Accuracy and Precision in Cranial Radiosurgery

Sonja Dieterich, University of California- Davis
David Schlesinger, University of Virginia

Conflicts of Interest

David Schlesinger : Elekta, AB - Research grant

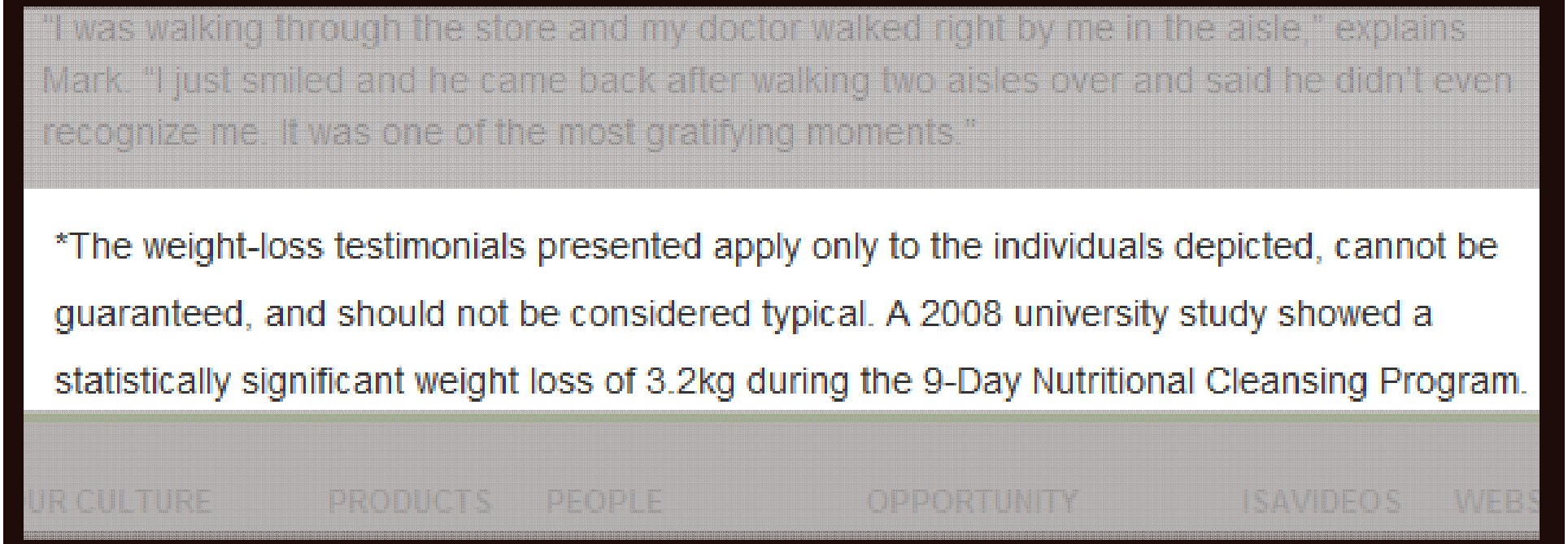
The world is full of claims…

Name: Mark W.
Location: Louisville, CO
Age: 50
Height: 6'0"
Was: 400+ lbs
Lost: 330 lbs*
As Of: October 2008

before *after*

Mark Transforms From Size 60 to 32*

For years, Mark's doctor encouraged him to lose weight to improve his health and wellness, but he just wasn't ready to commit to downsizing his 400-pound frame.



....the truth is often complicated

{Insert machine name} delivers sub-millimeter {accuracy/ precision}.

Why 1mm?

Which is it?
What part of the overall procedure?

Educational Objectives

- Advantages of various radiosurgery technologies
- Limitations of various radiosurgery technologies
- Main hurdles in achieving sub-millimeter treatment accuracy
- Overall treatment accuracy assessed by E2E testing

Medical Physics
The International Journal of Medical Physics Research and Practice

Submillimeter accuracy in radiosurgery is not possible

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Concepts

Gamma Knife Uncertainty

Cyberknife Uncertainty

Radiosurgery Uncertainty

Error: Result of the measurement minus the true value of the measurand

Accuracy: The closeness of the agreement between the result of a measurement and the true value of the measurand.

Precision: The closeness of agreement between independent test results obtained under stipulated conditions

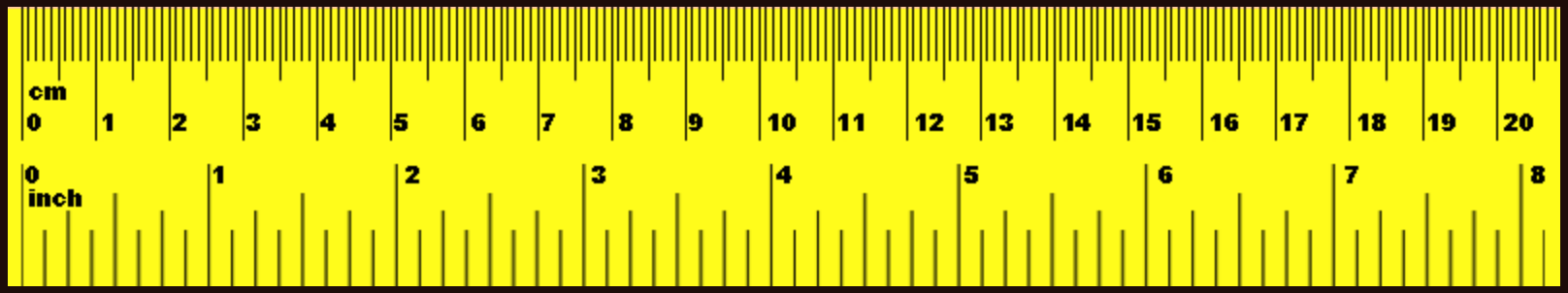
http://physics.nist.gov

Accurate, but not precise

Precise, but not accurate

Accuracy and precision are NOT interchangeable!

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



Precision ≠ Resolution

http://www.istl.nist.gov

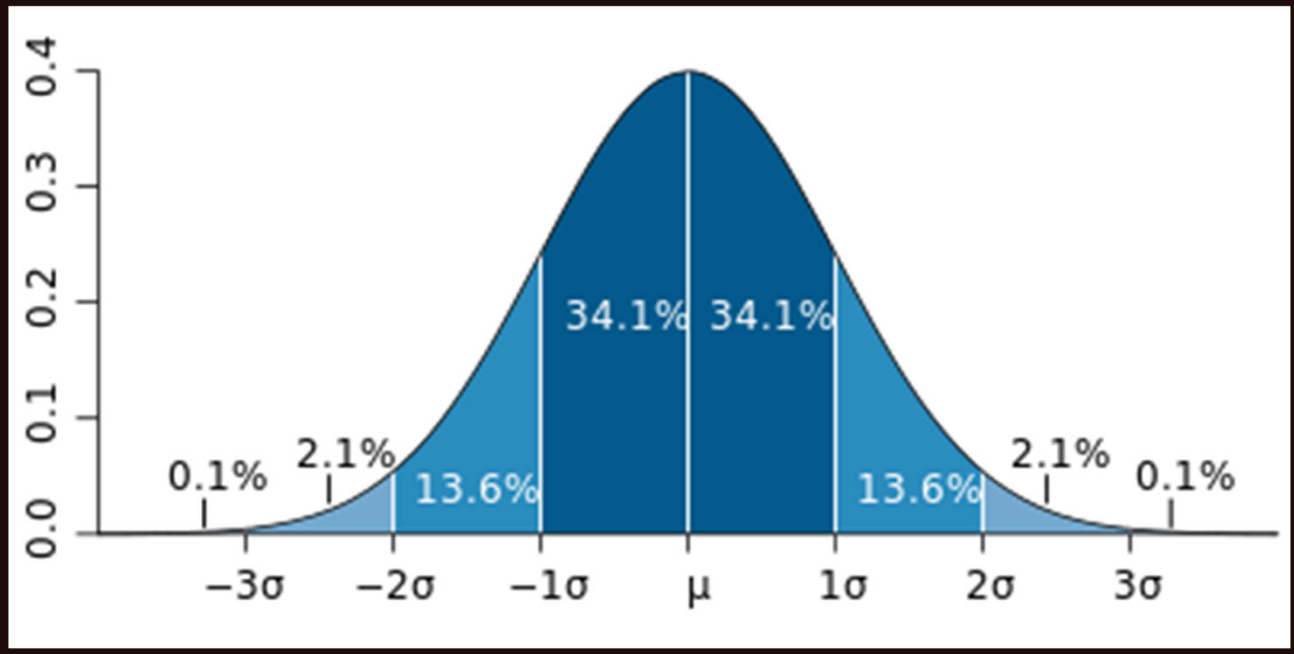
Repeatability: The closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement

Reproducibility: The closeness of the agreement between the results of successive measurements of the same measurand carried out under changing conditions of measurement

Both are part of the concept of precision.

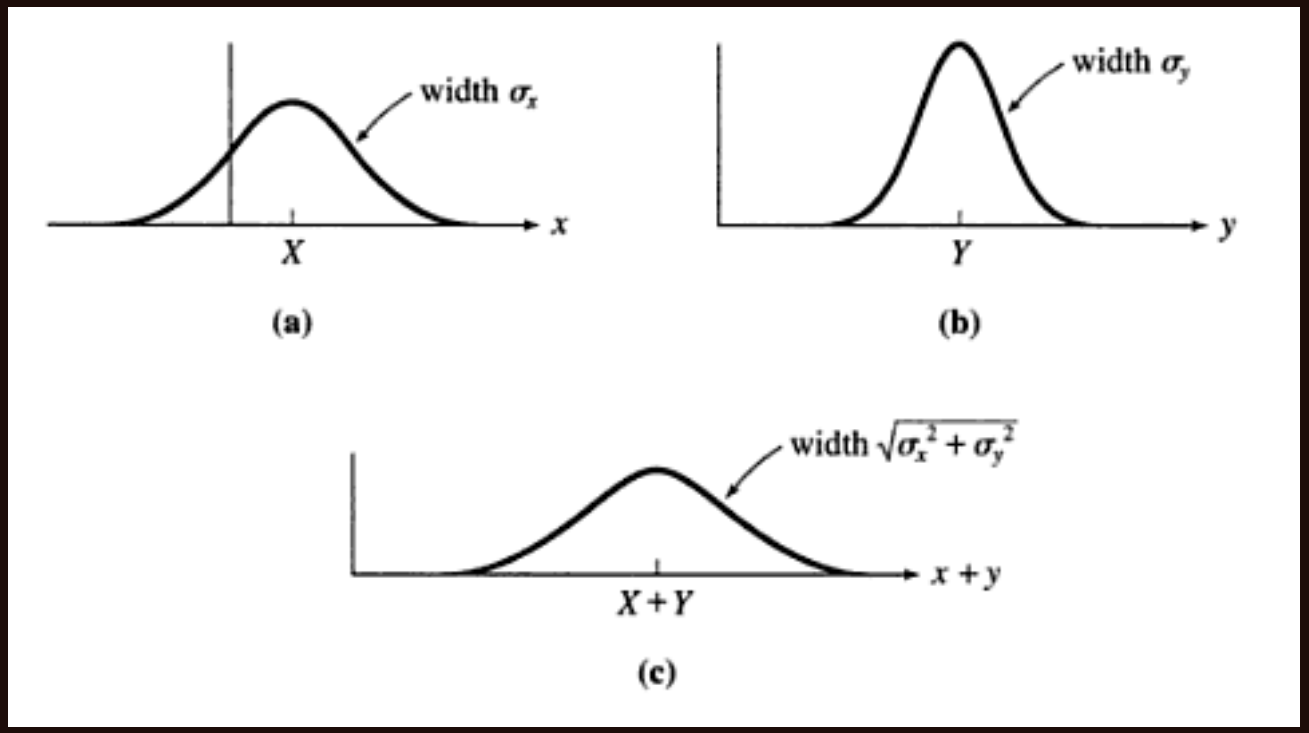
http://physics.nist.gov

Uncertainty: Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.



http://physics.nist.gov

Why do we add (independent) uncertainties in quadrature?



An Introduction to Error Analysis: The Study of Uncertainties in Physical Measurements, 2nd Edition

J. R. Taylor, University Science Books, 1997

http://www.istl.nist.gov

{Insert machine name} delivers sub-millimeter {accuracy/ precision}.

Why 1mm?

Which is it?
What part of the overall procedure?

Where does the 1mm requirement come from?

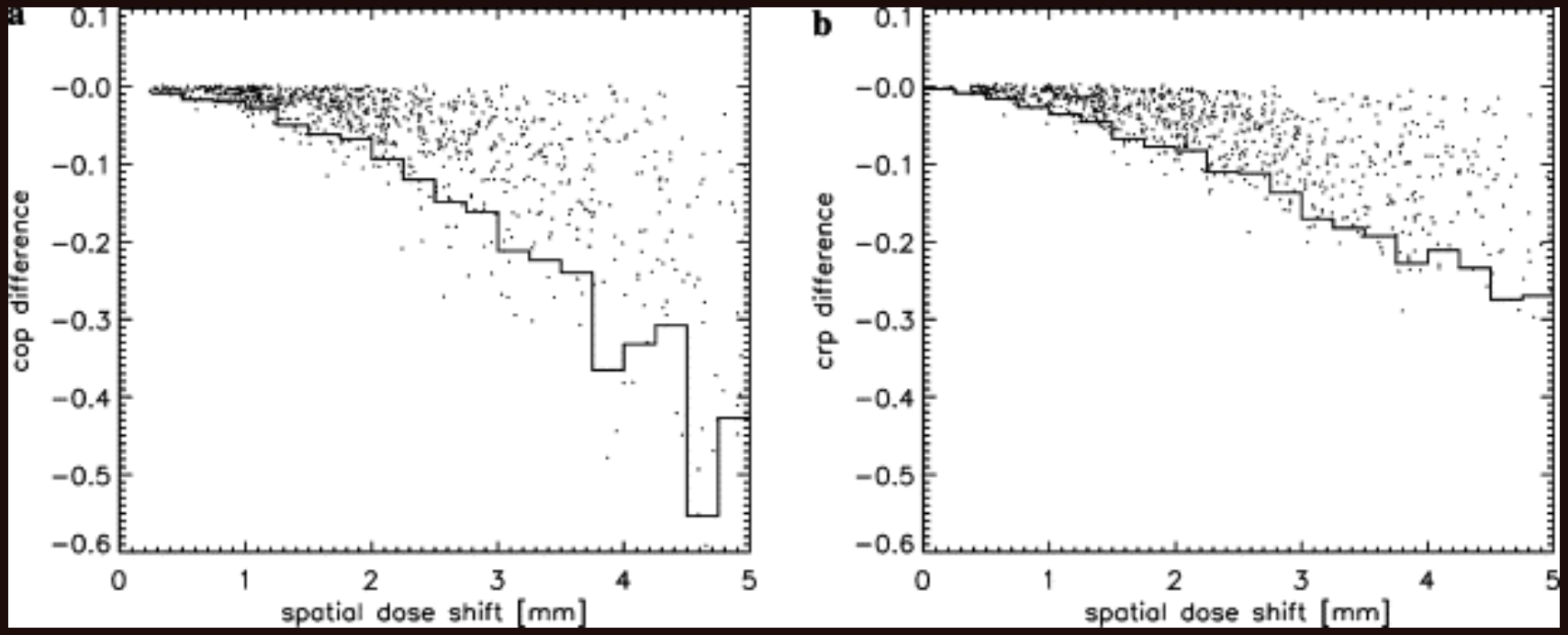
Possibly marketing, but…..

American Society for Testing and Materials Committee F-4.05. Standard performance specification for cerebral stereotactic instruments

In Annual Book of ASTM Standards, F 1266-89, 1990, p. 1-6.

States a voluntary performance specification that the mechanical accuracy of a stereotactic system shall be submillimetric.

Any biological basis?



Change in control probability (mets)

Change in obliteration probability (AVMs)

Impact of target point deviations on control and complication probabilities in stereotactic radiosurgery of AVMs and metastases.

Treuer H, Kocher M, Hoevels M, et al.

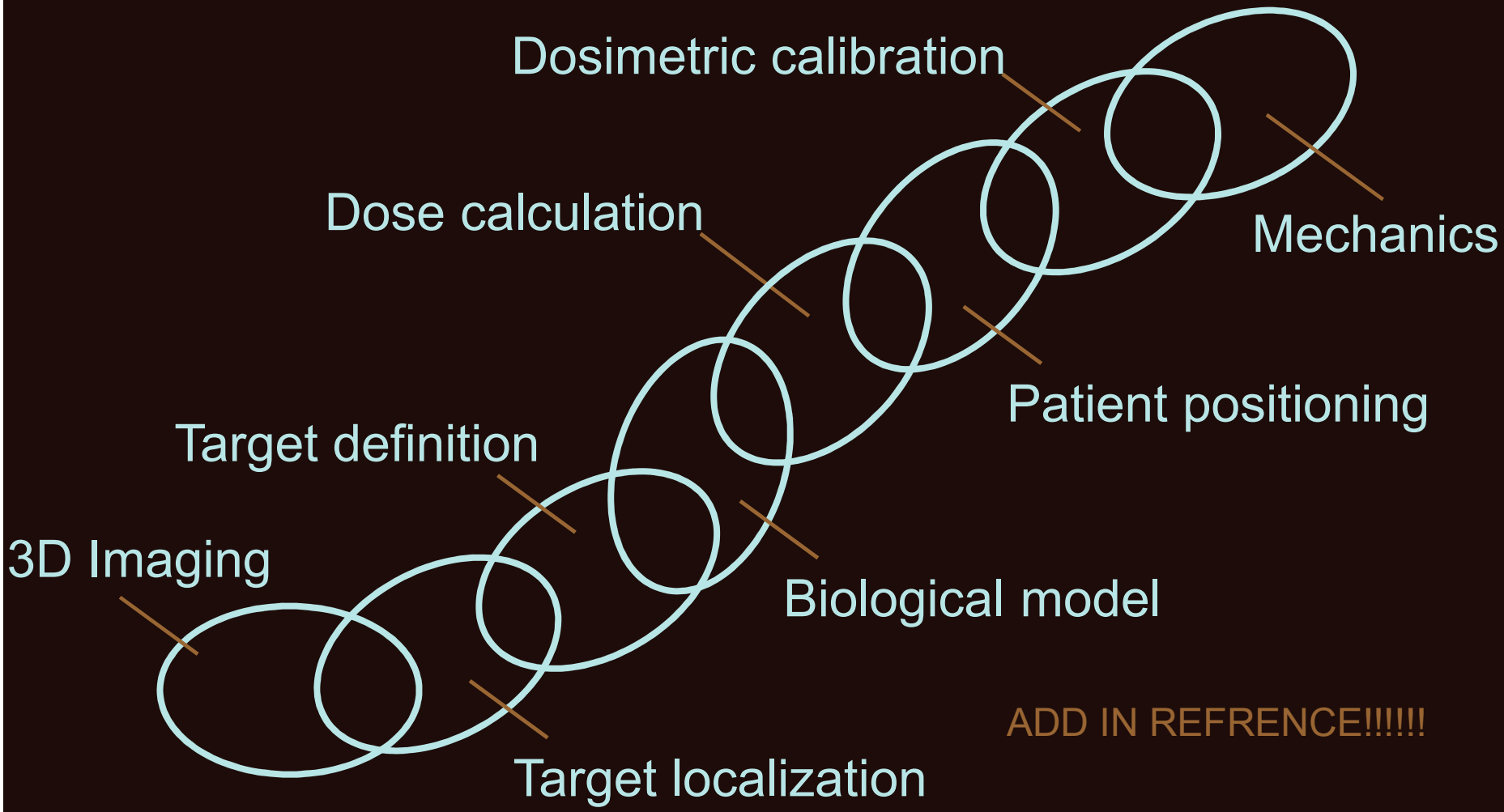
Radiother Oncol. 2006 Oct;81(1):25-32. Epub 2006 Sep 26.

Table 2
Median and mean − 2*SD of the relative value of COP and CRP as a function of the target point deviation *dr*

dr (mm)	Obliteration probability ratio		Remission probability ratio	
	Median	Mean − 2*SD	Median	Mean − 2*SD
1	0.991	0.964	0.963	0.902
2	0.954	0.879	0.909	0.792
3	0.891	0.747	0.835	0.671
4	0.800	0.566	0.744	0.537

So for both AVM obliteration and metastasis local control, probabilities drop quickly above 1mm target point deviations

Radiosurgery chain of uncertainty



ADD IN REFRENCE!!!!!!

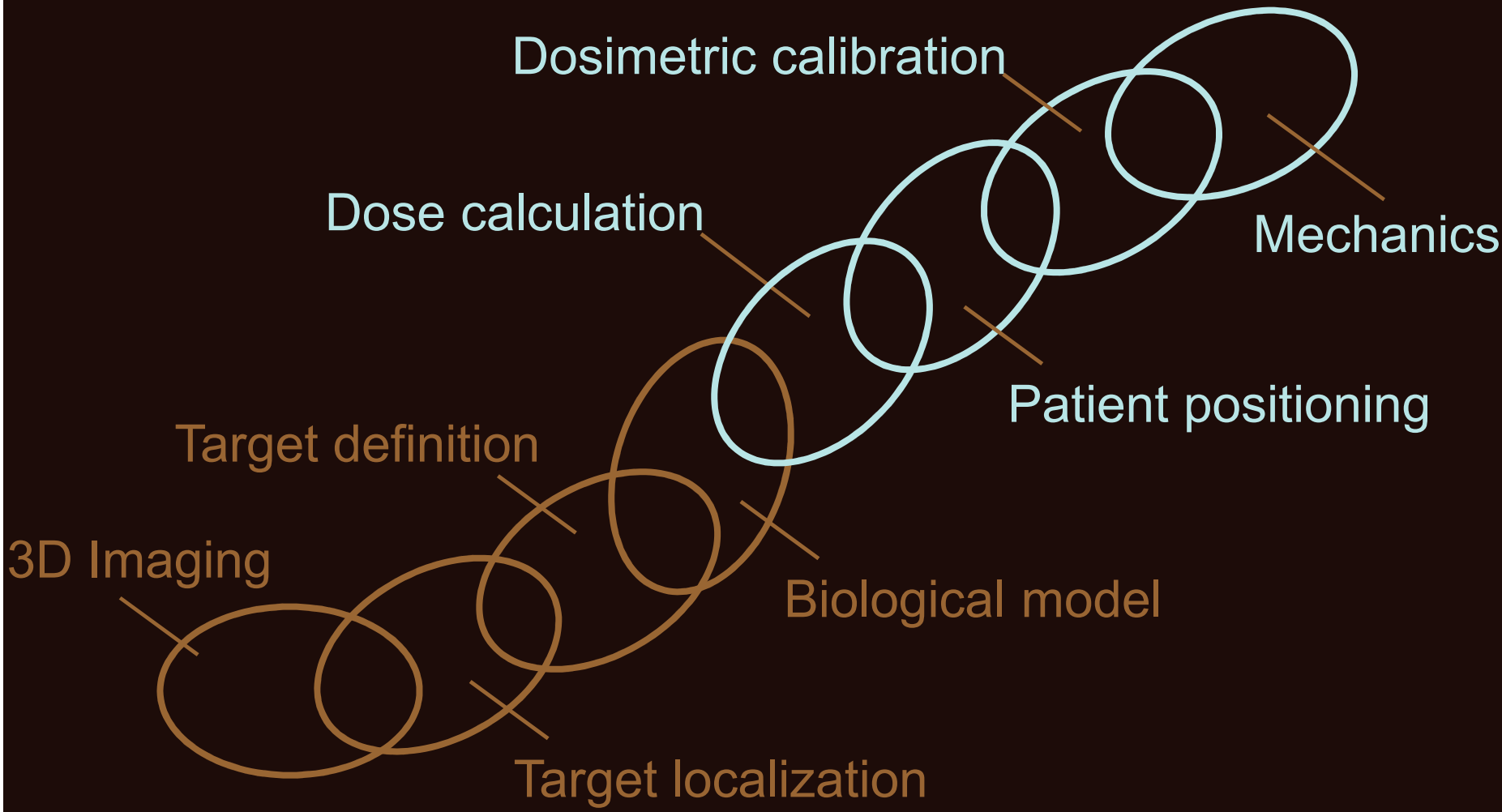
Concepts

Gamma Knife Uncertainty

Cyberknife Uncertainty

Radiosurgery Uncertainty

Radiosurgery chain of uncertainty



How is a Gamma Knife built?

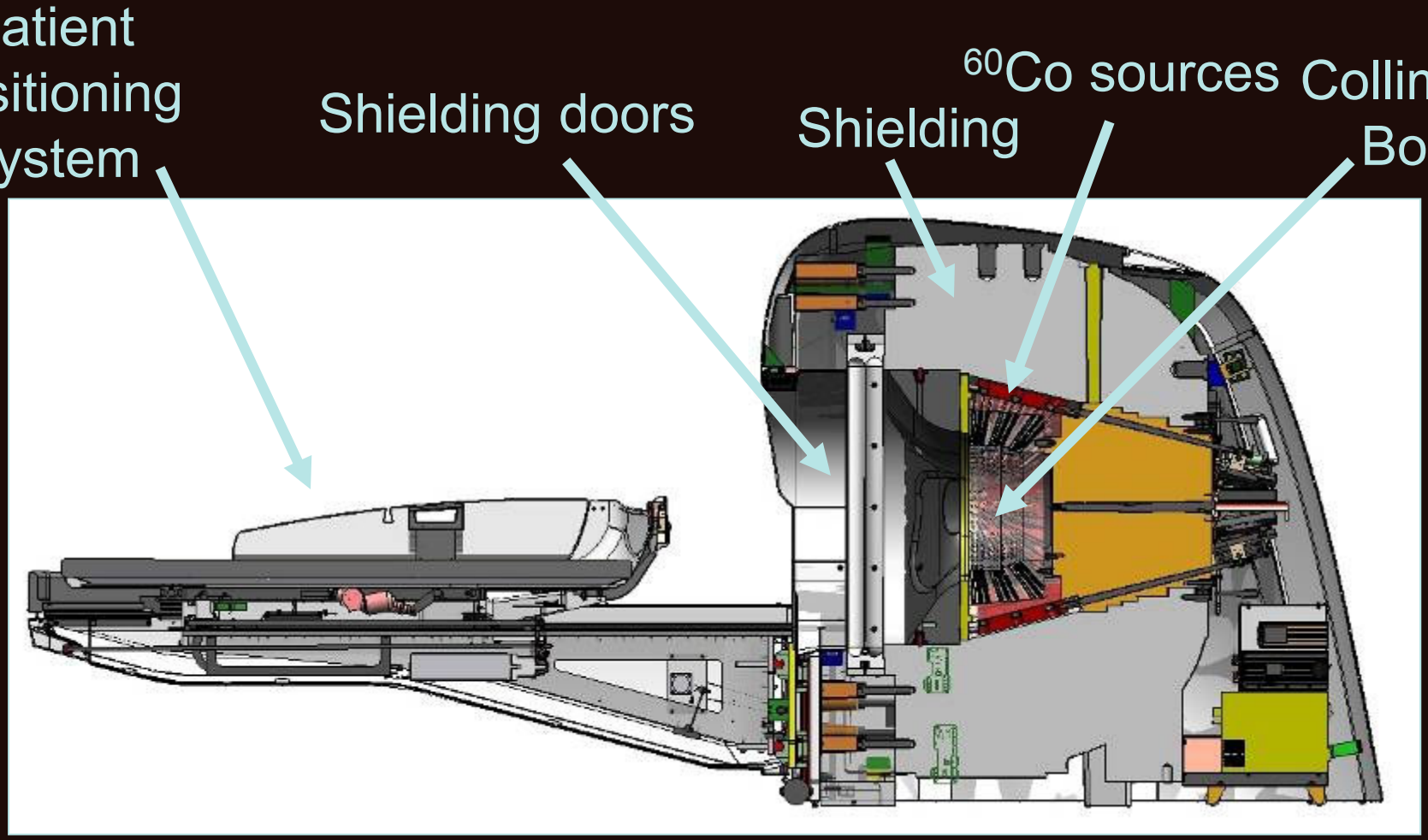
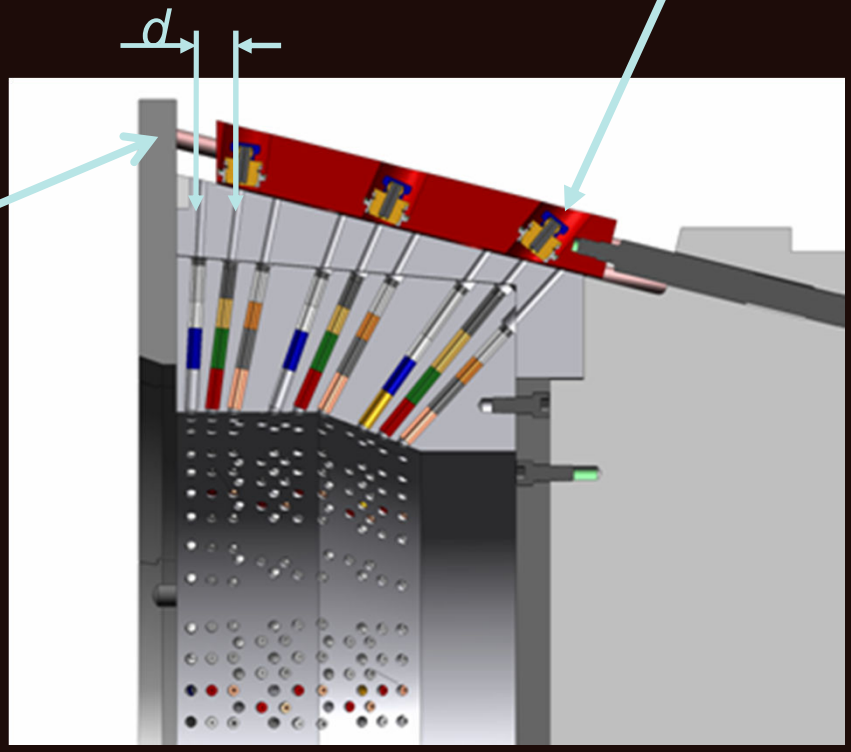


Image courtesy of Elekta, AB

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

Heidenhain linear encoders

Resolution: 0.01 µm

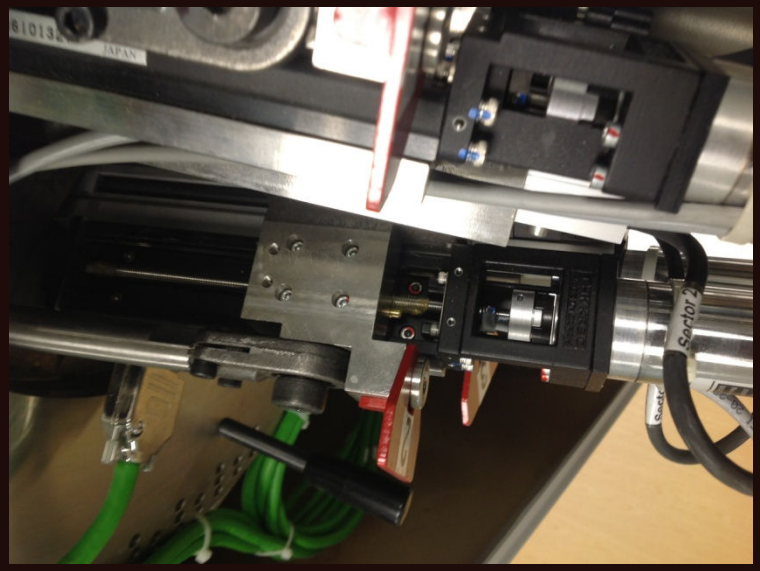
Accuracy over entire length of scale: ± 5 µm

THK rotational encoders

2000 pulses per rotation

Pitch on sector screws is 1mm

Resolution: 0.5 µm



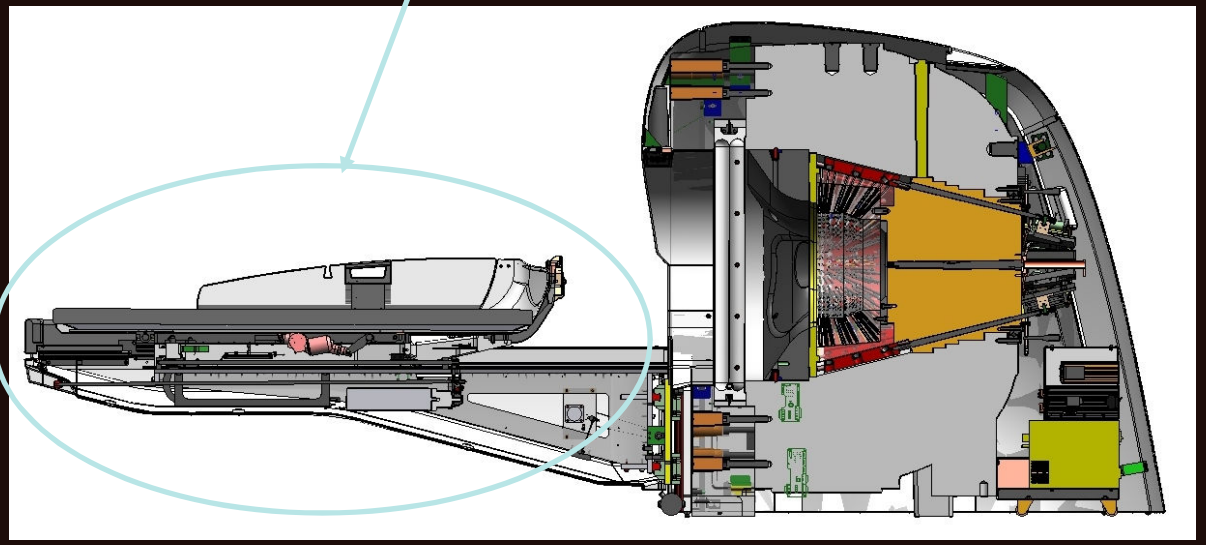
PPS Calibration

Mechanical calibration of orthogonality of movements

Creation of compensation curves for orthogonality

Laser interferometer calibration of absolute positioning

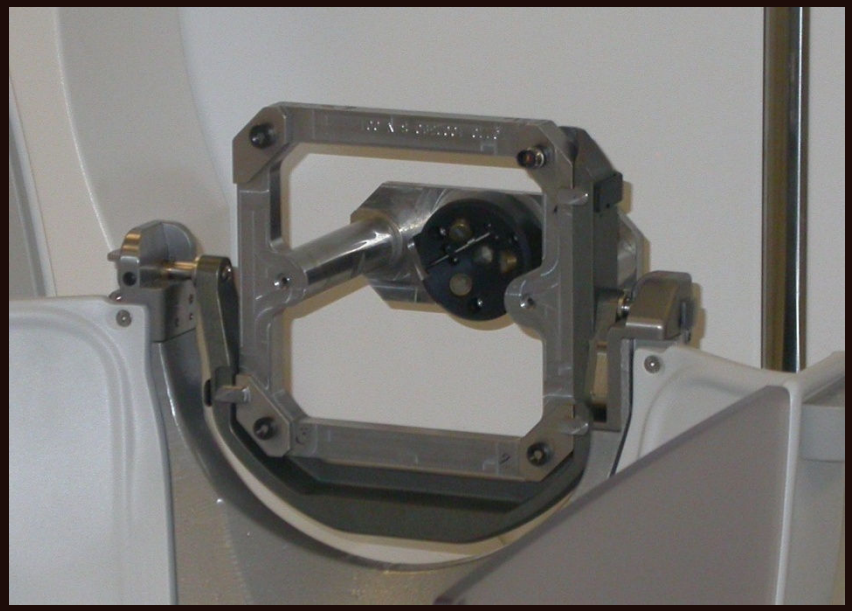
Patient Positiong System (PPS)



Leica Laser Interferometer

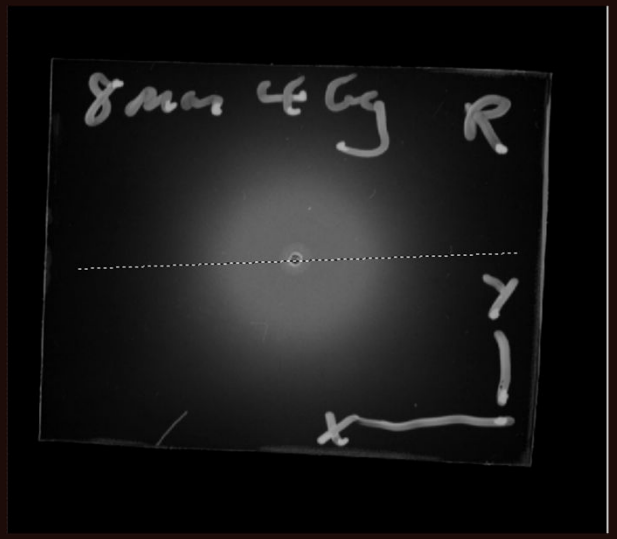
Used to validate accuracy of table motion.

Absolute accuracy: <0.01mm over 50m radius



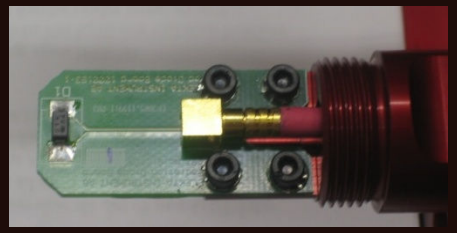
How to we validate this clinically?

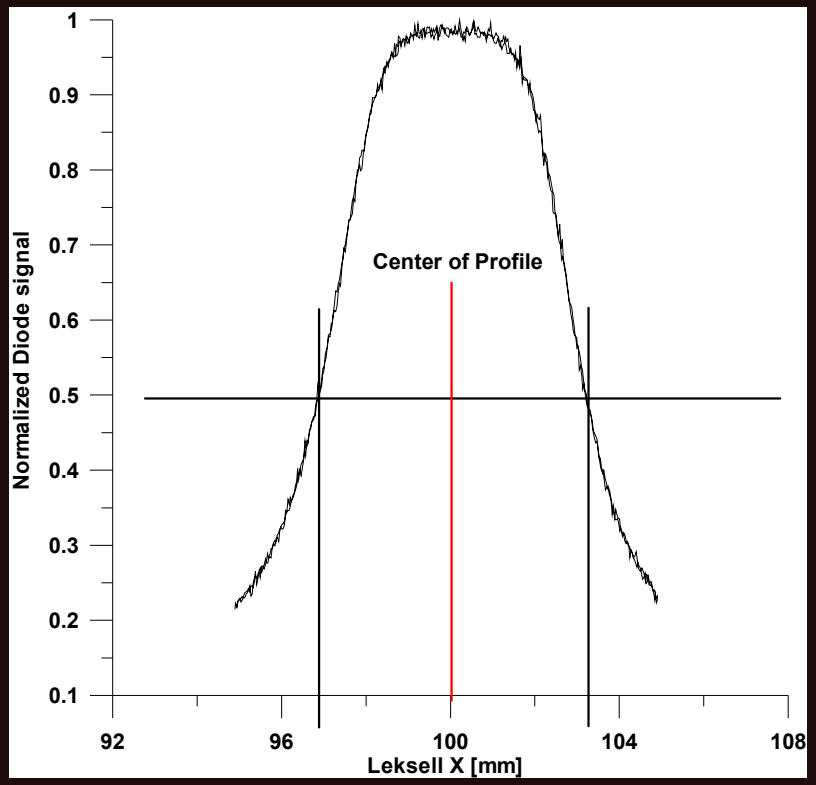
The old way:
Film

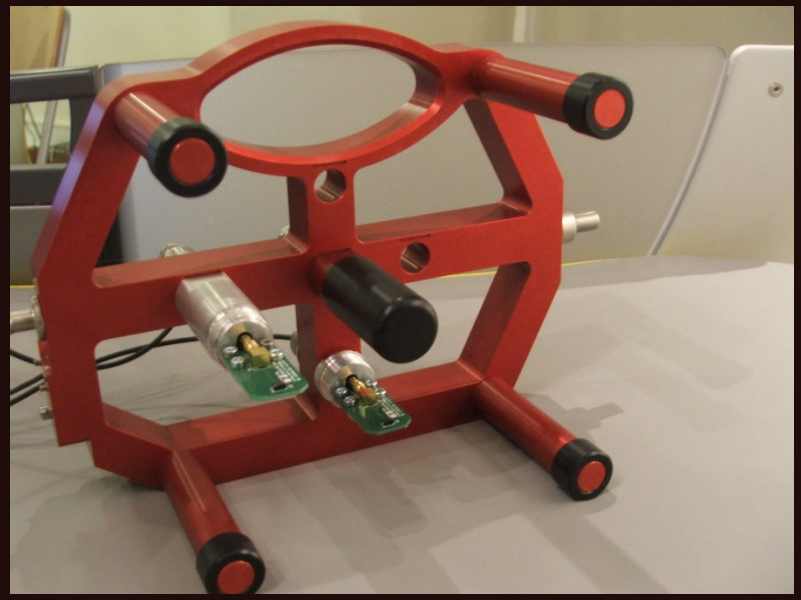


Manufacturer spec: 0.3 mm per axis, 0.4 mm radial (at 50% isodose line)

Master diode tools



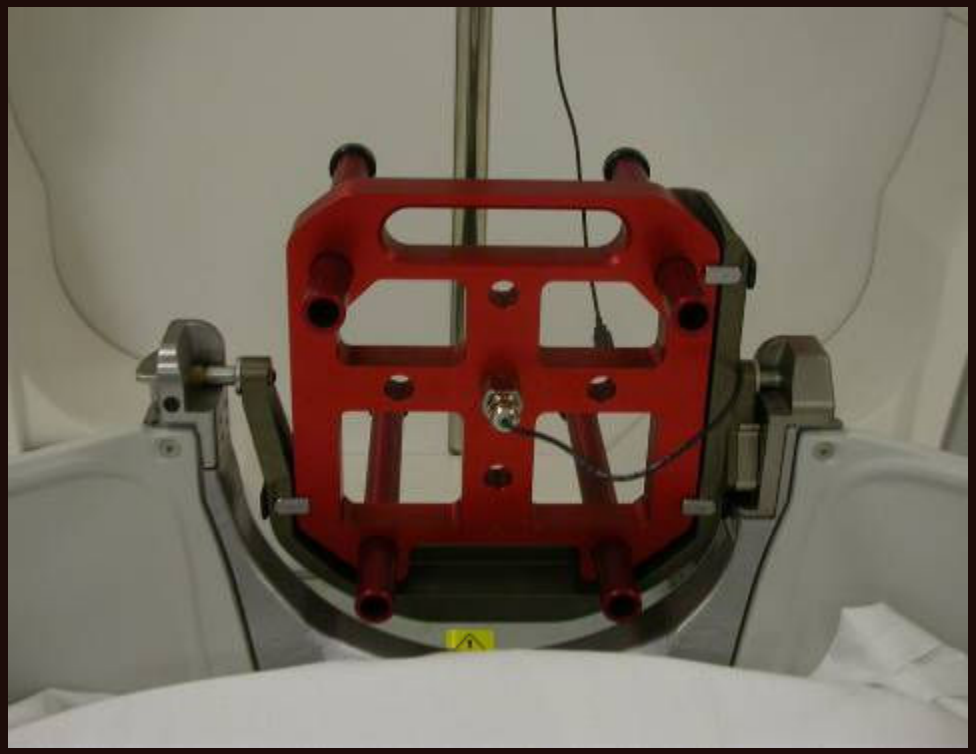




Calibrated at “reference” unit at Timome Hospital, Marseiile

Center diode < 0.08 mm repeatability at installation

Site-specific diode tool



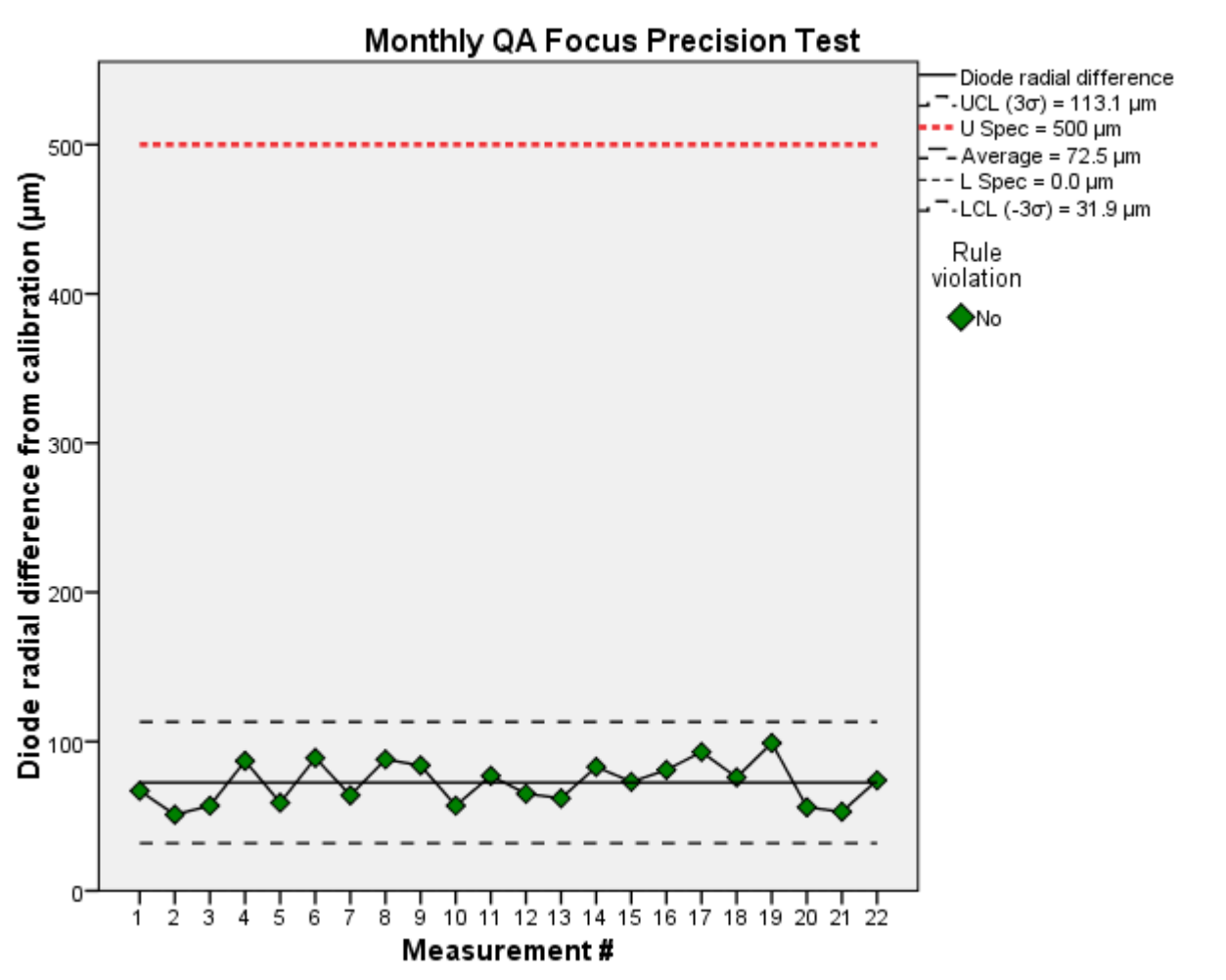
QA specification:
<=0.5 mm radial repeatability

Calibrated offset from “master” diode tool
Run at least 1 time per month

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 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

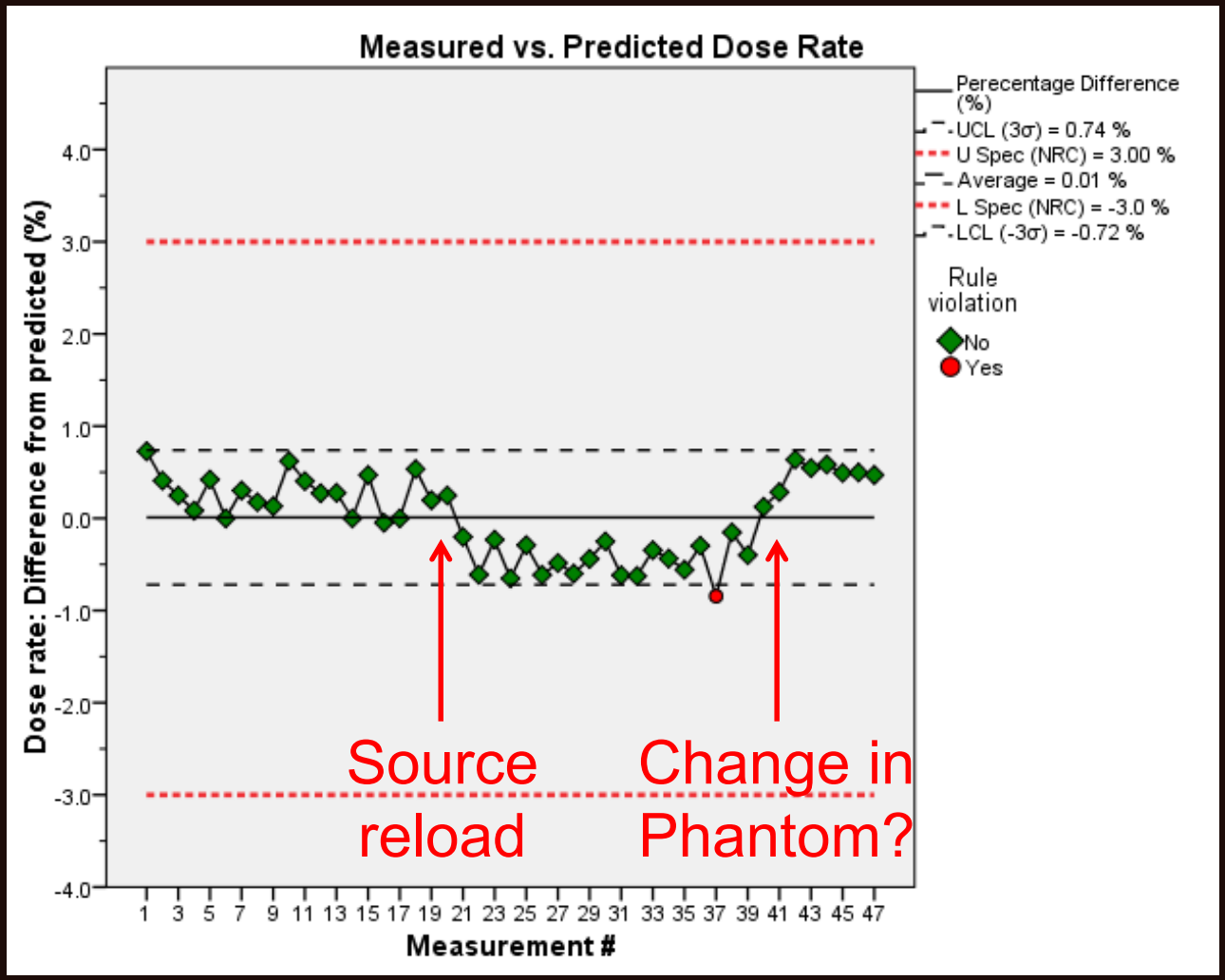
Elekta-provide polystyrene(?) phantom, solid water phantom, custom phantom

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



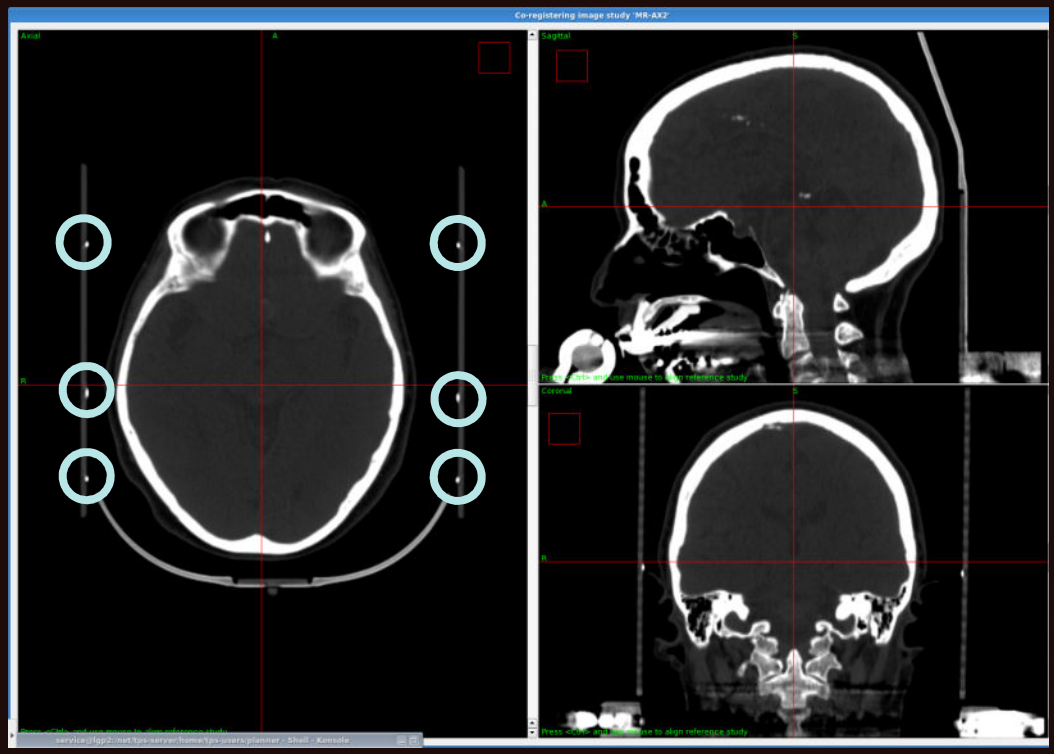
Control limits (3σ) determined from first 5 measurements

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

RPC TLD Ratio:
2012: 0.99
2013: 1.01

*with modified assumptions

Frame/Fiducial Uncertainty



Frame mechanical uncertainty: 0.2-0.7 mm (mostly in pin fixation) [1]
Fiducial registration uncertainty: 0.0 – 0.8 mm [2]

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

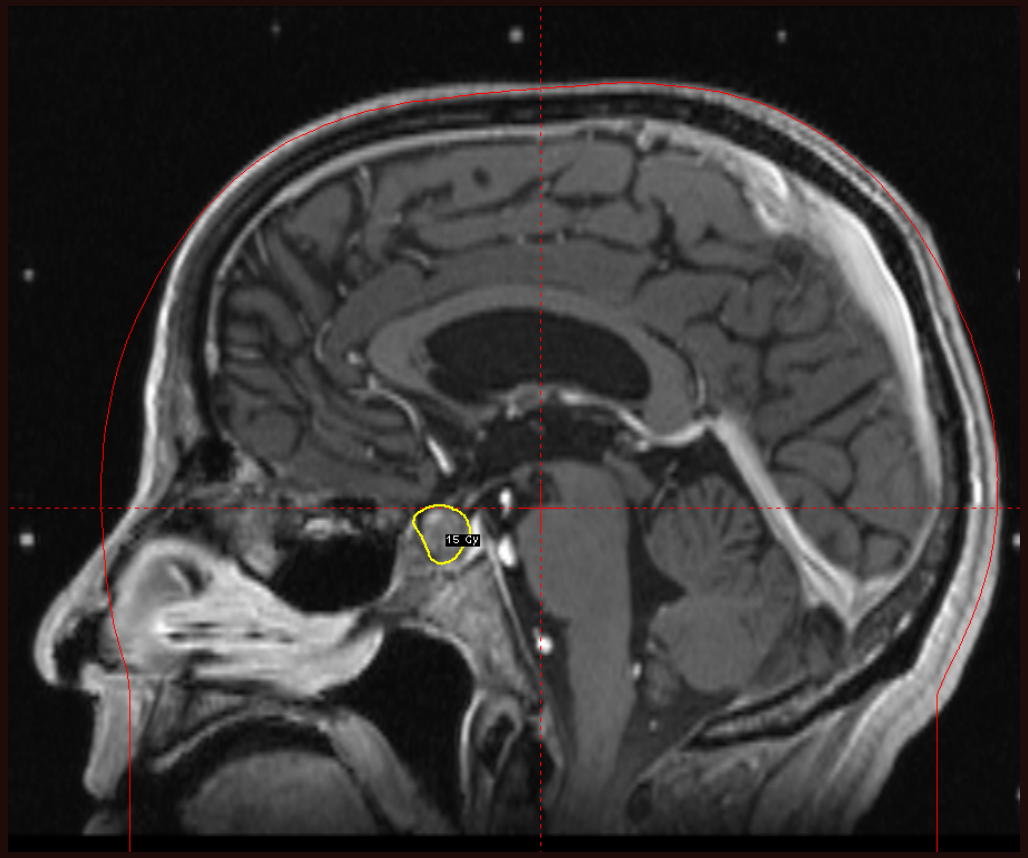
2. J-H Park, J. H. Han, C-Y Kim, et al., Med Biol Eng Comput, 2011

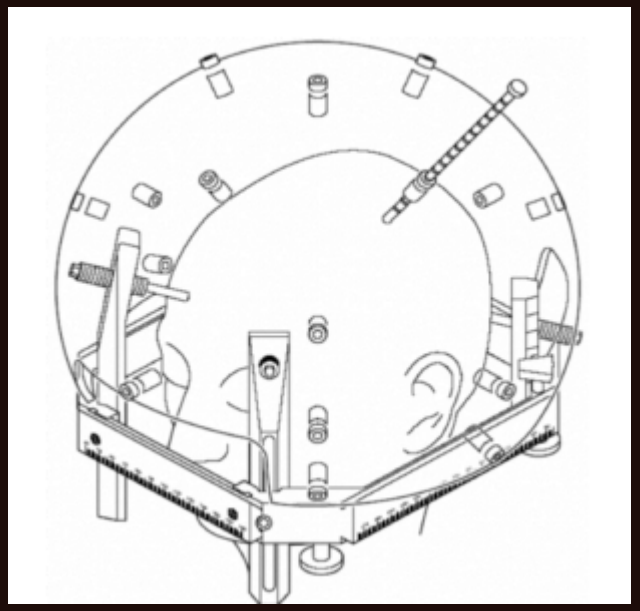
Patient Docking Uncertainty

Frame adapter x play:
<0.15 mm
Frame adapter angle play:
<60 µm
Frame adapter deflection:
0.15-0.20 mm

Source: Leksell Gamma Knife Perfexion Planned Maintenance Manual

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%)

TPS Uncertainty

Historically GammaPlan:

Treats the brain as a homogeneous ball of water

Ignores build-up region effects

Ignores tissue interface effects

Uses a poor approximation of the skull shape

BUT….

It is fast – good for Gamma Knife workflow!

Not a bad approximation in the brain

How bad can it get?

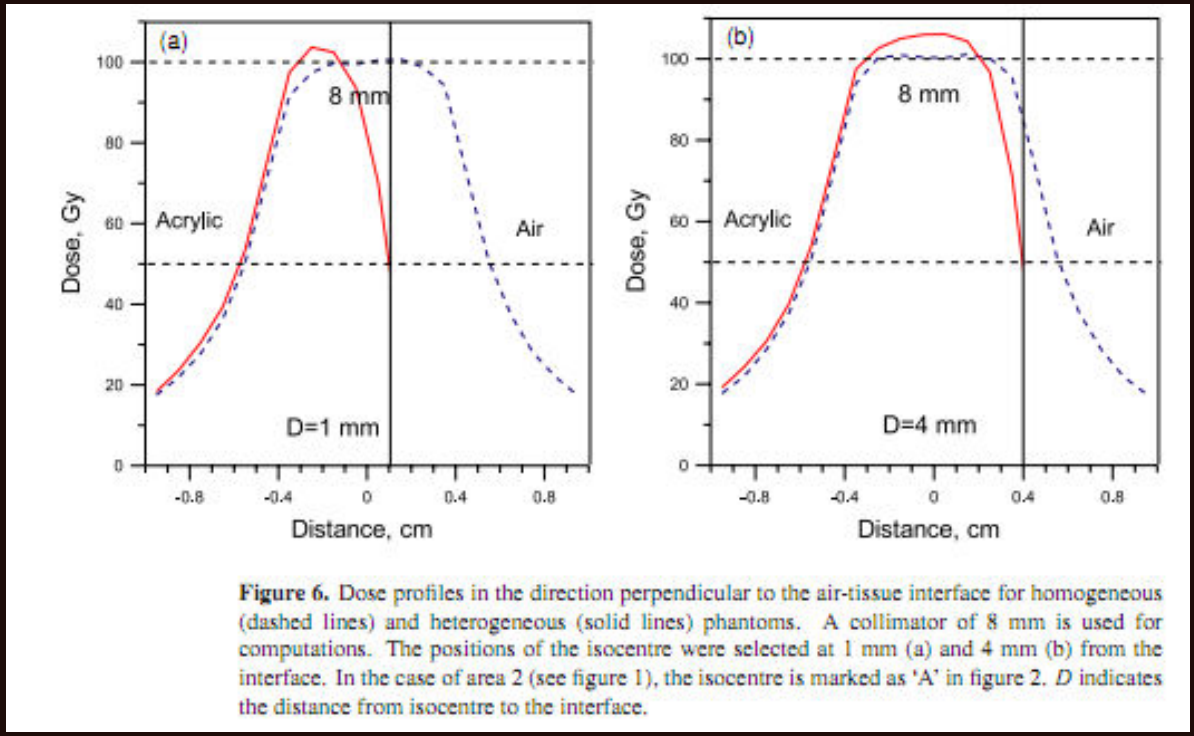


Figure 6. Dose profiles in the direction perpendicular to the air-tissue interface for homogeneous (dashed lines) and heterogeneous (solid lines) phantoms. A collimator of 8 mm is used for computations. The positions of the isocentre were selected at 1 mm (a) and 4 mm (b) from the interface. In the case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

- ~7% underdose of regions adjacent to air interface
- Dose away from cavity is under-attenuated, so overdose regions further from cavity
- In most cases, this isn't an issue

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.

But….now there is a convolution option!

Other TPS uncertainty

Primary GammaPlan algorithm has recently changed (TMR classic to TMR 10)

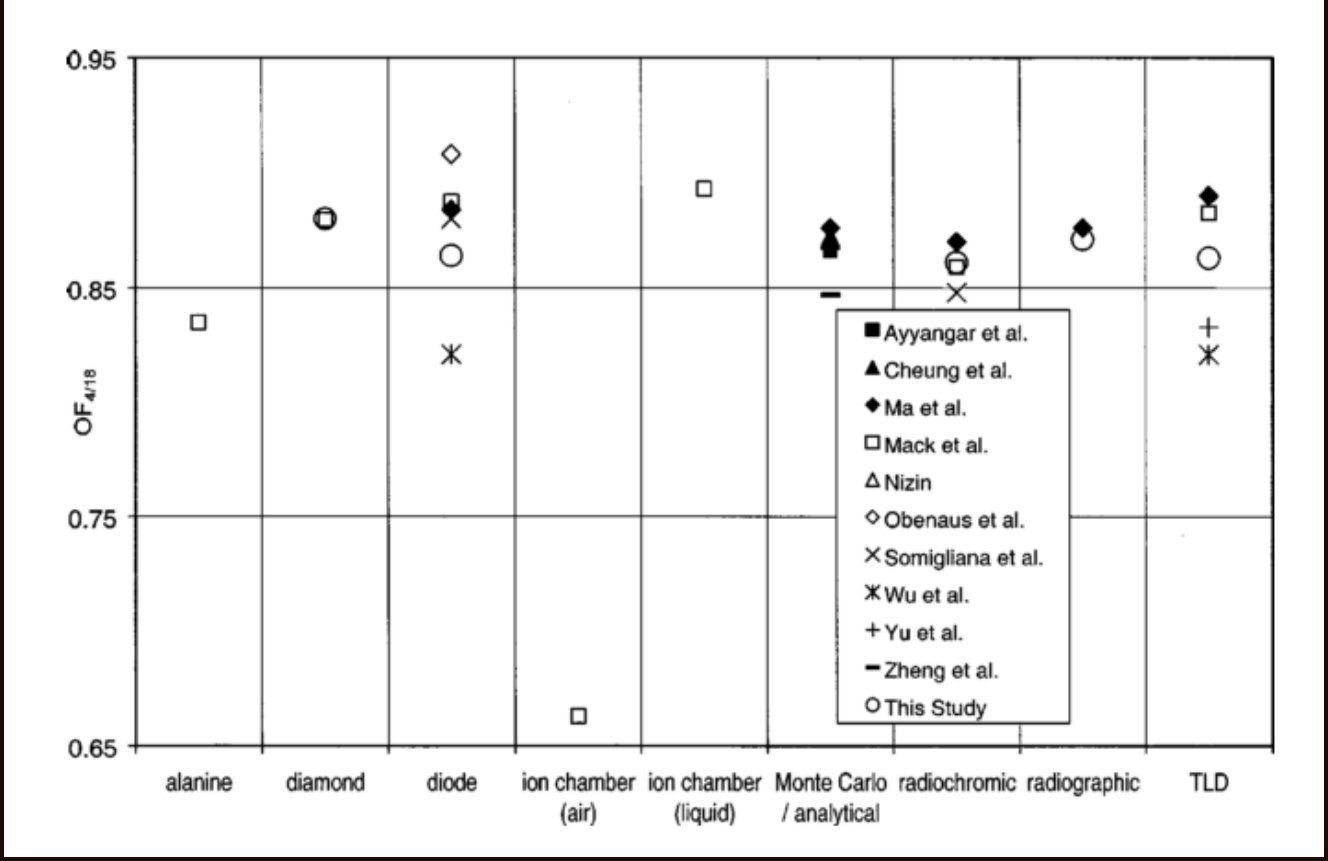
Example: Changes in beam profiles

TMR 10 / TMR Classic	FWHM x (mm)	FWHM y (mm)	FWHM z (mm)
4mm	6.16 / 6.01	6.16 / 6.01	5.04 / 4.94
8mm	11.06 / 10.79	11.06 / 10.79	9.80 / 9.60
16mm	21.75 / 21.38	21.75 / 21.38	17.44 / 17.21

Effect depends on the precise geometry of the situation
Brings algorithm closer to monte-carlo results

Data from: Nordström, H., "A new TMD dose algorithm in Leksell GammaPlan", whitepaper, Elekta AB, 2011.

Small-Field Uncertainty

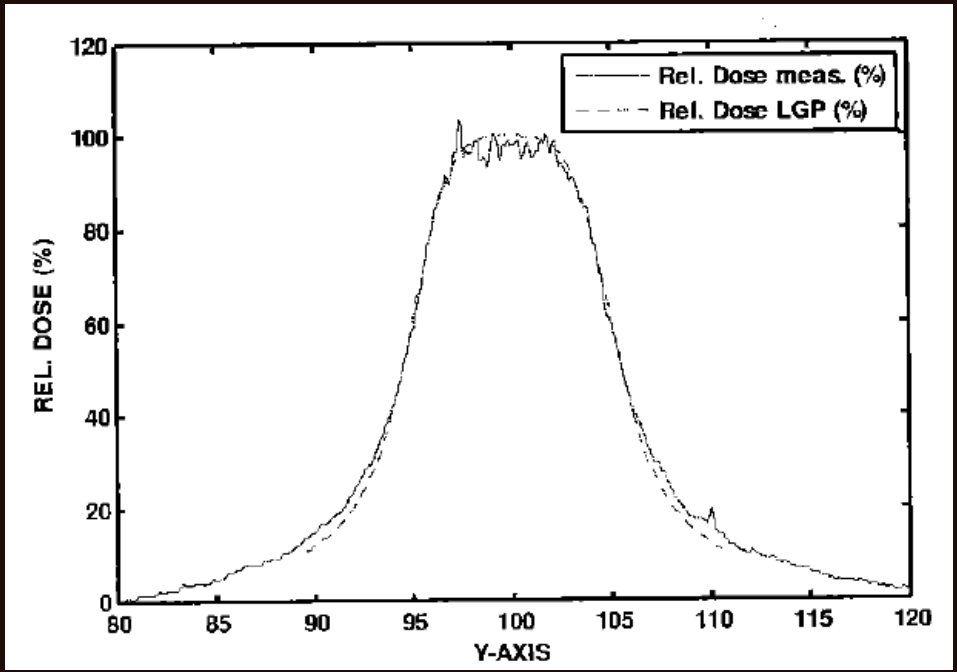


4mm/18mm output factor, by detector type and study

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
Phys 37(6), 2010

I don’t know how to sum all this uncertainty, but:



Acceptance specification for shot profile:

1 mm film/TPS difference at 50% isodose line

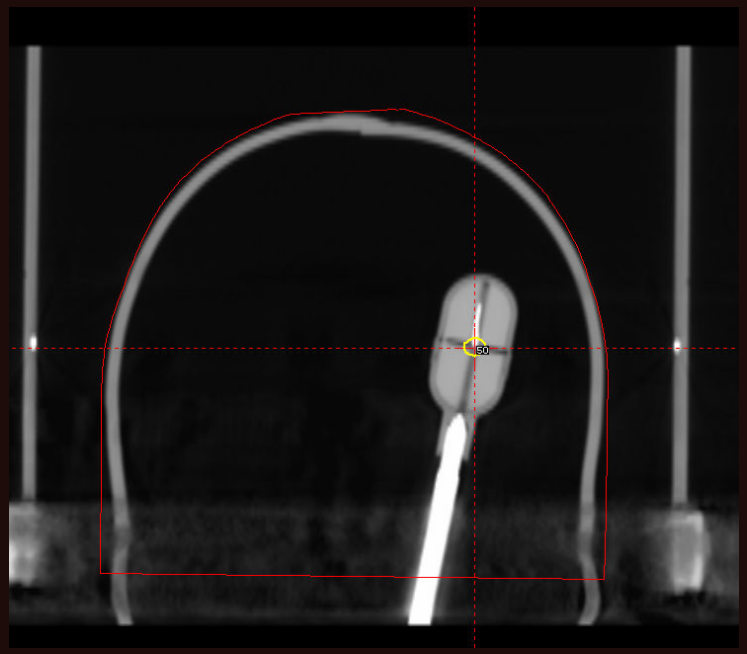
http://rpc.mdanderson.org

MD Anderson SRS Head Phantom

Measured dose to TLDs: 29.6 Gy
Planned dose to TLDs: 29.7 Gy

Measured along	Δ field size 50% isodose (measured – institution)	Offset 50% isodose
Sagittal (axial profile)	0.4 mm	0.6 mm
Axial (coronal profile)	0.1 mm	0.1 mm
Sagittal (axial profile)	-0.4 mm	0.5 mm

End-to-End Accuracy



Our method at UVA

- 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: 0.35mm

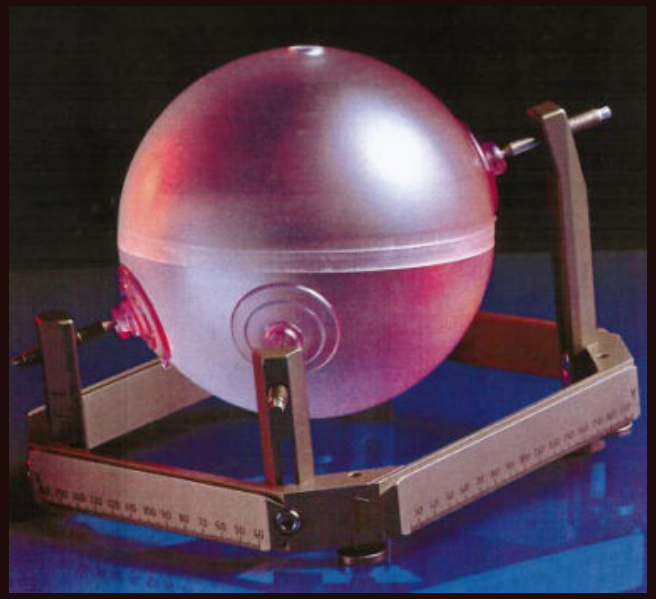
TABLE I. Investigation plane axial versus coronal (stereotactic *xy* plane vs *xz* plane). $p < 0.0001$ (*t*-test unpaired), $p = 0.0002$ (ANOVA).

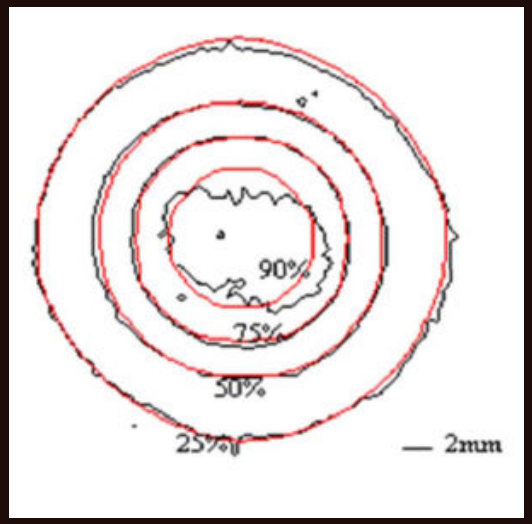
	All	Axial	Cor
Mean	0.48	0.42	0.60
Std.deviation	0.23	0.24	0.15
Number	170	116	54
Min	0.10	0.10	0.32
Max	1.12	1.12	0.92
Median	0.44	0.32	0.63

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

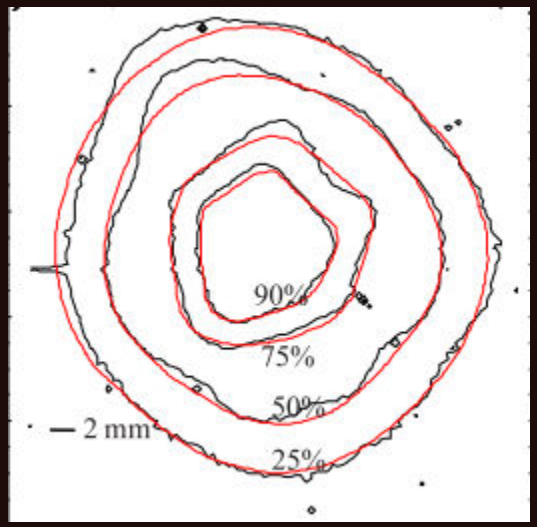
A. Mack, H. Czempiel, H-J Kreiner, et. al.

Med Phys 29(4), 2002





1.6cc lesion, 1 shot



6.9cc lesion, 16 shots

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