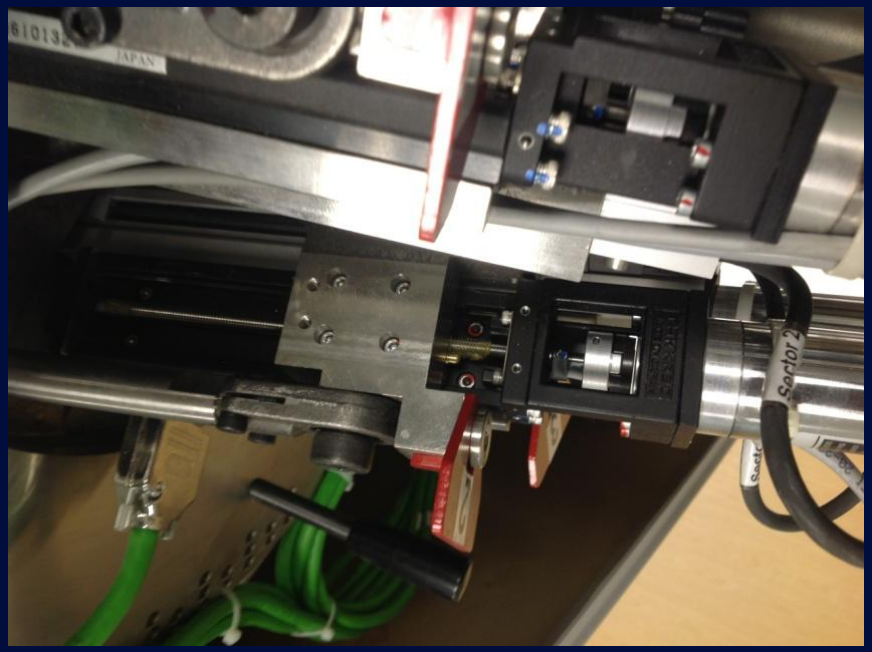
Accuracy over entire length of scale: ± 5 µm

Rotational encoders

2000 pulses per rotation

Pitch on sector screws is 1mm

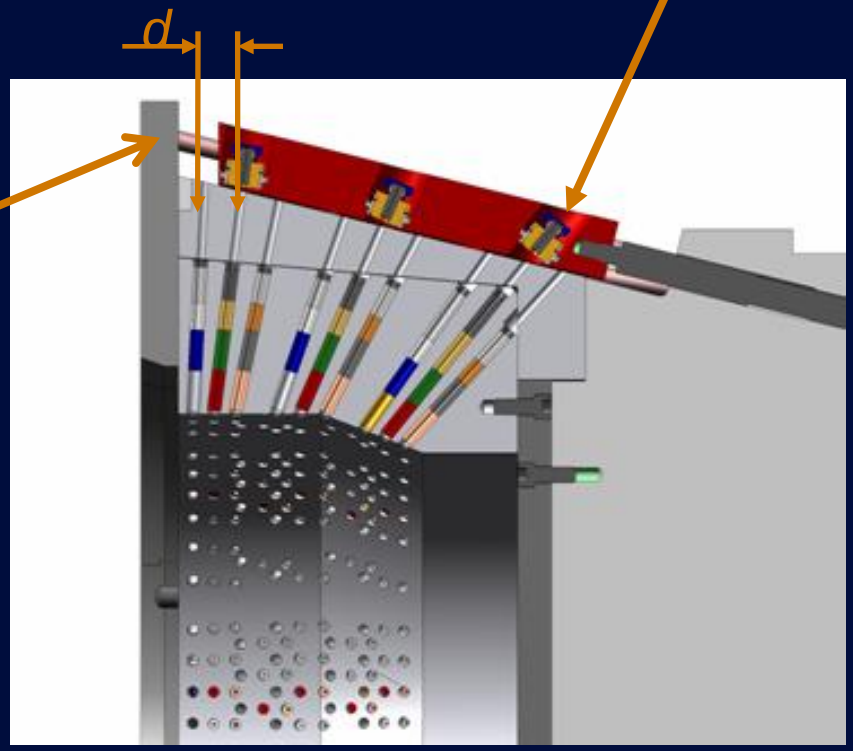
Resolution: 0.5 µm



Sector Position Calibration

Linear and rotational encoders both monitor sector position

Outer 4mm beam channels mechanically aligned with holes in sector



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

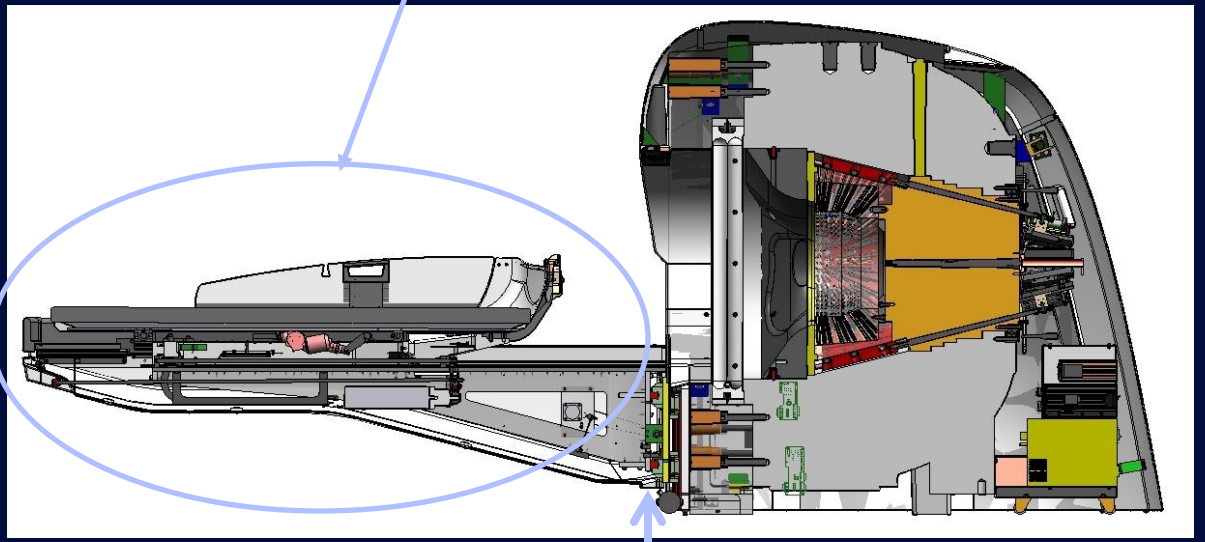
PPS Calibration

Mechanical calibration of orthogonality of movements

Creation of compensation curves for orthogonality

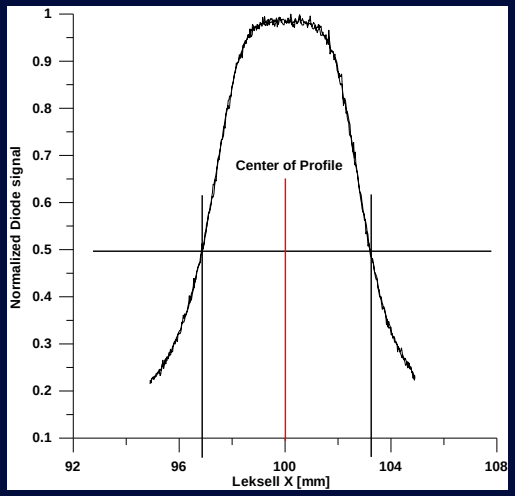
Laser interferometer verifies calibration of absolute positioning (<0.01mm absolute accuracy)

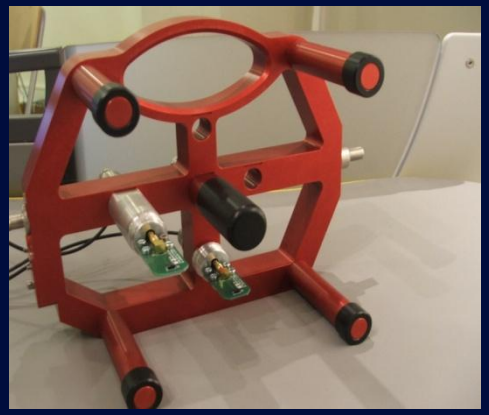
Patient Positiong System (PPS)

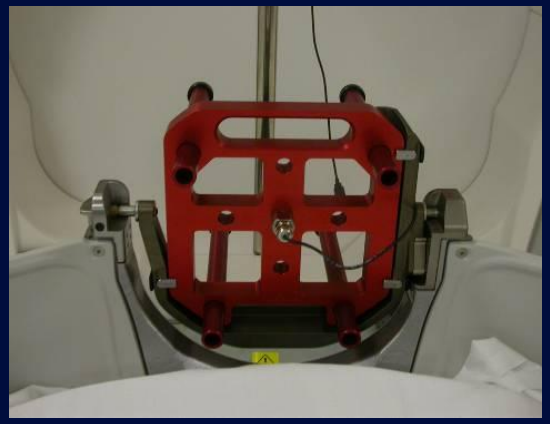


Mechanial interface

How is this validated?







"Master" diode calibrated at "reference" unit at Timone Hospital, Marseille

Center diode < 0.08 mm repeatability at installation

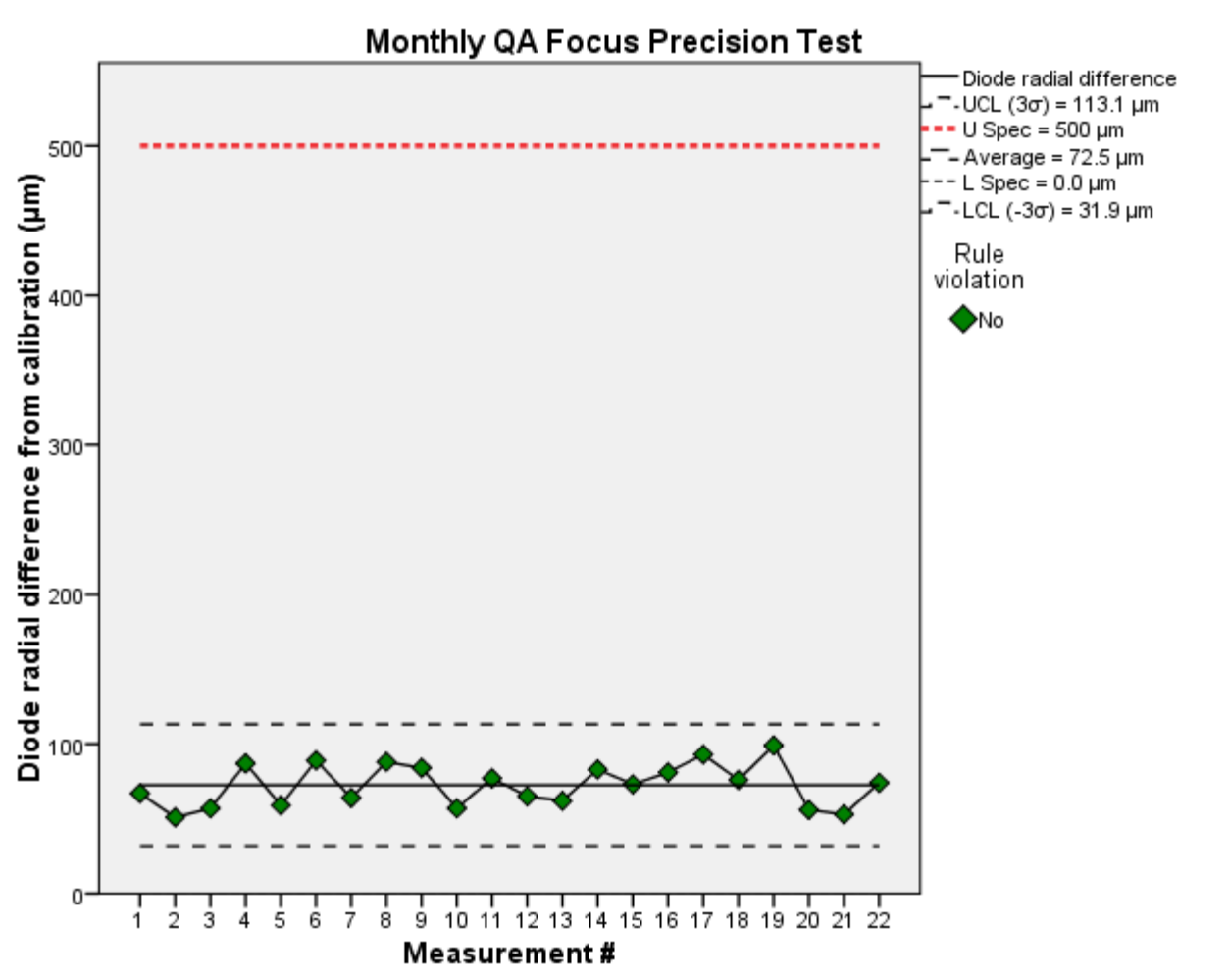
Site-diode tool (Focus Precision Tool) calibrated offset to master

Manufacturer tolerance for monthly test
< 0.5 mm radial

Mechanical Specifications

Specification	Tolerance	Source
RFP vs PPS (master diode, center target, 4mm isocenter)	<0.15mm (0.08 at installation)	Preventive maintenance procedures
RFP vs PPS (master diode, center target, 8/16 mm isocenter)	<0.2mm	Preventive maintenance procedures
RFP vs PPS (master diode, off-center target, 4mm isocenter)	<0.4mm	Preventive maintenance procedures
RFP vs PPS (site diode)	<0.5mm	Perfexion user's manual
Film RFP vs PPS	<0.3mm per axis, <0.4mm radial, at 50% line	Acceptance procedures
Sector positions	<0.1mm, all sectors/sector positions	Preventive maintenance procedures

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

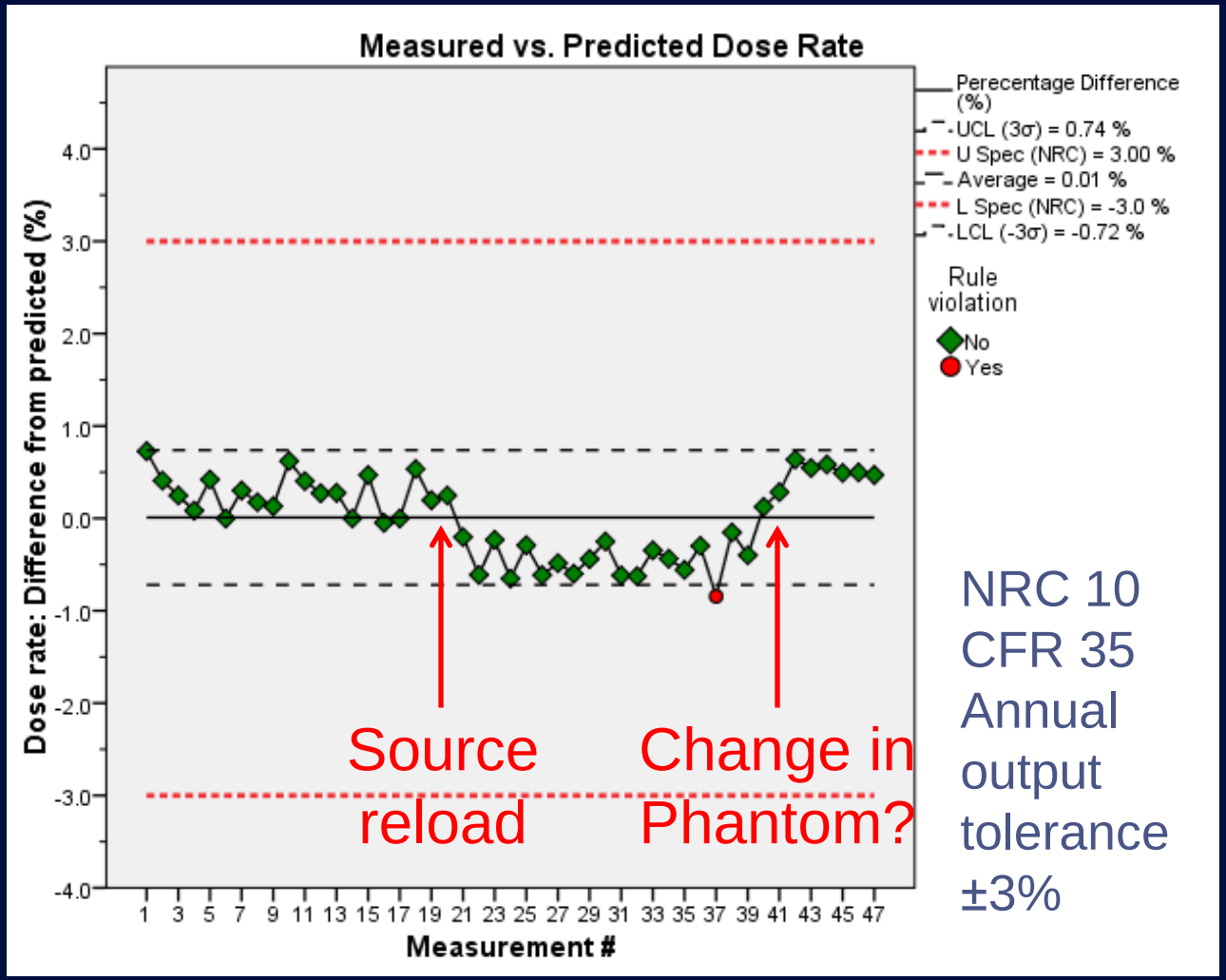
Elekta-provide polystyrene(?) phantom, solid water phantom, custom phantom

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



NRC 10 CFR 35 Annual output tolerance ±3%

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

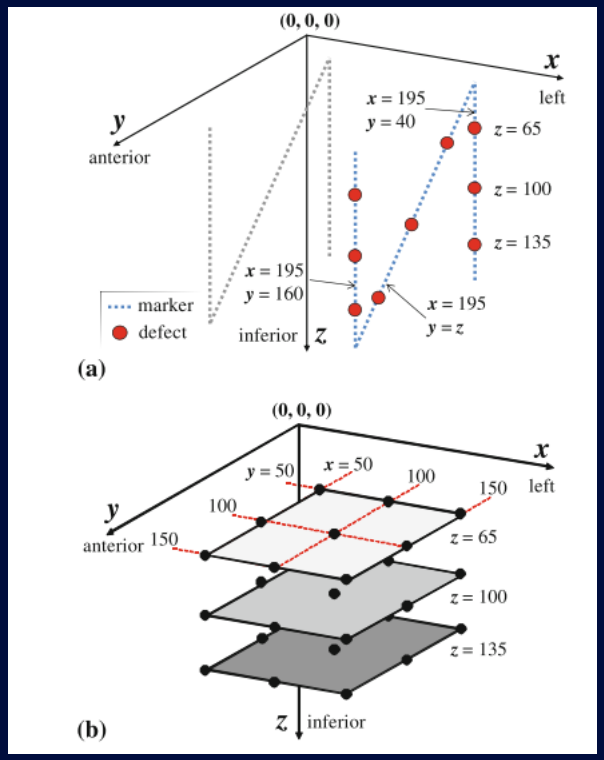
Frame adapter angle play: <60 µm

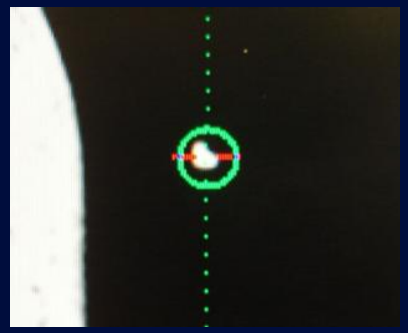
Frame adapter deflection: 0.15-0.20 mm

Leksell Gamma Knife Perfexion Planned Maintenance Manual

L. Lunsford, D. Kondziolka, D. Leksell, in Textbook of Stereotactic and Functional Neurosurgery, 2009.

Fiducial Registration Uncertainty

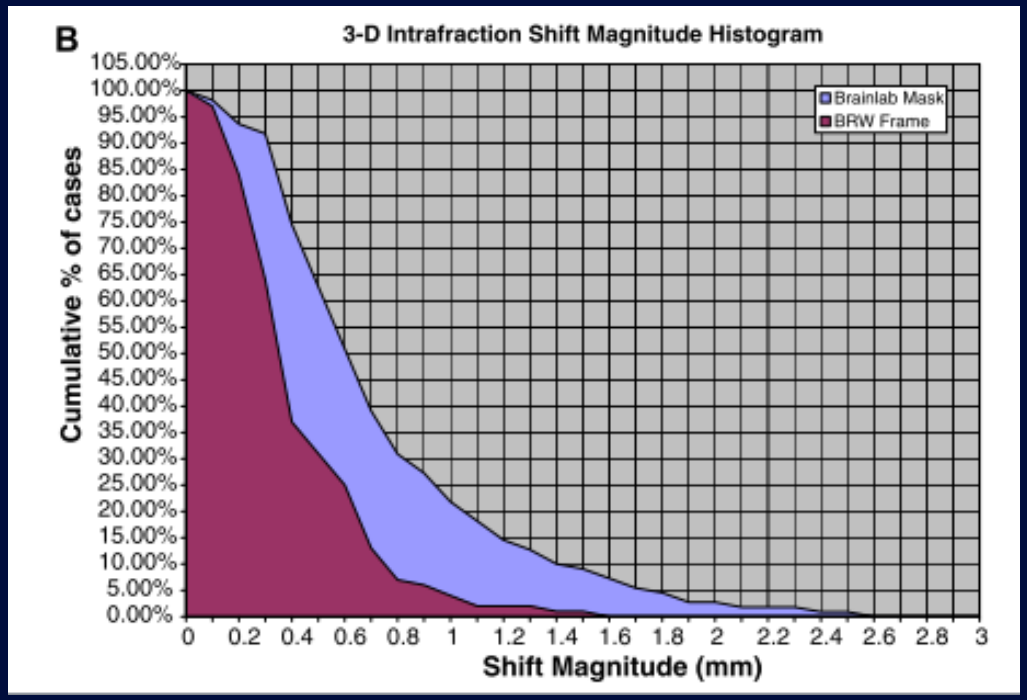




Worst-case image registration error – mean (max): 0.1mm (1.4mm)
Resulting localization error – mean (max): 0.0 mm (0.2 mm)

J-H Park, J. H. Han, C-Y Kim, et al., Med Biol Eng Comput, 2011

Immobilization Uncertainty



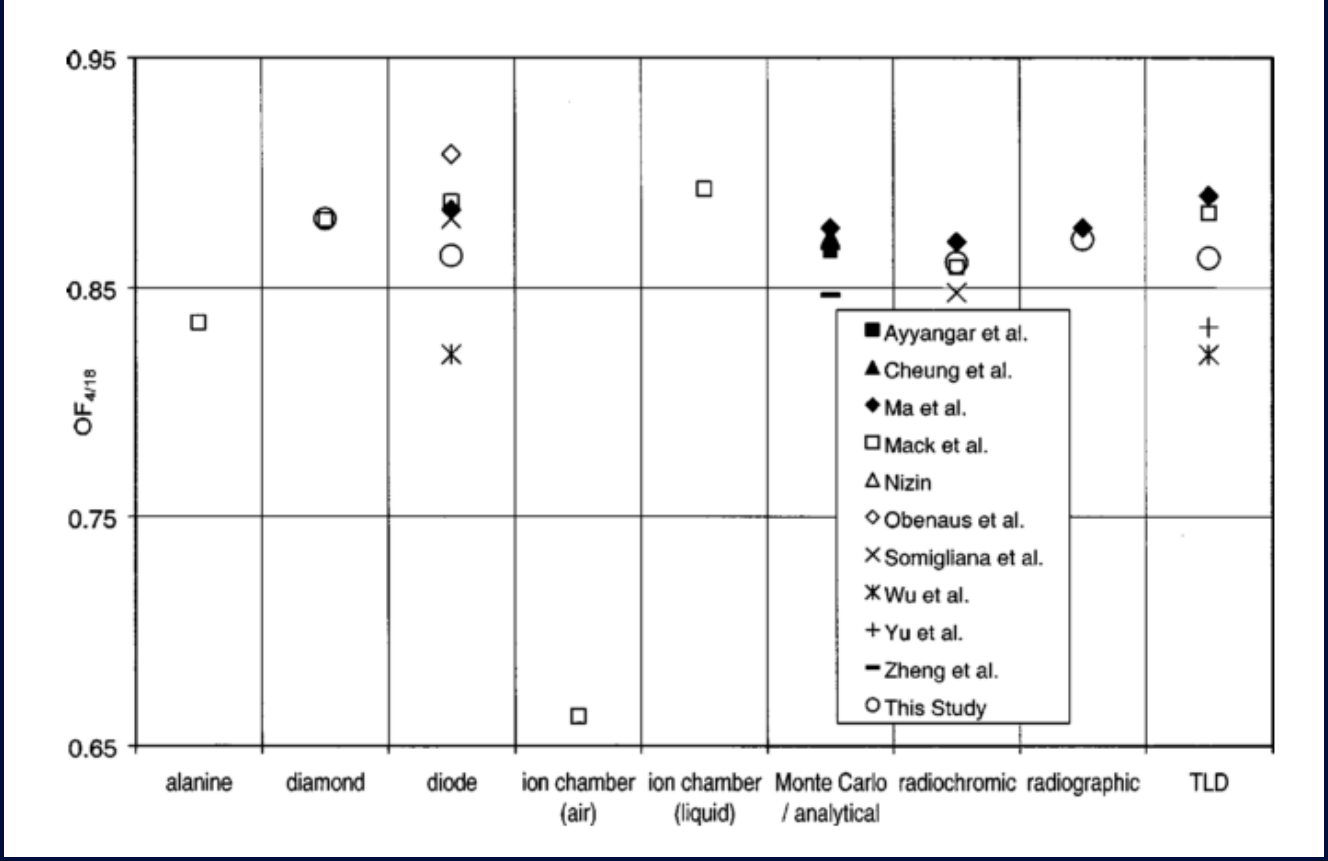
Study includes both mechanics and imaging

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)

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

Small-Field Uncertainty



4mm/18mm output factor, by detector type and study

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

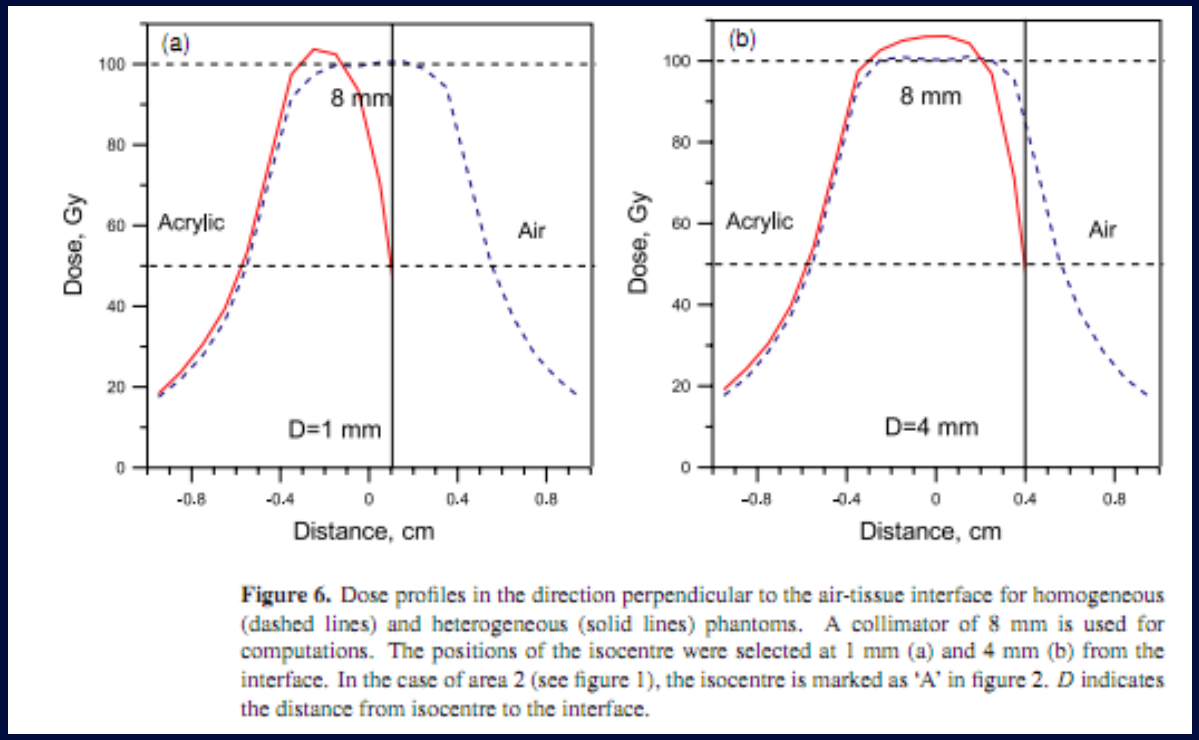


Figure 6. Dose profiles in the direction perpendicular to the air-tissue interface for homogeneous (dashed lines) and heterogeneous (solid lines) phantoms. A collimator of 8 mm is used for computations. The positions of the isocentre were selected at 1 mm (a) and 4 mm (b) from the interface. In the case of area 2 (see figure 1), the isocentre is marked as 'A' in figure 2. *D* indicates the distance from isocentre to the interface.

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

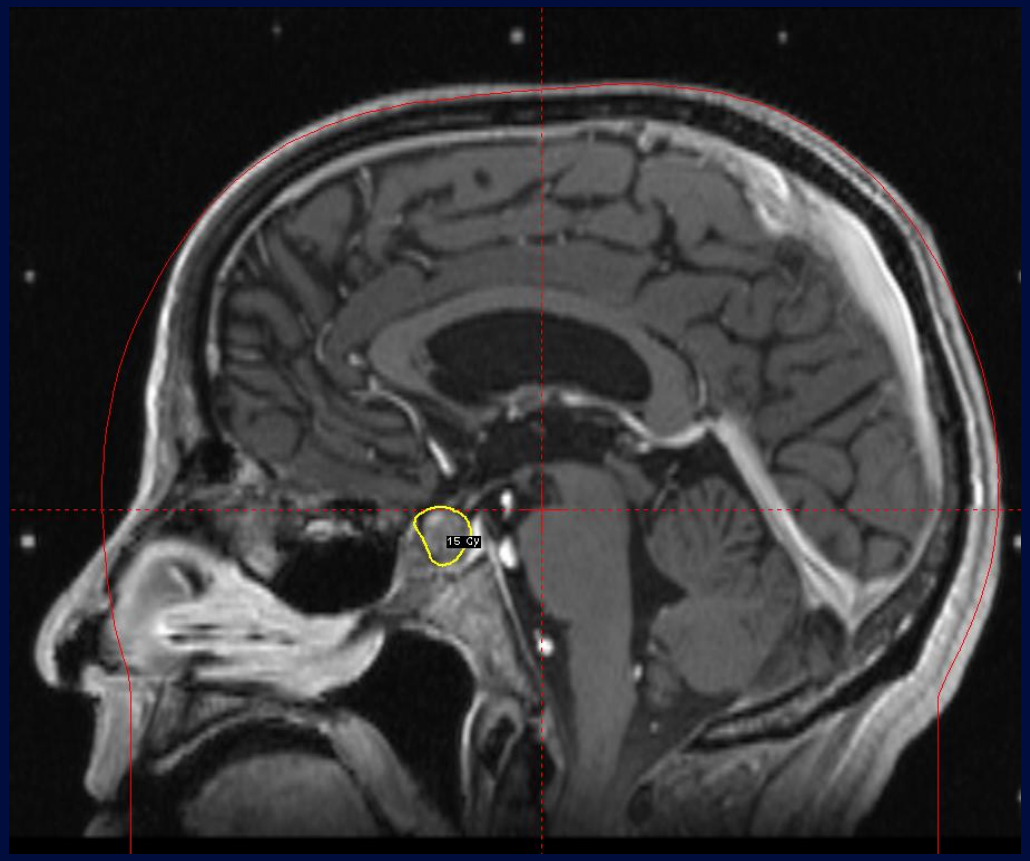
Planning system under-predicts dose away from cavity because it over-attenuates beams in air region

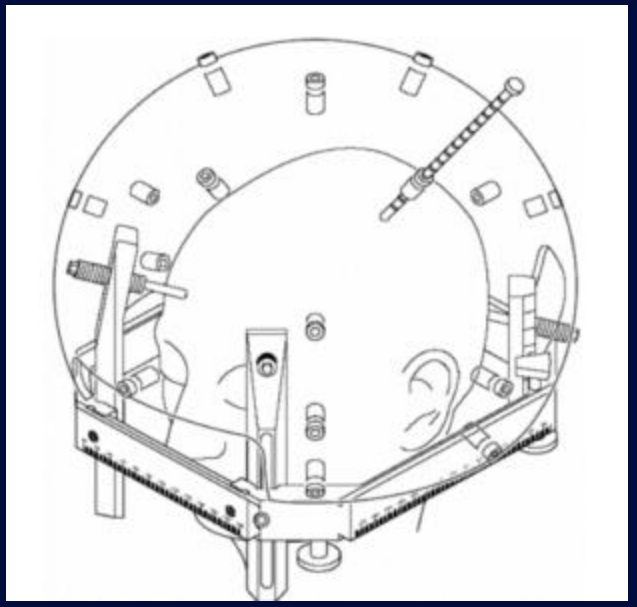
In most cases, this isn't an issue

But….now there is a convolution option!

Moskvin, et al., Monte Carlo simulation of the Leksell Gamma Knife: II. Effects of heterogeneous versus homogeneous media for stereotactic radiosurgery, Phys Med Bio 49(21), 2004.

Skull Contour Uncertainty





Peripherally-located targets most effected

Shot time differences of up to 4% (most less than 1%)

Effect of skull shape approximations in Gamma Knife dose calculations

A. Berndt, J. Beck

J. Appl Clin Med Phys 8(3)

Basic Principles

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Other Radiosurgery Uncertainty

Management Strategies

Visualization Uncertainty

Timing of contrast injection can have significant effects on GTV definition

Immediate scan			Delayed scan			
Lesion	Mean volume (SD) (mm^3)		Mean volume (SD) (mm^3)		% change in volume	3D shift in isocentre (mm)
A1	279	(79)	474	(59)	70	1.4
A2	not analysed					
B1	290	(87)	325	(63)	12	1.0
B2	879	(114)	1134	(103)	28	0.7
C	477	(15)	492	(21)	3	0.9
D1	1479	(32)	1798	(22)	21	1.3
D2	1780	(33)	1767	(35)	−1	0.4
E	1708	(33)	2093	(101)	22	0.6
F1	1807	(21)	2731	(39)	51	0.5
F2	2326	(23)	3179	(45)	36	1.5
G1	1961	(161)	2871	(559)	46	0.2
G2	3764	(234)	5952	(188)	58	1.4
H1	5333	(138)	6434	(166)	20	2.4
H2	not analysed					
I	11358	(344)	13047	(115)	14	4.6
J	19787	(894)	16688	(5009)	−16	not planned

Br J Radiol. 77, 2004

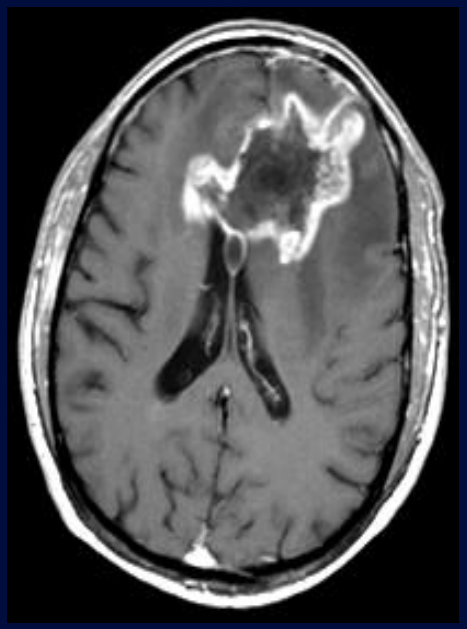
Delineation of brain metastases on CT images for planning radiosurgery: concerns regarding accuracy

K. Sidhu, P Cooper, R. Ramani, et. al.

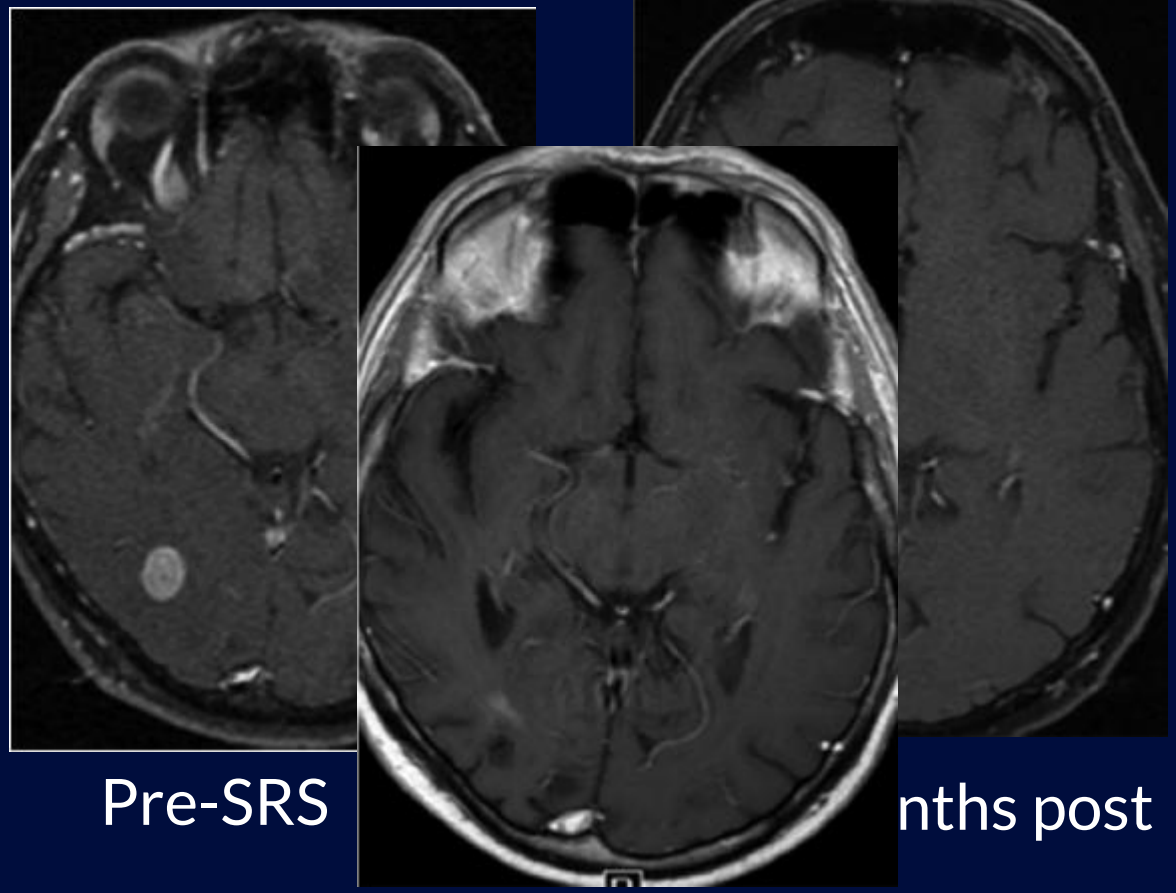
Mean delay: 65 min

92% would select larger collimator sizes

Radio- Biological Uncertainty



Radiation necrosis



Pre-SRS

nths post

16 months post

R. Shah, et al, RadioGraphics 32(5), 2012

Basic Principles

Gamma Knife Delivery Uncertainty

Other Radiosurgery Uncertainty

Management Strategies

End to End Tests

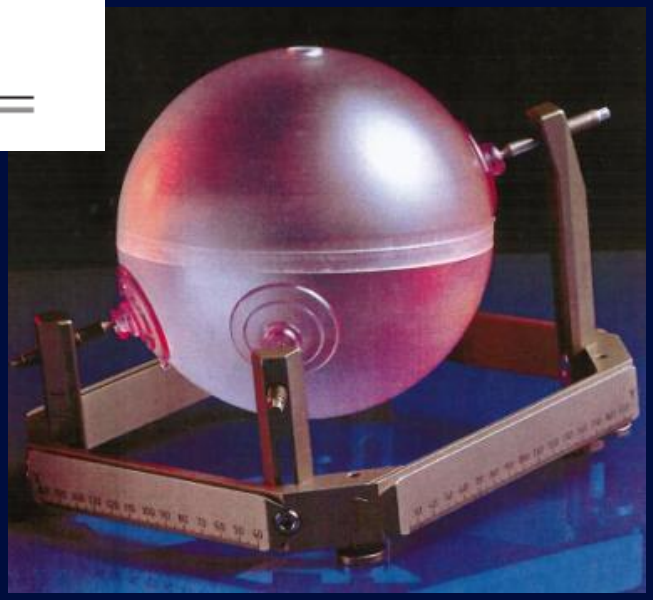
TABLE I. Investigation plane axial versus coronal (stereotactic *xy* plane vs *xz* plane). $p<0.0001$ (*t*-test unpaired), $p=0.0002$ (ANOVA).

	All	Axial	Cor
Mean	0.48	0.42	0.60
Std.deviation	0.23	0.24	0.15
Number	170	116	54
Min	0.10	0.10	0.32
Max	1.12	1.12	0.92
Median	0.44	0.32	0.63

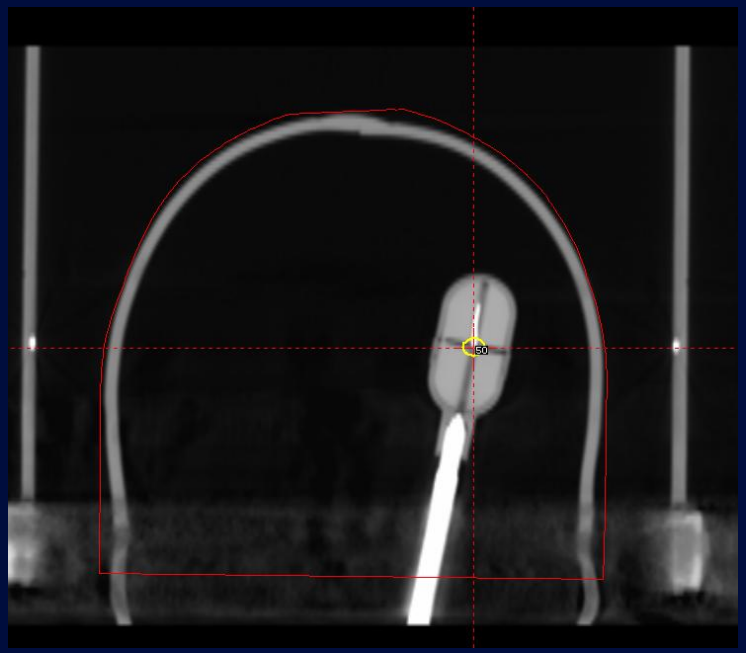
Quality assurance in stereotactic space: A system test for verifying the accuracy of aim in radiosurgery

A. Mack, H. Czempiel, H-J Kreiner, et. al.

Med Phys 29(4), 2002



Doing it yourself – keep it simple!



Two separate exposures

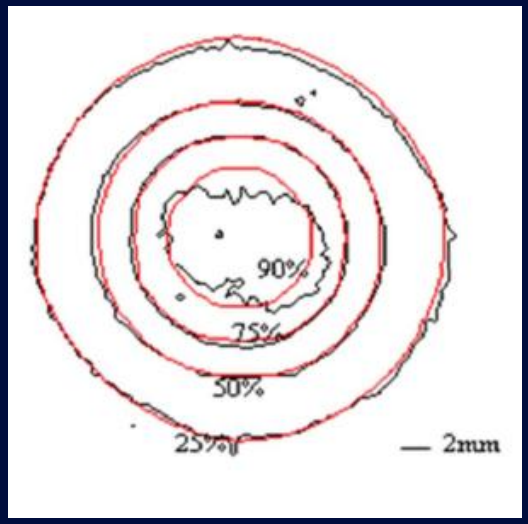
Approximately orthogonal film placement

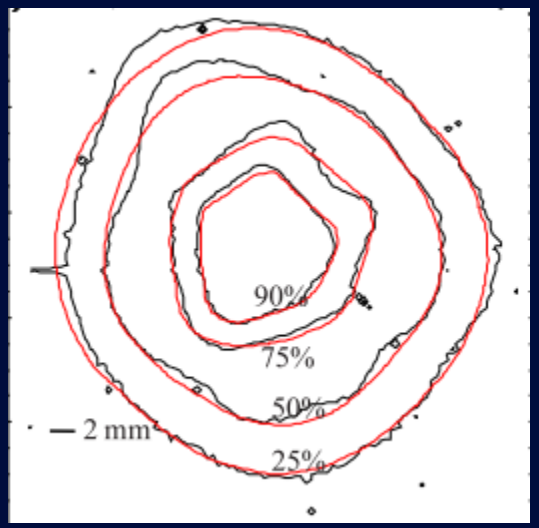
Two profiles per film

End of copper wire used to localize target

Last time for us - mean radial offset: 0.37mm

Don’t forget IROC!





Case	# shots	Distance to agreement (mean ± STD) (mm) Δ25%	Δ50%	Δ90%
1	1	0.4±0.28	0.2±0.15	1.2±0.76
2	2	0.6±0.31	0.3±0.16	0.6±019
3	9	1.2±0.5	1.1±0.49	1.0±0.65
4	12	1.5±0.49	0.9±0.36	1.3±0.58
5	12	1.6±0.39	0.5±0.46	0.8±0.48
6	16	1.4±0.59	1.2±0.71	0.4±0.37

Whole procedure clinical accuracy of Gamma Knife treatments of large lesions

L. Ma, C. Chuang, M. Descovich, et. al.

Med Phys 35(11), 2008

Conclusions

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

Elekta, AB – R&D Group