2014 AAPM SUMMER SCHOOL
University of Vermont • Burlington, VT • June 22–26, 2014
SRS/SBRT/SABR:
Safely and Accurately Delivering
High-Precision, Hypofractionated Treatments

Historical and Technical Overview of Gamma Knife Radiosurgery

David Schlesinger, Ph.D.
University of Virginia

Disclosures

Research support: Elekta, AB

Learning Objectives

- To understand the basic characteristics of radiosurgery and how they differ from traditional external-beam techniques.
- To learn the basic operational concepts of the Gamma Knife.
- To understand the historical evolution of the Gamma Knife and possible future directions.

History of the Gamma Knife

Design and Physical Principles

Treatment Procedures

Acceptance/Commissioning/QA

Recent/Future Developments

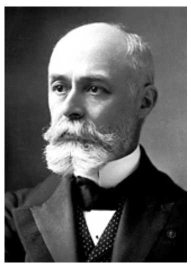
The “first” stereotactic surgery

Prehistoric female skull, San Damian, Peru, showing trephination marks.

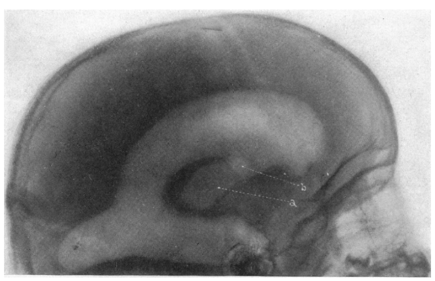
Prehistoric female skull, Cinco Cerros, Peru, left frontal and parietal incision with no signs of healing.

Images from the San Diego Museum of Man, San Diego, CA

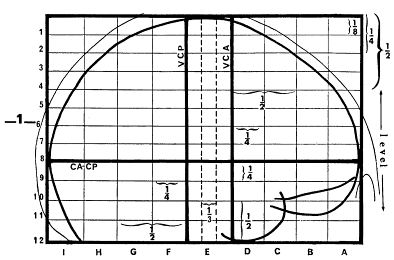
Thousands of years later…..

Wilhelm Röentgen (x-rays) 1895
Henri Becquerel (spontaneous radioactivity) 1896

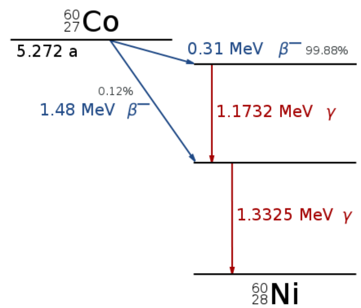


Walter Dandy (air ventriculography) ~1919

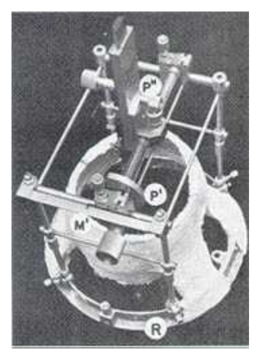


Jean Tailarach (human atlas) 1967

Horsley and Clarke apparatus (animals) 1908

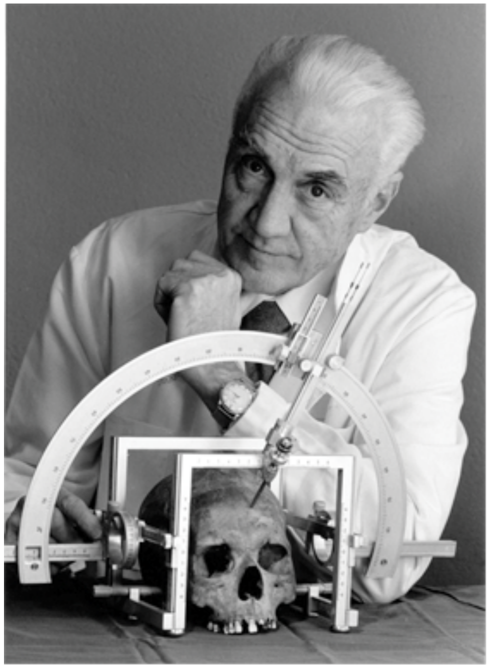


Glen Seaborg, John Livingood (Cobalt-60) Late 1930s



Spiegel and Wycis Apparatus (people) 1946

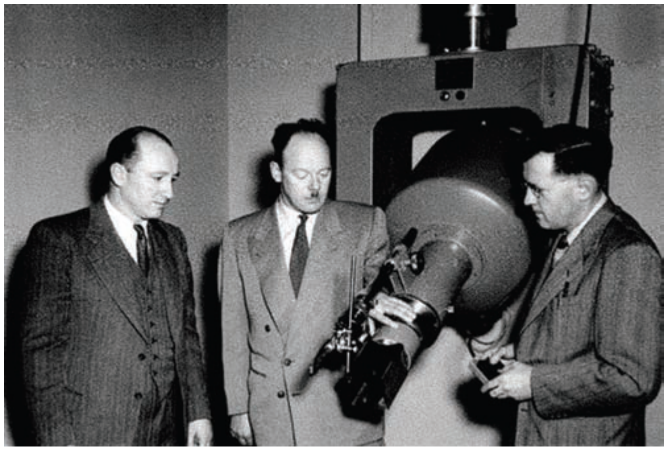
1951: "The Stereotactic Method and Radiosurgery of the Brain"



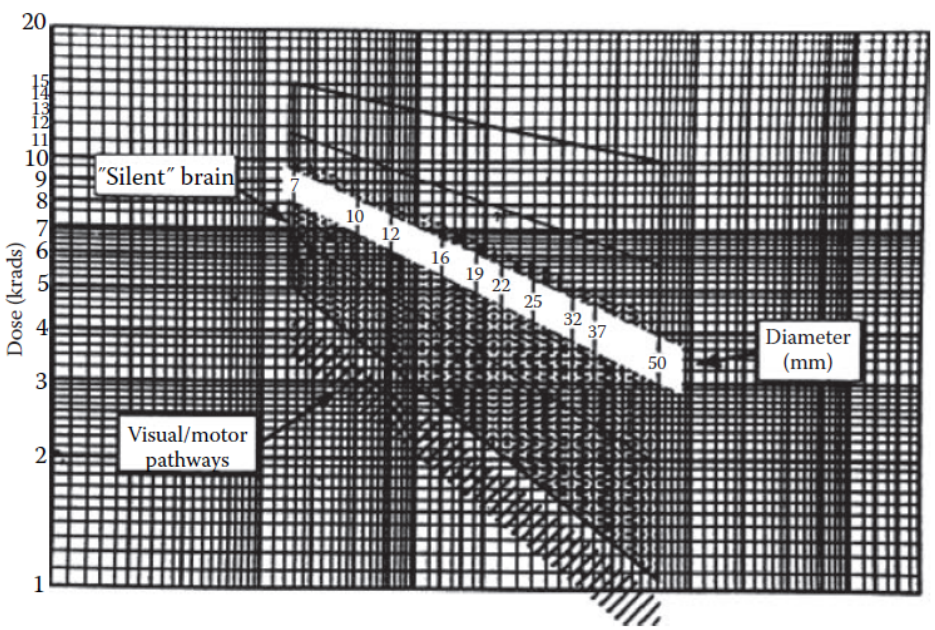
Lars Leksell with arc-centered stereotactic frame
(image courtesy of Elekta, AB)

Leksell at the 185 MeV Uppsala cyclotron facility circa 1958

Leksell, L. 1951. The stereotactic method and radiosurgery of the brain. *Acta Chir. Scand*. 102:316–9.



First cobalt-60 teletherapy source at Saskatoon Cancer Centre, with Sandy Watson, John MacKay, and Harold Johns.
(image source: University of Saskatchewan)



Raymond Kjellberg dose versus total volume risk curve for proton therapy of AVM.

Kjellberg RN, Hanamura T, Davis KR, Lyons SL , Adams RD: Bragg-peak proton-beam therapy for arteriovenous malformations of the brain. **New England Journal of Medicine 309:**269-74, 1983.

1967 - The first "Gamma Knife"

Lars Leksell and Ladislau Steiner

Tony DeSalles and Catherine Gilmore (the first president of Elekta) with original Gamma Knife at UCLA

Leksell, L. 1971. *Stereotaxis and Radiosurgery: An Operative System*. Springfield: Thomas Publishing.

ELEKTA

(1972)

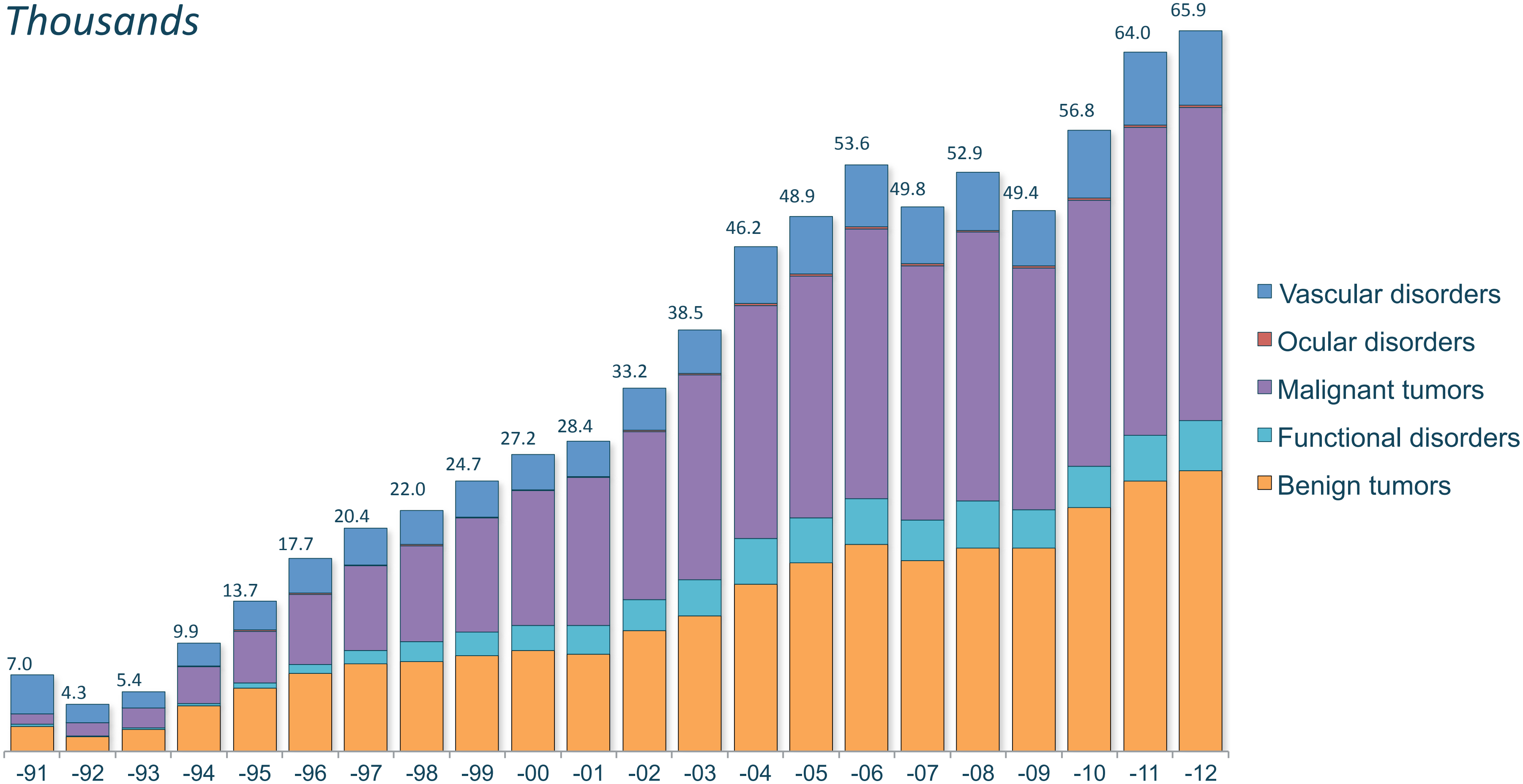
1987 - Model U
201 sources, ~30 Ci each
Circular collimators
Beam alignment ~0.2mm

1988 - Model B introduced

Wu, A., et al., Physics of Gamma Knife approach on convergent beams in stereotactic radiosurgery. *IJROBP,* 18:941–9, 1990.

Annual Indications Treated, 1991-2012

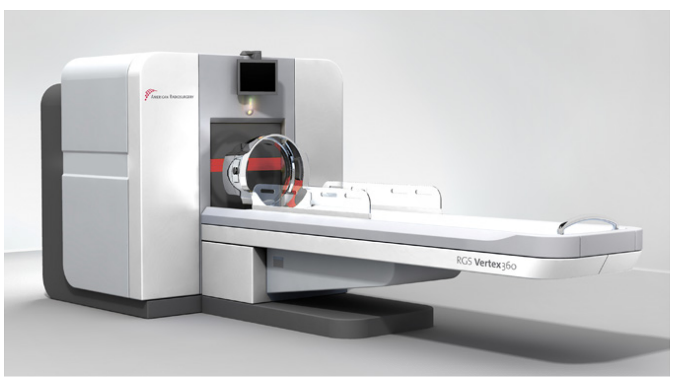
Thousands



Source: Leksell Gamma Knife Society

Model C/4C (1999)	201 sources (5 annular rings)	Automatic positioning system

Model Perfexion (2006)	192 sources 8 sectors (no helmets)	Couch positioning system



OUR/American Radiosurgery (1998/2007)	30 sources (rotating, no helmets)	Automatic couch positioning

History of the Gamma Knife

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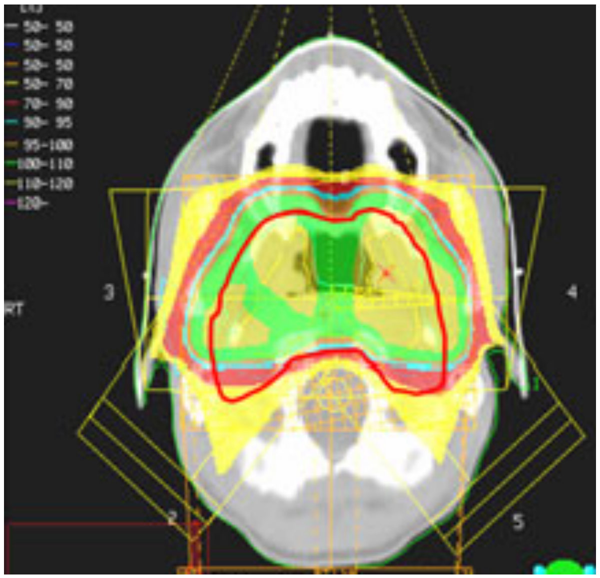
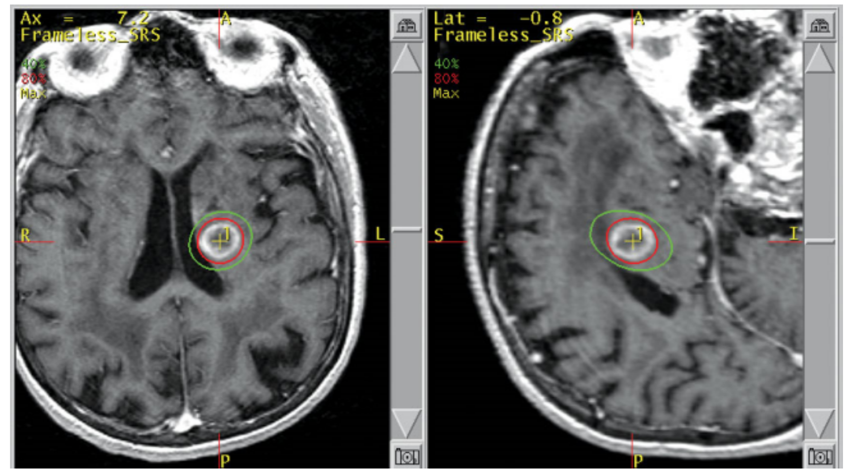
6-field 3D conformal plan



Cheung, Biomed Imaging Interv J 2006; 2(1):e19

- •Tumor + normal tissue targeted
- •Formalized treatment margins (GTV/CTV/ITV/PTV)
- •Homogenous dose
- •Low doses per fraction, high # fractions

Intracranial SRS treatment plan



www.varian.com

- •Small fields, differential targeting
- •High doses per fraction, small # fractions
- •Treatment margins not as formal
- •Steep dose gradients
- •Inhomogeneous dose within tumor
- •Extremely high requirement for accuracy!

Superposition of Beams

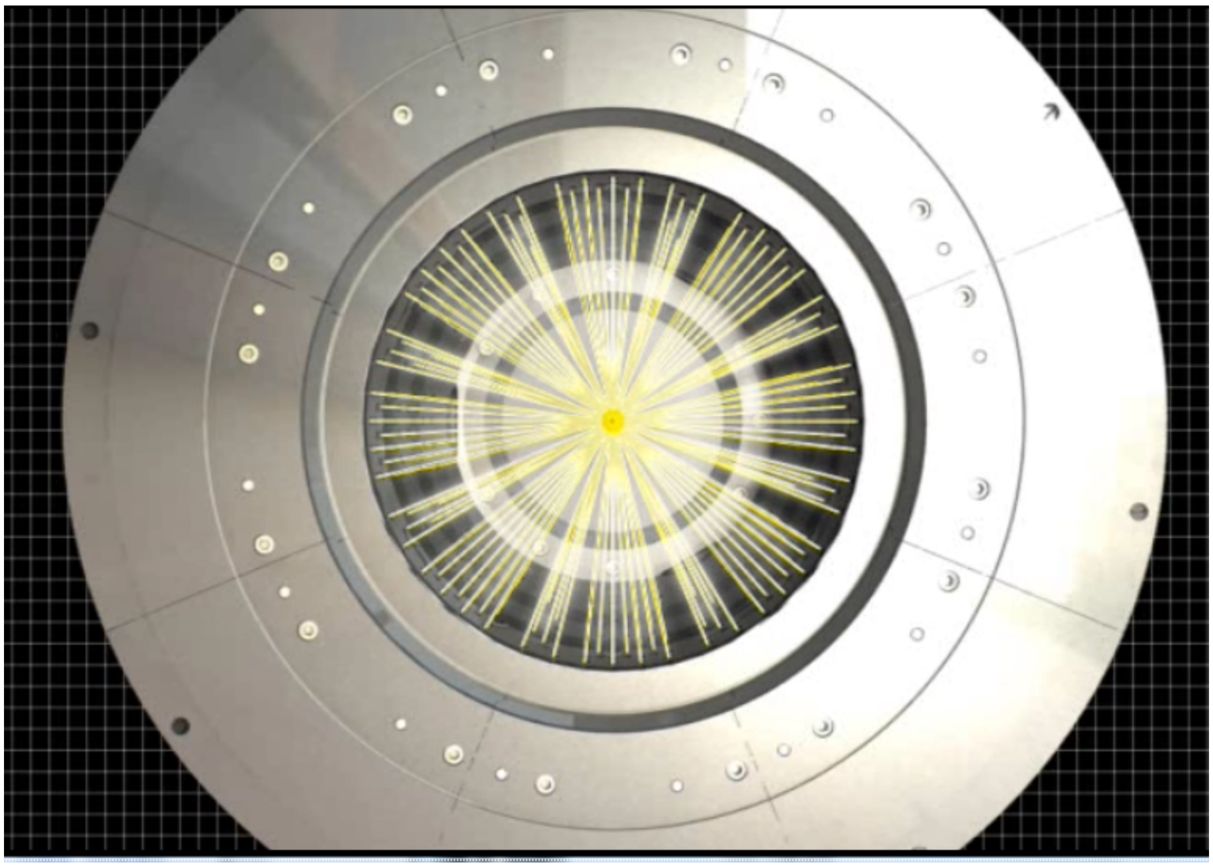


Image courtesy of Elekta, AB

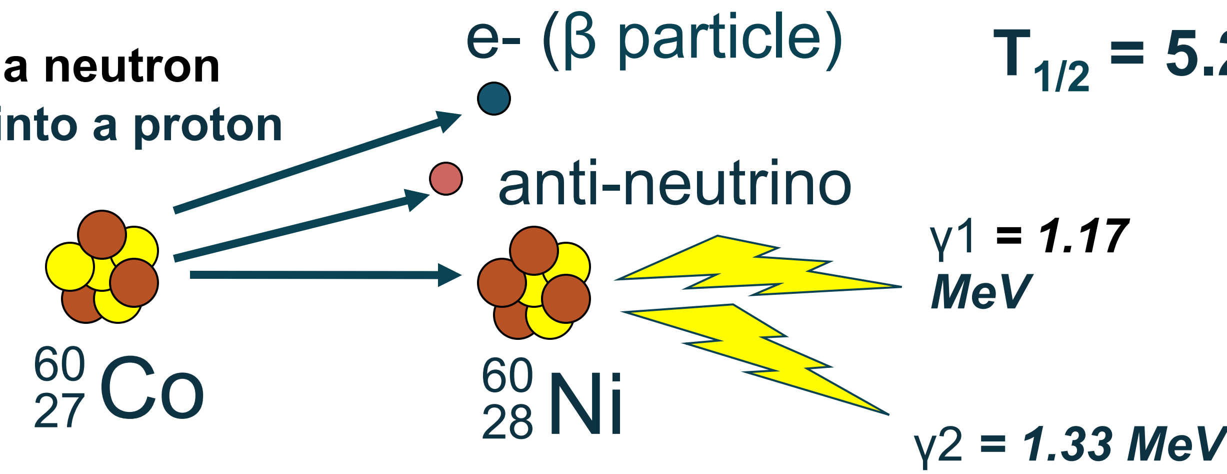
Technical ability to create many individual small beams led directly to the use of ^{60}Co

Spreading the energy out generates the steep dose gradients

Cobalt-60 Powered

β- decay: a neutron converts into a proton

$T_{1/2}$ = 5.26 years



60Co decay is a very stable photon source

Requires less technical complexity than a linac

192/201 beams per isocenter!

Stereotactic Targeting

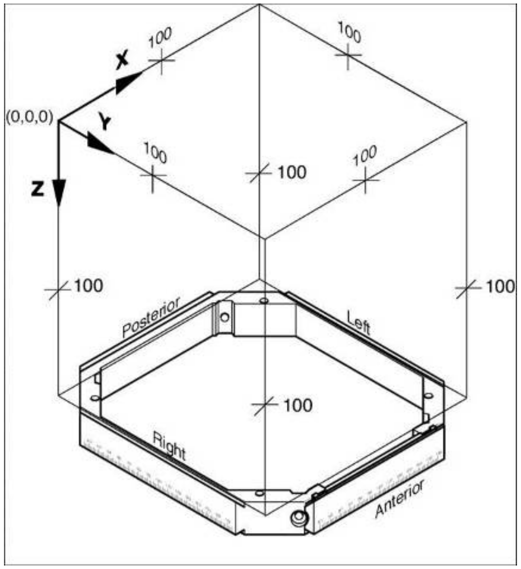


Image courtesy of Elekta

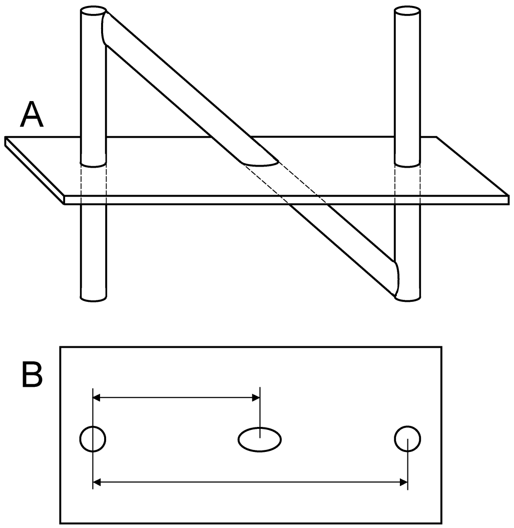
The frame defines the coordinate system

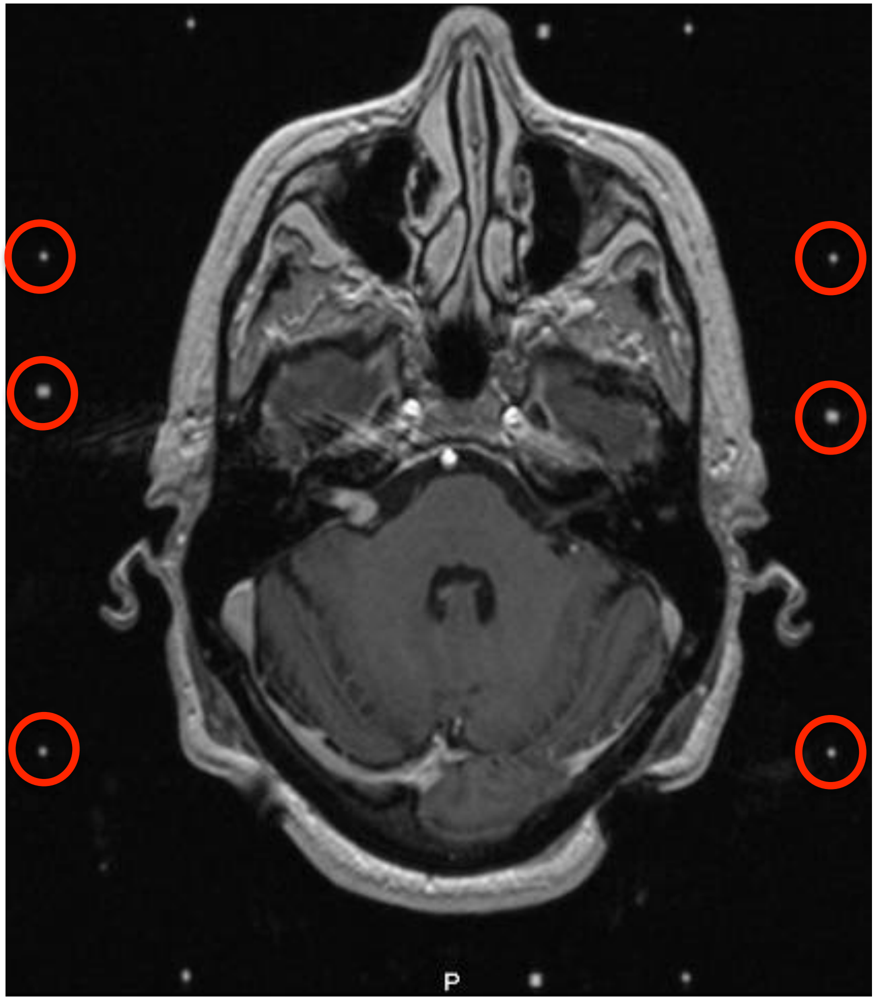
Coordinate system origin is to the right, superior, posterior of the patient's head

All coordinates are positive – no sign mistakes

Center of the system is considered to be (100, 100, 100) (mm)

Stereotactic Fiducials



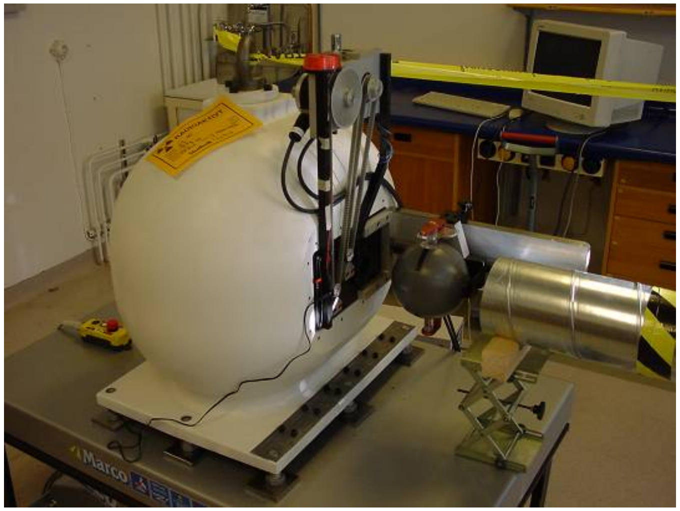


Brown R A, et al. (2013) The Origin of the N-Localizer for Stereotactic Neurosurgery. Cureus 5(9)

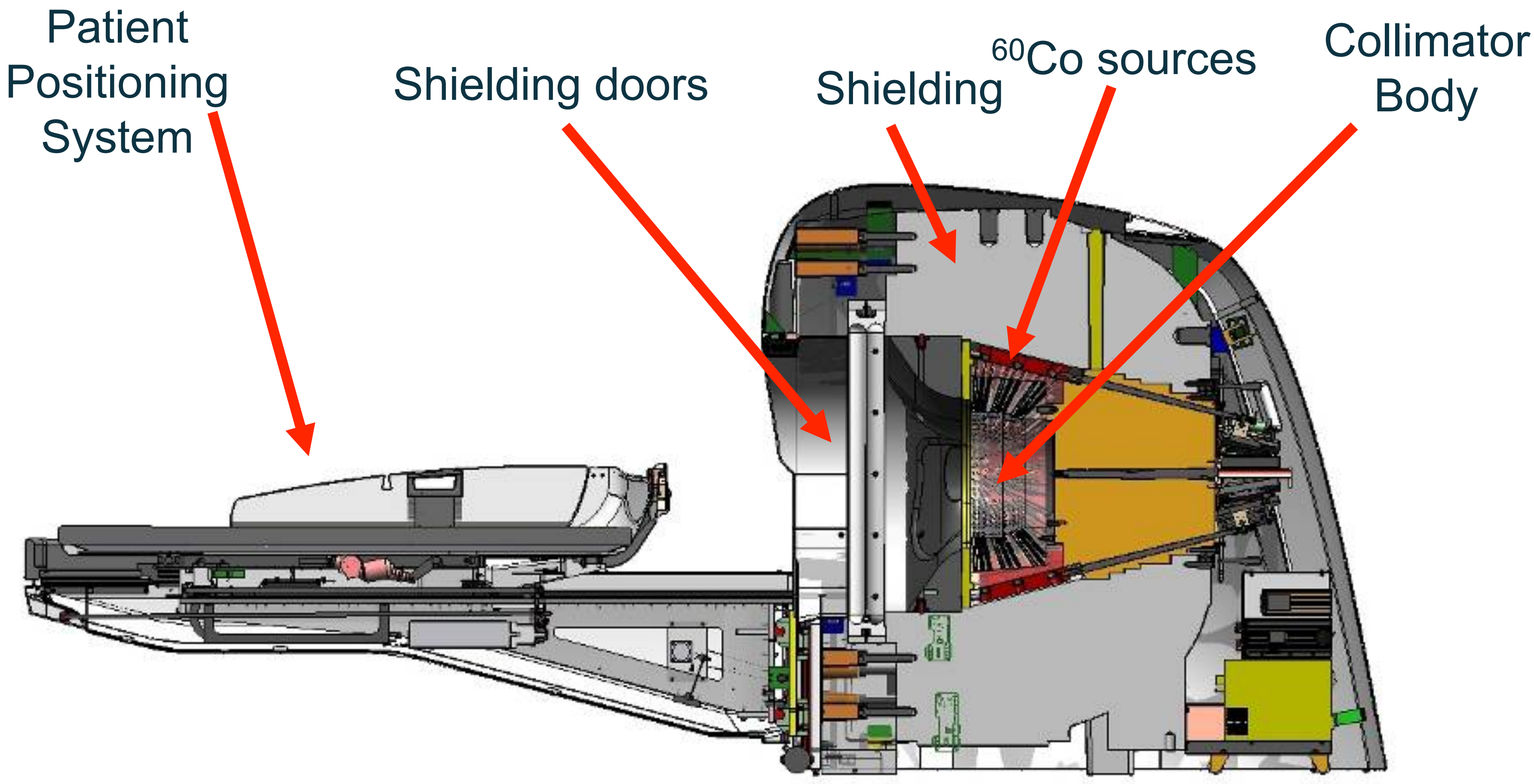
Model C – Dosimetry

- Each helmet has a single-size collimator
- Each beam has an identical (400 mm) source to focus distance
- 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



Gamma Knife Perfexion

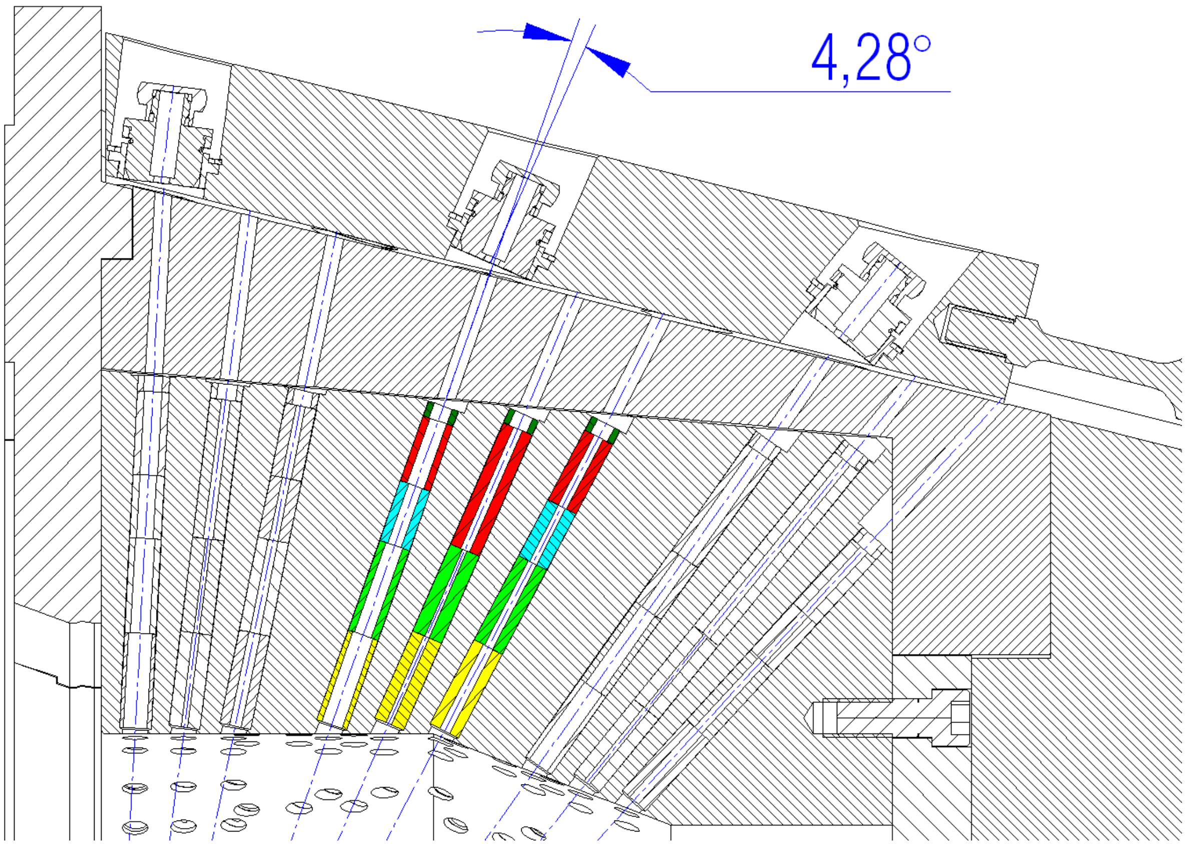


~20 metric tons to protect you from ~20 grams of ^{60}Co

Perfexion Dosimetry

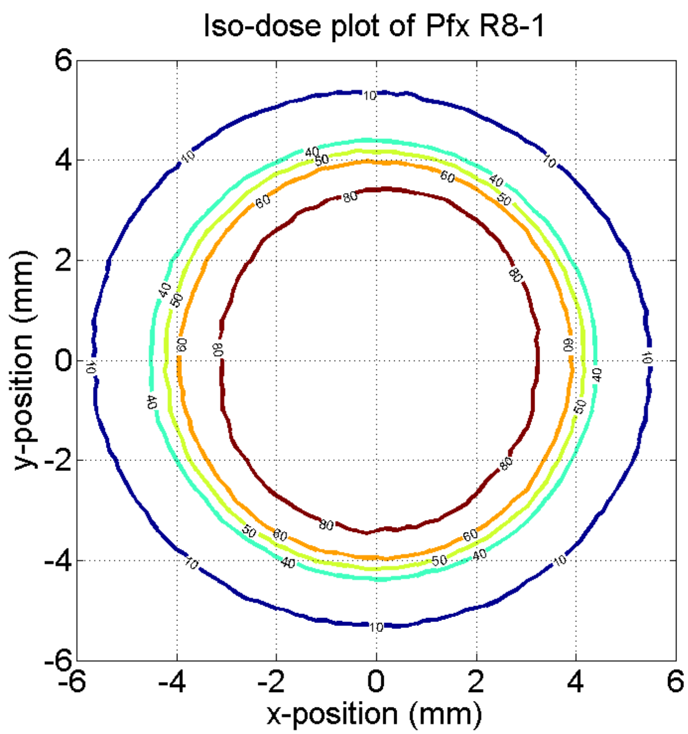
Source to focus distance depends on ring

Sources are angled relative to beam channels



2D Dose Profiles

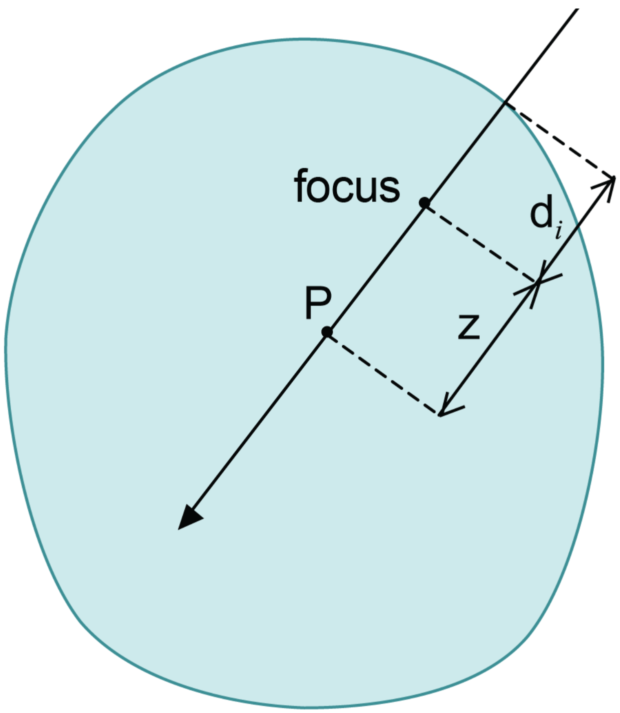
Angled sources requires 2D OARs



Collimator	Output factor	Attenuation constant (1/mm)	Scaling distances (mm)	Virtual source-to focus distance (mm)
P4_1	0.799	0.00678	377	521
P4_2	0.815	0.00704	380	546
P4_3	0.792	0.00690	387	533
P4_4	0.725	0.00712	398	595
P4_5	0.663	0.00698	420	607
P8_1	0.957	0.00658	374	431
P8_2	0.946	0.00660	382	437
P8_3	0.901	0.00681	394	468
P8_4	0.808	0.00665	408	480
P8_5	0.730	0.00680	433	522
P16_1	0.961	0.00694	381	481
P16_2	1	0.00685	379	459
P16_3	0.986	0.00675	383	455
P16_4	0.920	0.00690	389	488
P16_5	0.851	0.00694	409	519

The Basic Dose Model

$$\dot{D}_i(P) = \dot{D}_{calibration,16} \times \frac{1}{192} \times of_i \times e^{-\mu_0 (d_i - R_{calibration})} \times \frac{e^{-\mu_i z}}{(1+\frac{z}{R_{vsf,i}})^2}$$



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.

History of the Gamma Knife

Design and Physical Principles

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Stereotactic Frame Placement

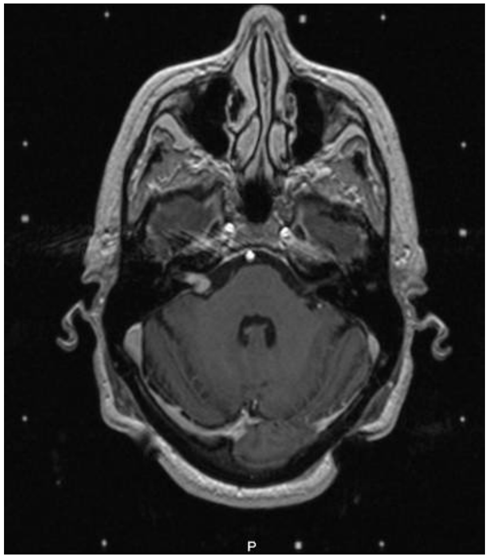
UVA Gamma Knife
(patient consented to photo use)

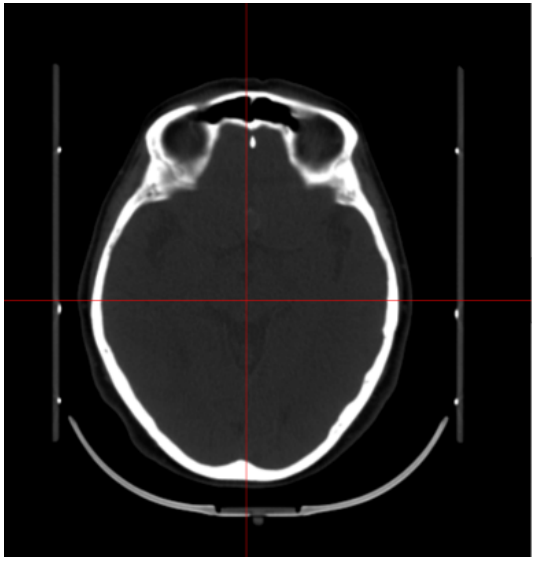
- Takes 5-10 minutes
- Usually done with local anesthesia and light sedation
- Pins minimally break skin, penetrate to outer table of skull
- Pin marks heal within a day or two of frame removal

Treatment Planning Images

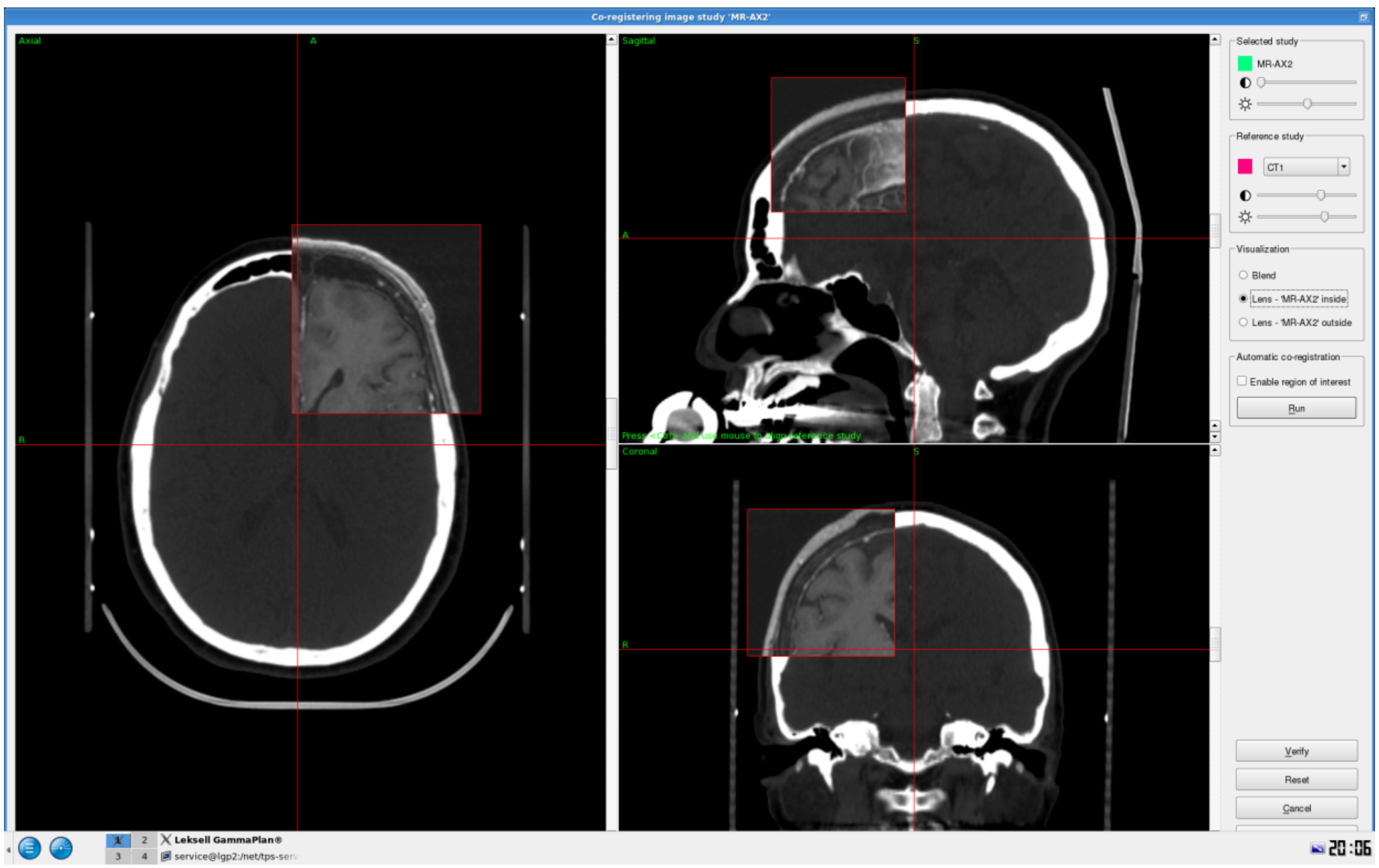
Typical imaging protocols:

Solid tumors	**AVMs**	**Skull-base and pituitary**
T1-weighted MR + contrast	Biplane DSA T1-weighted MR + contrast MRA	T1-weighed MR + contrast T2 CISS or SPACE T1-weighted + fat saturation

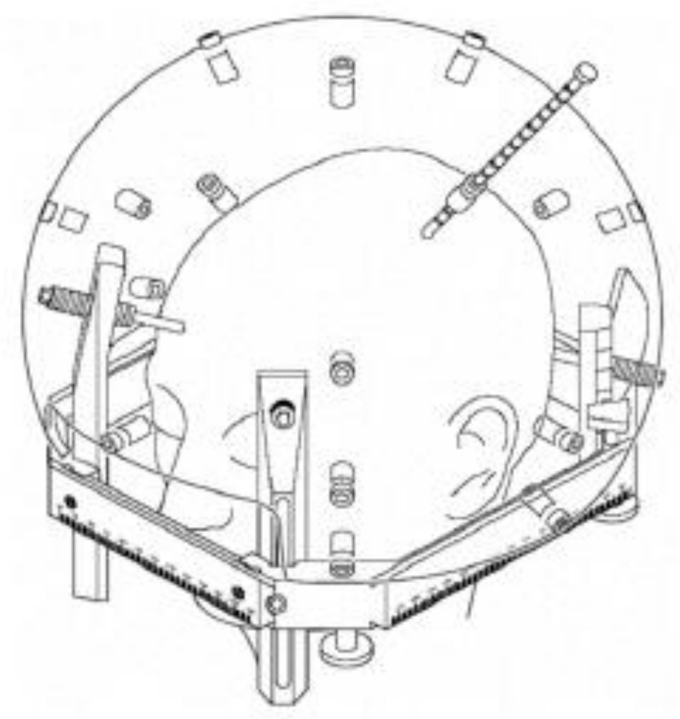


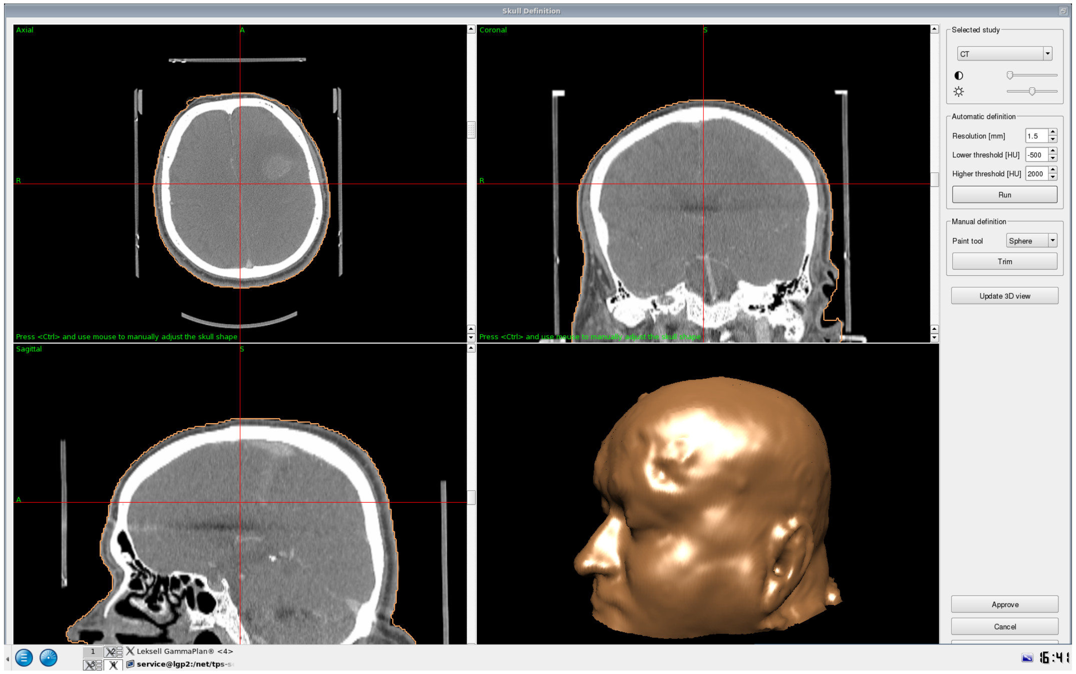


Co-registration of non-stereotactic imaging



Skull Contours

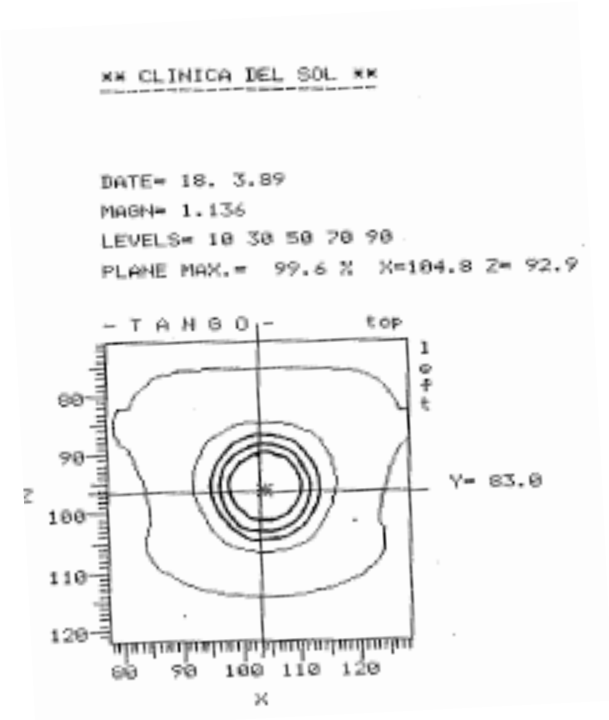




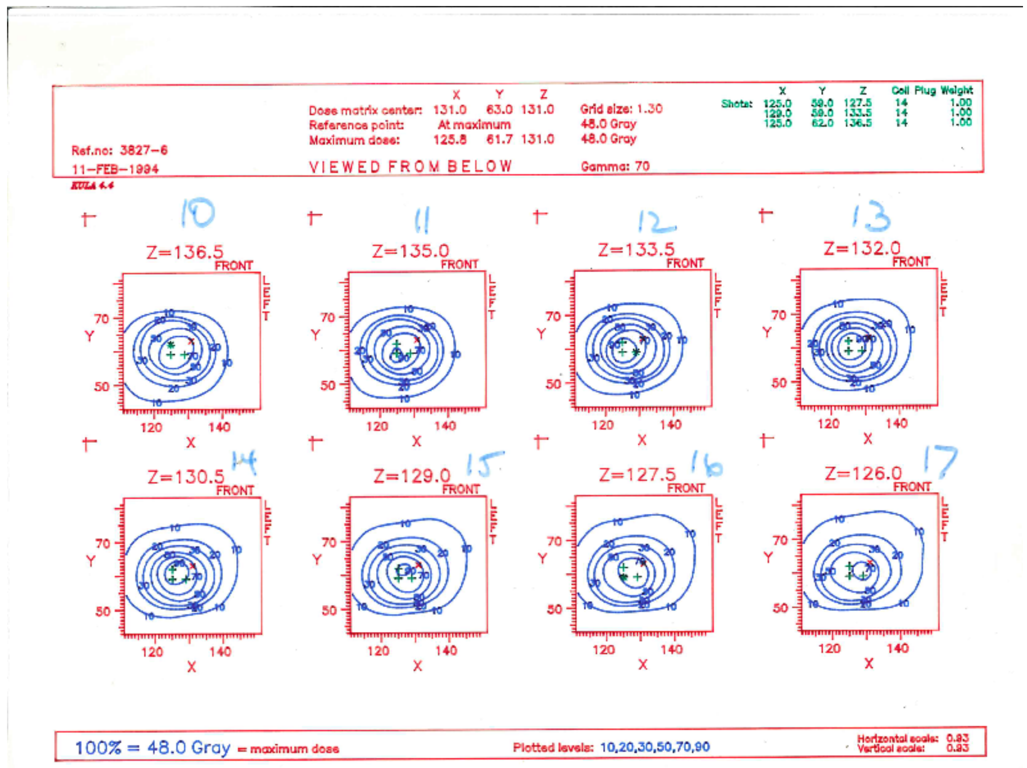
Used to calculate SSD and depth of each beam

Also used to determine potential collisions between patient and helmet or side of collimator

Evolution of Treatment Planning

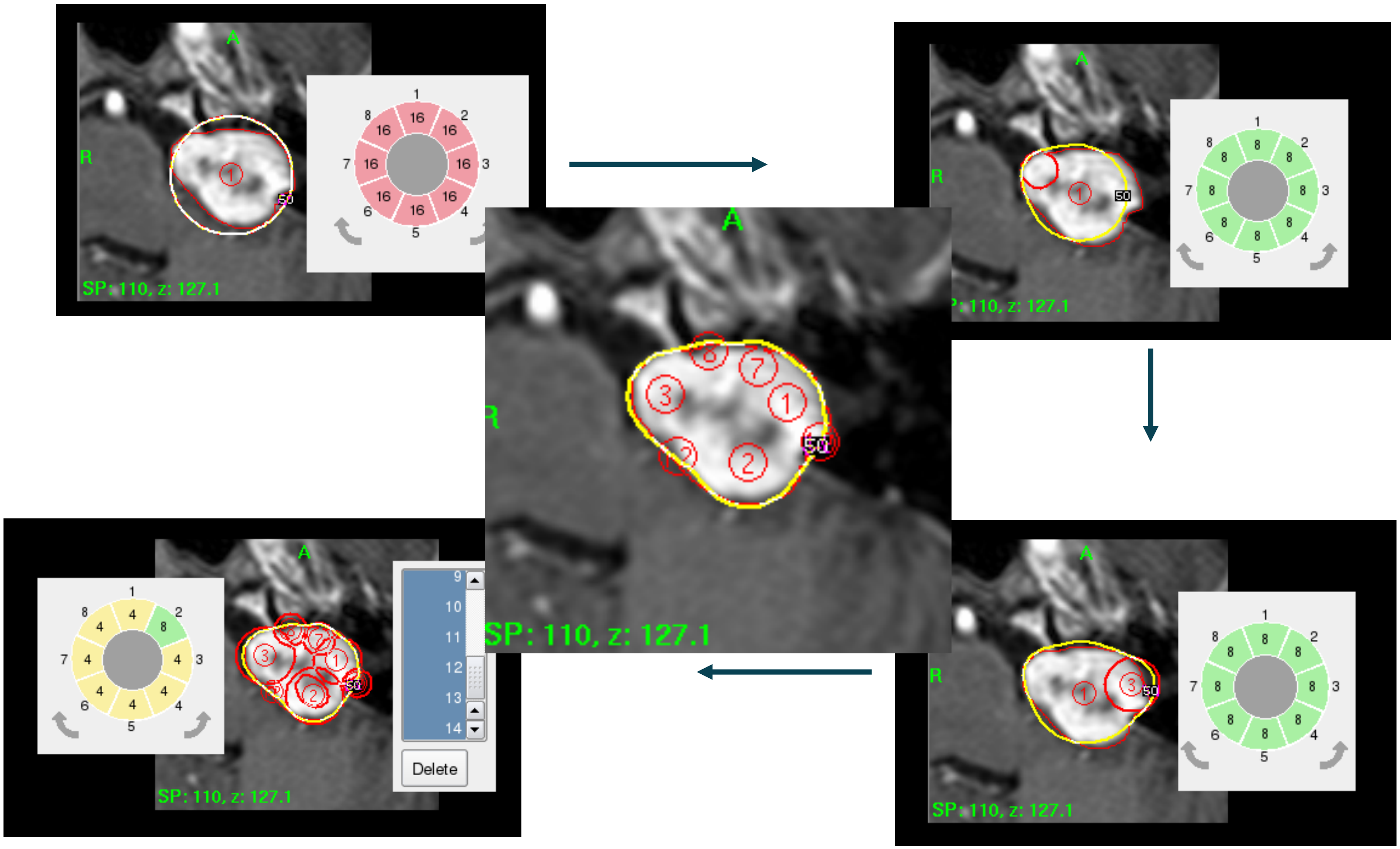


Tango treatment planning system
Buenos Aires,
plan circa 1989



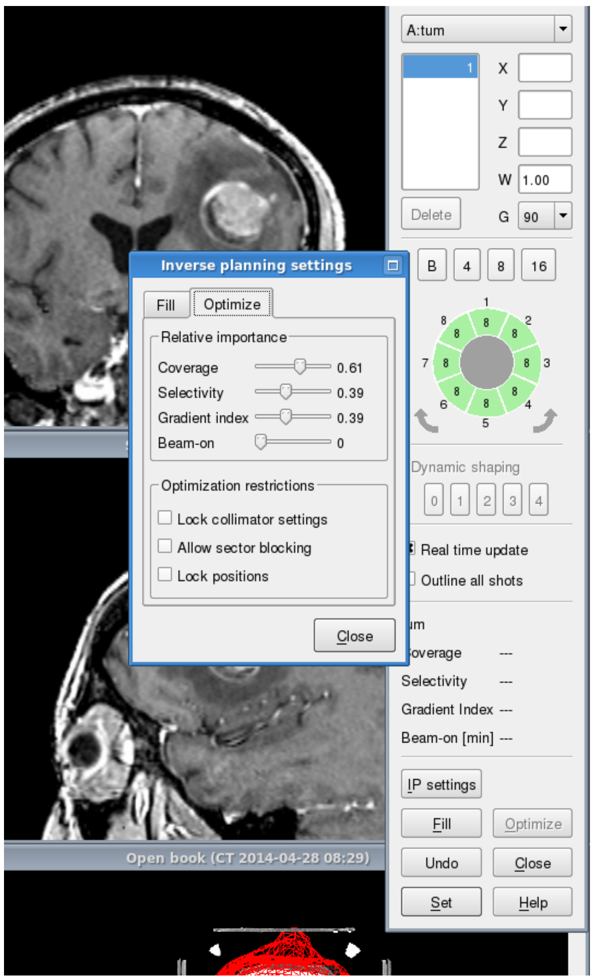
KULA treatment planning system
Elekta, AB, plan circa 1994

GammaPlan Treatment Planning



Doses are usually prescribed to 50% isodose line

Gamma Knife "Inverse" Planning



Automatically fills a volume with isocenters

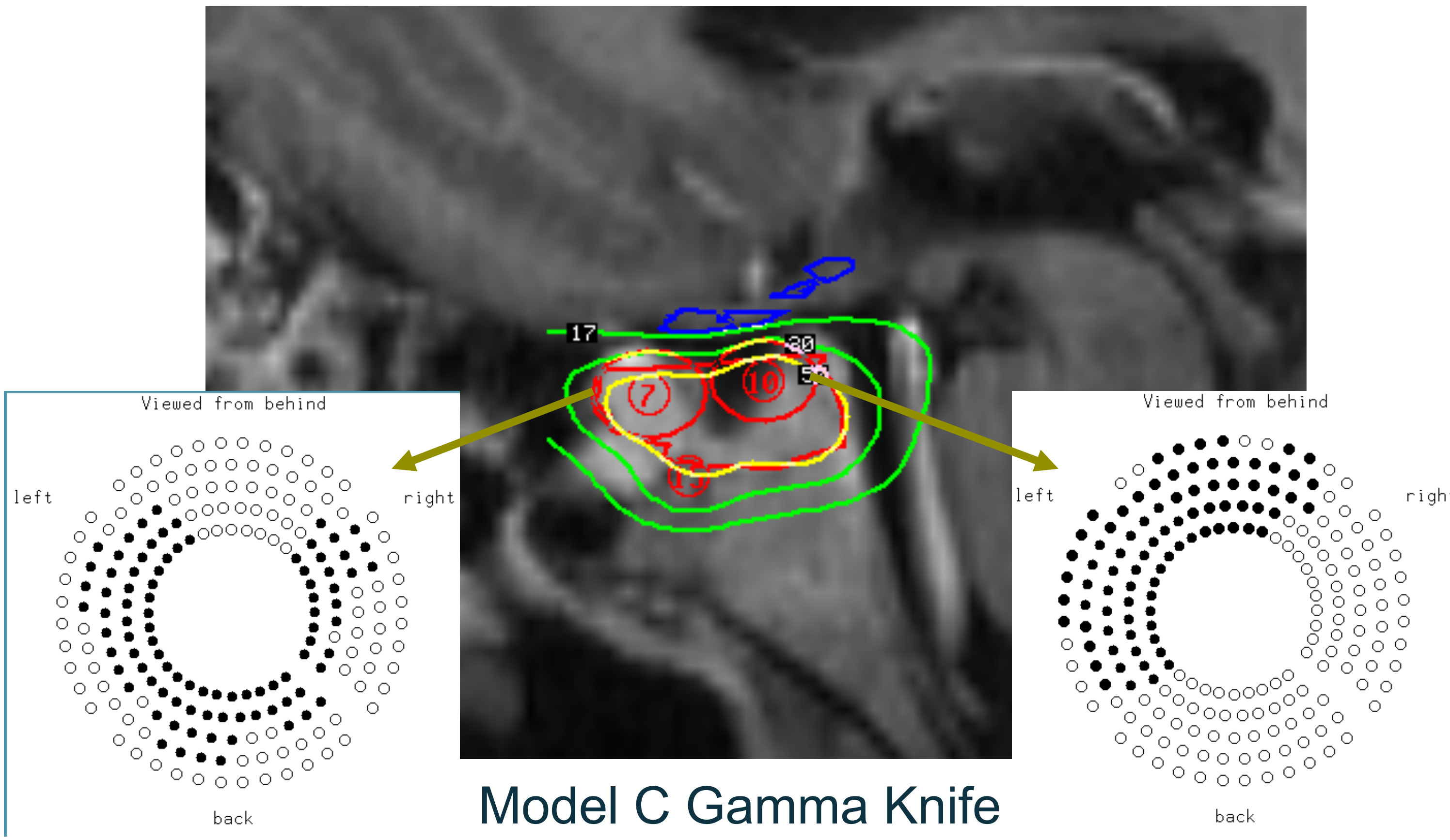
Optimizes against plan metrics such as coverage, conformity, dose falloff, and beam time

Dose NOT involve dose/volume constraints

Plan can be manually adjusted via typical forward-planning techniques

Shielding – Protecting Critical Structures

- Combinations of plug patterns are applied to one or more isocenters
- Example: Isocenter #7 has a different optimal plug pattern than isocenter #10

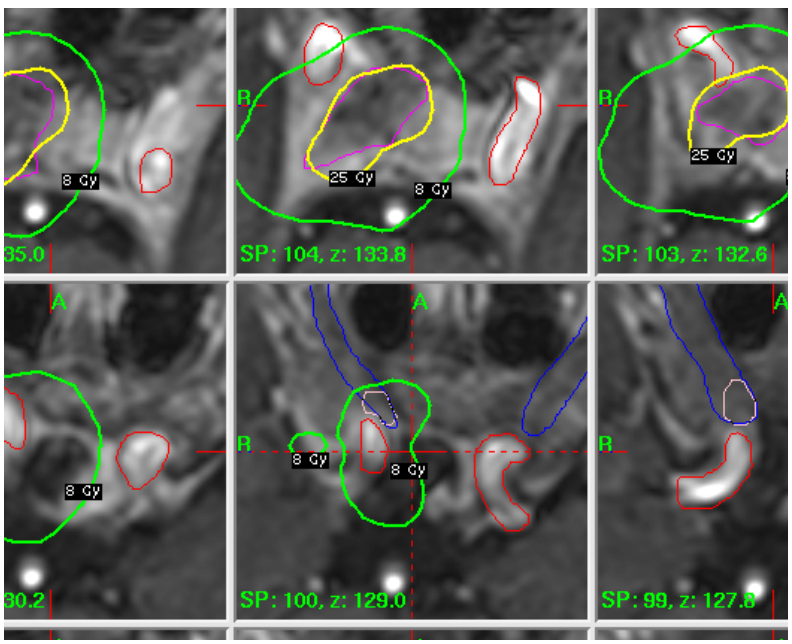


Model C Gamma Knife

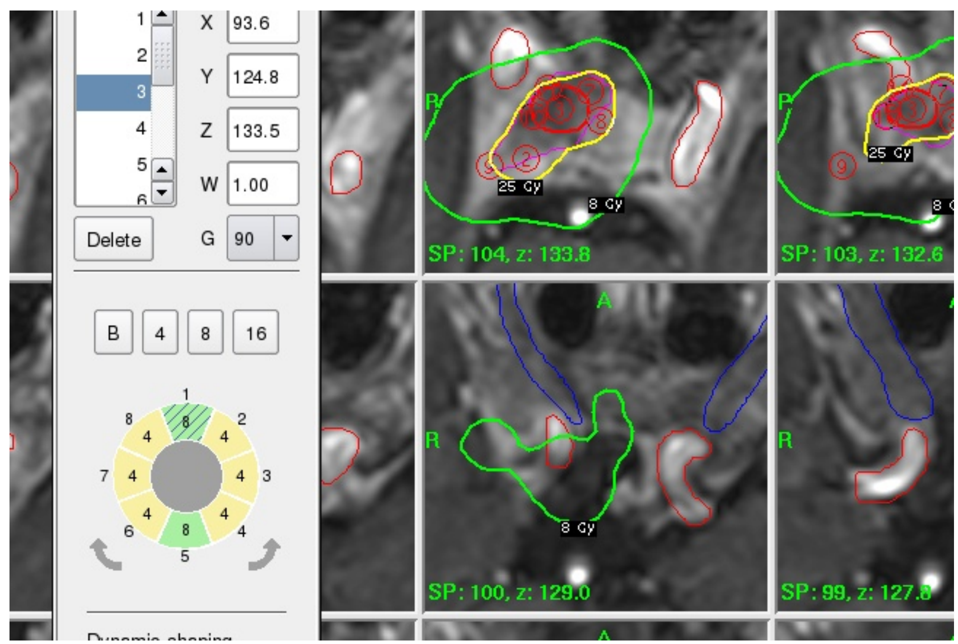
Shielding on the Perfexion

- Shielding is an automated process.
- Effortless to use multiple shielding patterns
- However, can only shield at the level of a sector
- No annular shielding patterns

Before



After



Evaluation – Conformity Index

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

↓ Overtreatment Ratio

↓ Undertreatment Ratio

CI = 1.0 represents perfect conformity

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

Evaluation – Gradient Index

$$GI = \frac{\text{Volume of isodose that is ½ of PI}}{\text{Volume of PI}}$$

Measures how quickly dose is dropping outside of target:

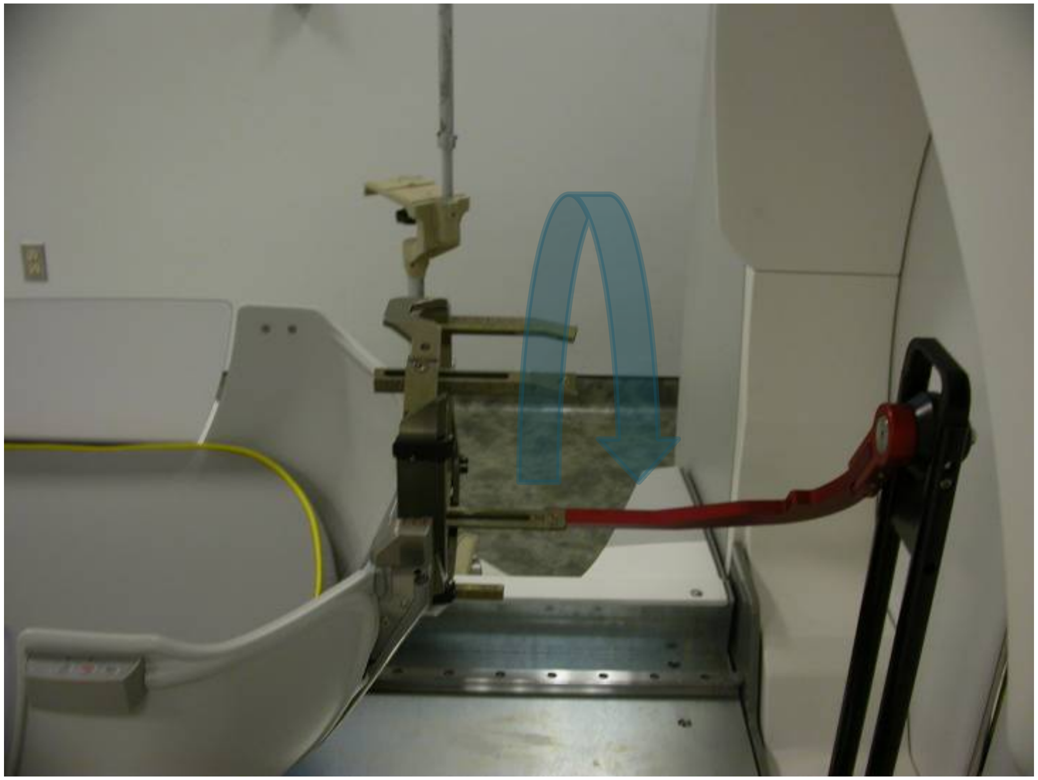
Example: If prescription isodose is at 60%, measure volume of 30% / 60%

GI < 3.0 is "good" dose falloff

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

Preventing Collisions

Add picture
Of space between
helmet



Written Directives

UVA Gamma Knife Clinic Treatment Planning Protocol *for* *PERFEXION™* *Leksell GammaPlan® 9.0.0*	
Patient:	*TEST, TLD*
Patient ID:	*222333222111*
Diagnosis:	*Trigeminal Neuralgia*
Plan ID:	*20100715-020*
Approval Date:	*2010-07-15*
Print Date:	*2010-07-27*
Operator:	*DJS*
Gamma Knife:	*MV004 (MV004)*

EXPORTED

Approved for Treatment

____

____

____

Gamma Knife Data

Calibration dose	3.196 Gy/min at 2007-09-12
Days since calibration at approval date	1037
Treatment dose rate (2010-07-15)	2.198 Gy/min
Effective output factors (4, 8, 16)	0.805 0.924 1
Ring 1 output factors (4, 8, 16)	0.799, 0.957, 0.961
Ring 2 output factors (4, 8, 16)	0.815, 0.946, 1.000
Ring 3 output factors (4, 8, 16)	0.792, 0.901, 0.986
Ring 4 output factors (4, 8, 16)	0.725, 0.808, 0.920
Ring 5 output factors (4, 8, 16)	0.663, 0.730, 0.851

Frame Configuration

Leksell® Coordinate Frame G

Treatment Data

Target	Shots	Prescription	100% [Gy]	Max [Gy]	X [mm]	Y [mm]	Z [mm]	Grid [mm]
A:test	1	6.0 Gy @ 99%	6.1	6.1	100.0	100.0	100.0	0.9
Total number of shots: 1 Treatment plan name: Plan1 Beam-on time: 2.7 min								

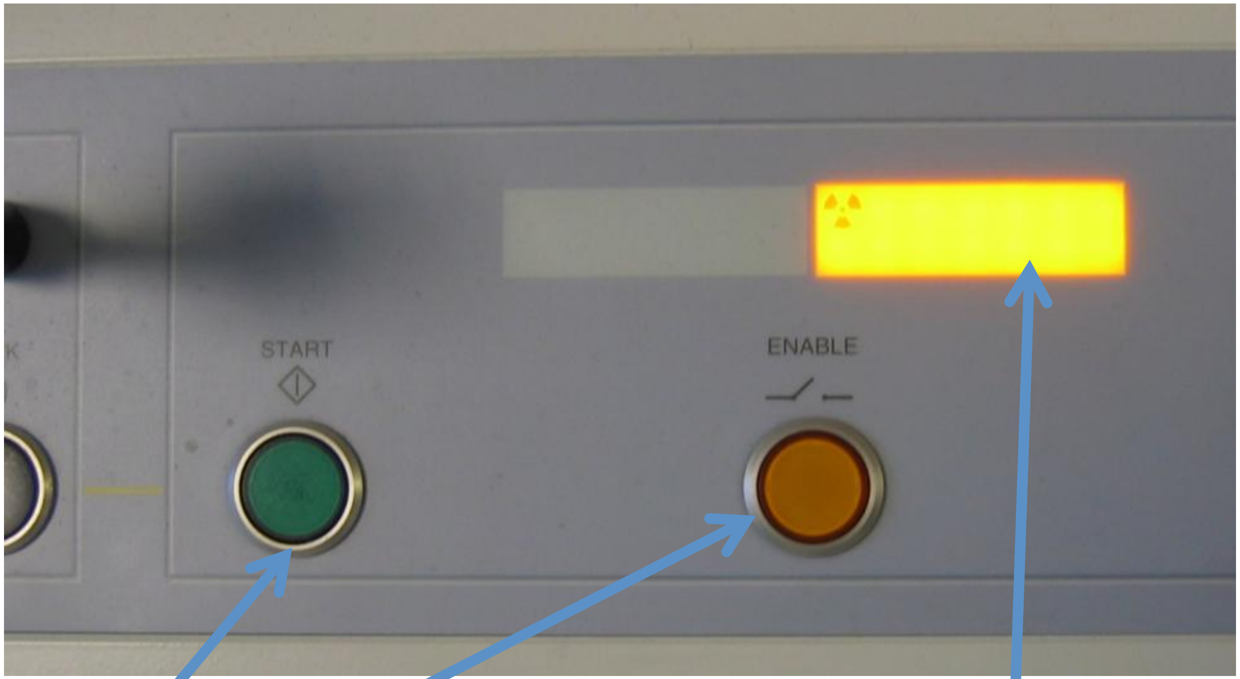
Run 1 (90 degrees)

Run-Step	Shot	X [mm]	Y [mm]	Z [mm]	Collimator [sectors 1-8]	Time [min]	Notes
1-1	A1	100.0	100.0	100.0	16 16 16 16 16 16 16 16	2.73	

TEST, 222333222111 Page 1 of 2 2010-07-27 12:18:06

- Treatment plan serves as a “written directive”
- Official record of the prescribed treatment
- Must be signed and dated by the AU, AMP, and neurosurgeon <u>before</u> treatment
- AU and AMP required to be present (in normal voice range) throughout the treatment!

(Finally) Push "Go"



2 "Go" Buttons

Radiation light indicator comes on (or flashes) in any state where radiation may exist in room

Monitor Treatment

- Check off shots as they happen
- Watch to make sure each shot ends at the correct time
- Watch patient to make sure they are not in distress
- Notice that the correct side of patient's head is at isocenter

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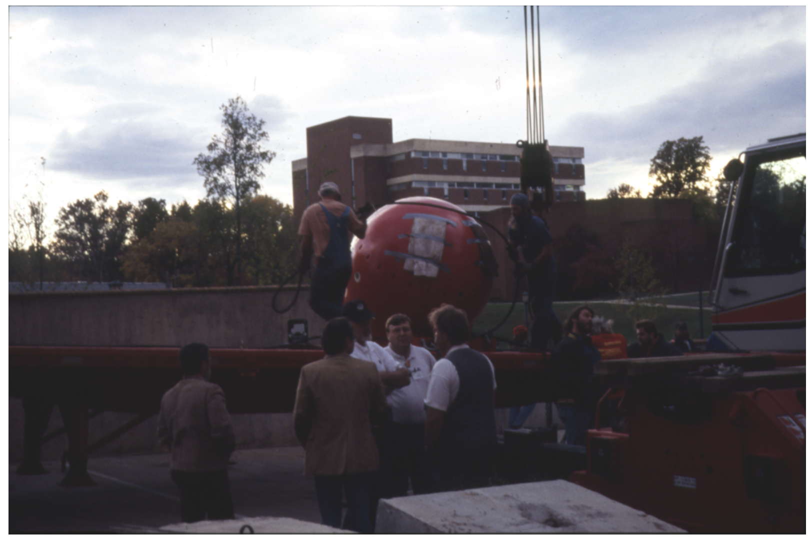
Loading / Reloading (the old way)

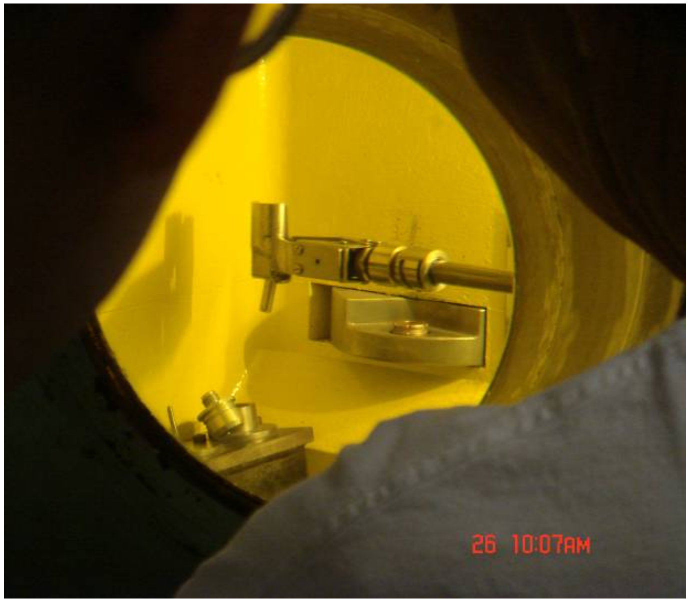


Model U unit had to be loaded somewhere remote using a crane.

Reloads required removing the unit from the building entirely!

The modern way is much less trouble….

- Loading performed in-room
- Loader weighs several tons
- Manipulator arms are used to assemble each source bushing



But…still requires detailed planning!

Still a 3-4 week process!

Acceptance	Commissioning
Contractual performance obligations (initial dose rate, etc.) Tests usually performed by vendor Signoff by receiving physicist and others	Determine the baseline characteristics of the unit (output, output factors, end-effects, etc.) Generate confidence in the safety of the unit Performed by receiving physicist (NOT vendor)

ELEKTA INSTRUMENT AB **Work Instruction**

Article No	Doc No	Revision	Page(pages)
1002420	1002420	07	23(51)

#	Action:	Expected Response:	Pass	Fail	Fault ID:
3.	Select 8 mm collimator size Diode Type Centre Note the result :	Service completed PPS precision radial within 150 microns X: 11 Y: −28 Z: 5 Rad: 30	☑	☐	
4.	Select 16 mm collimator size Diode Type Centre Note the result: Disconnect the cable to the centre diode	Service completed PPS precision radial within 150 microns X: 35 Y: −16 Z: −7 Rad: 39	☑	☐	
5.	Connect the cable for the long diode position. Make sure that the cable will be able to follow the movements of the PPS without risk of getting tangled. Select 4 mm collimator size Diode Type Long Note the result: Disconnect the cable to the long diode	Service completed PPS precision radial within 300 microns Each axis within 200 microns X: −25 Y: 21 Z: 51 Rad: 60	☑	☐	
6.	Connect the cable for the short diode position. Make sure that the cable will be able to follow the movements of the PPS without risk of getting tangled.		☑	☐	

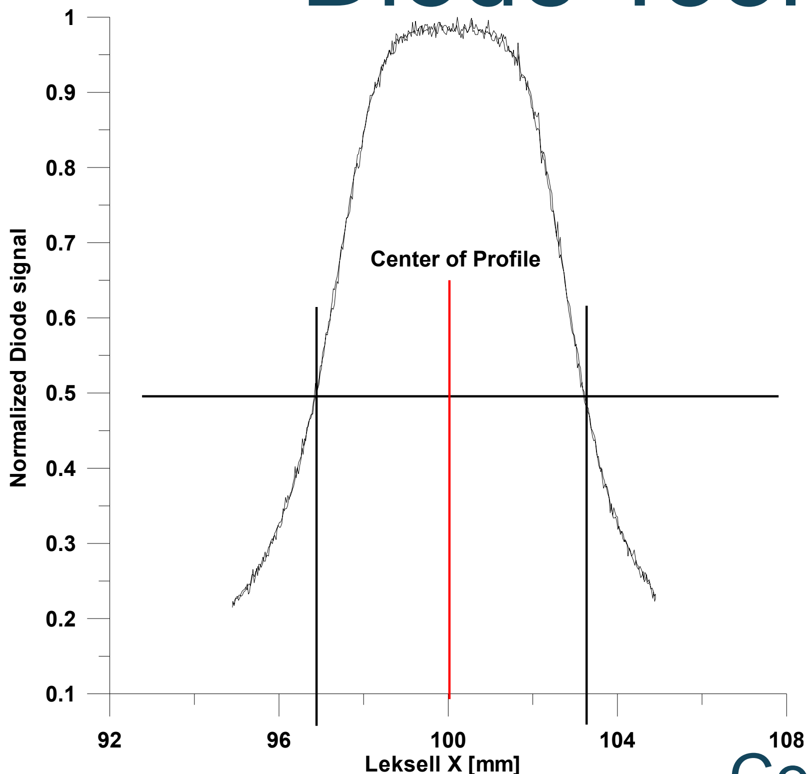
All of the checks on this page performed:	Initials: RO	Date: 4/10 −11

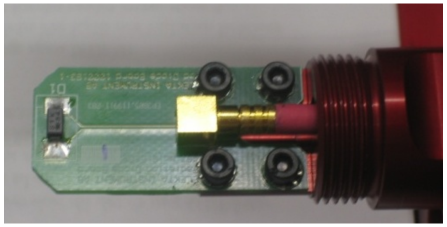
JS: NOT RELEASED, DATE: 08-06-2010, TIME: 12:33

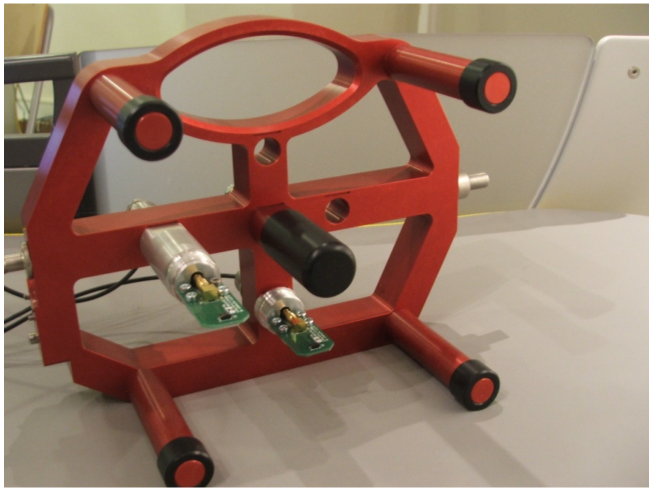
Acceptance

- Source inventory
- Dose rate verification
- Isocenter verification
- Positioning accuracy
- Communications / networking
- TPS configuration
- Field size verification
- Sector position measurements

Installation (master) Diode Tool



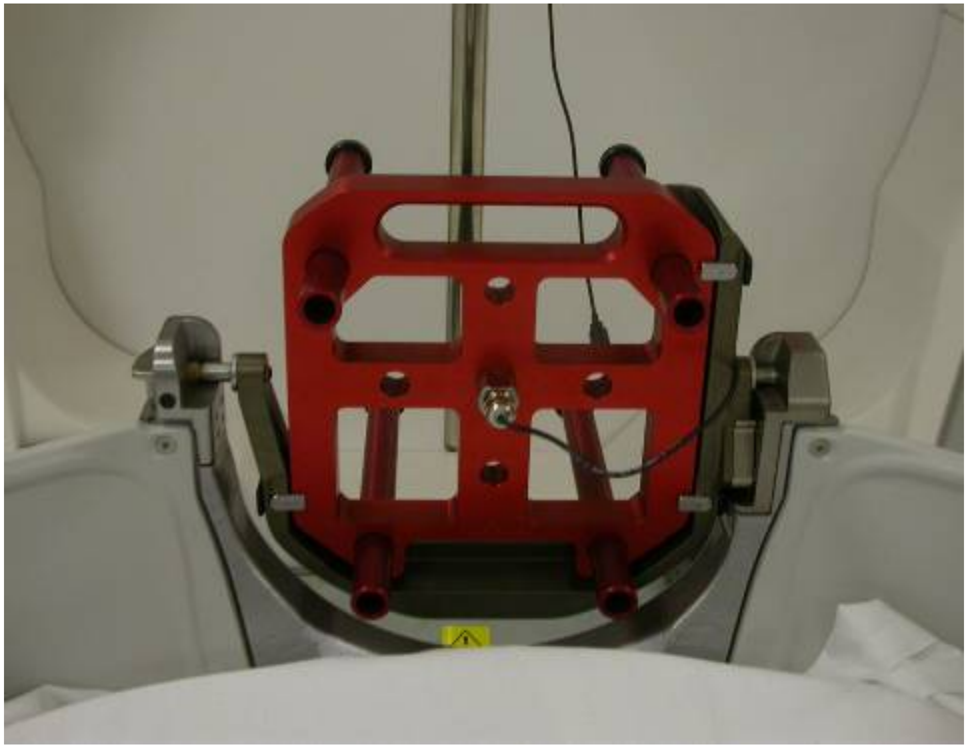




Calibrated at “reference” unit at Timone Hospital, Marseille

Center diode < 0.08 mm repeatability at installation

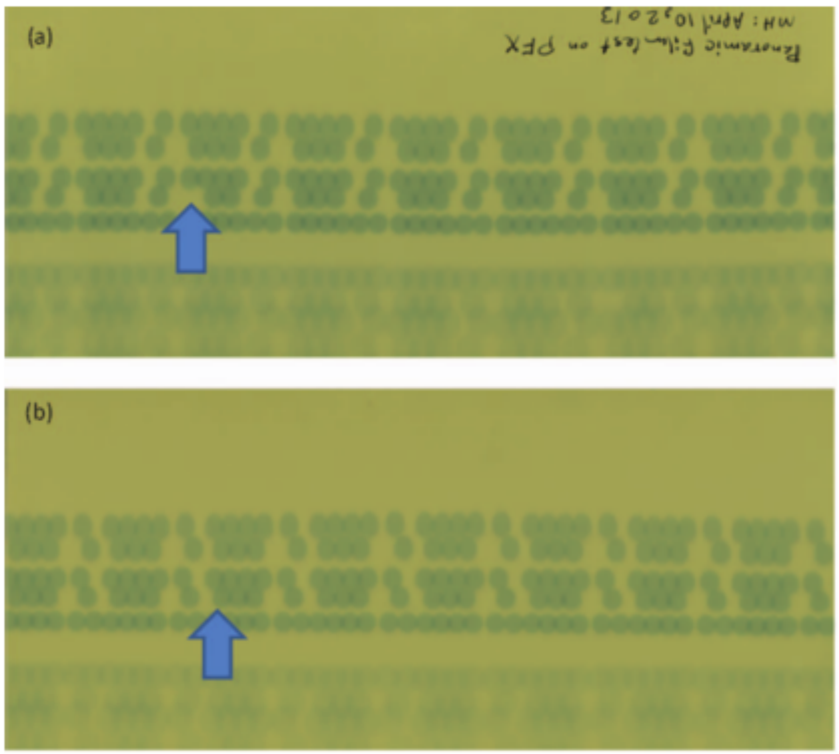
Site-specific diode tool



QA specification:
<=0.5 mm radial repeatability

Has a calibrated offset from “master” diode tool
Run at least 1 time per month by client site

Commissioning



Make sure you have all of your sources!
Also, don't forget staff training!

Y. Chao, et al., Med Phys 40(9), 2013

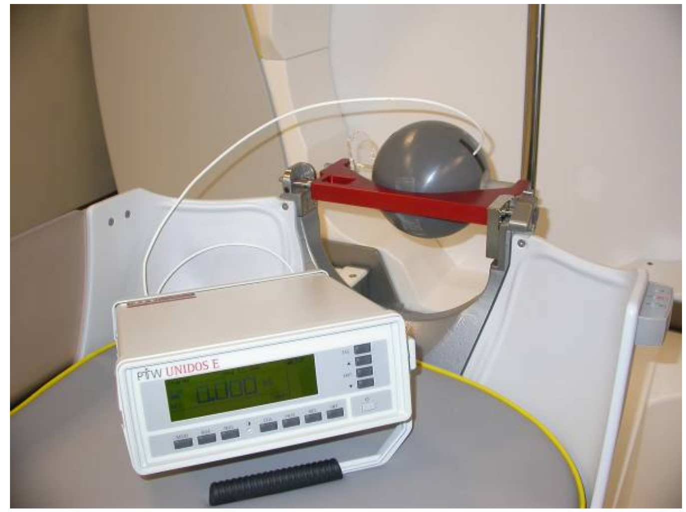
- Radiation surveys
- Dose rate verification / calibration
- Output factor validation
- Beam alignment precision
- Beam accuracy
- Mechanical checks
- TPS accuracy
- Interlock tests
- Sector position measurements
- Updated OP notes / documentation

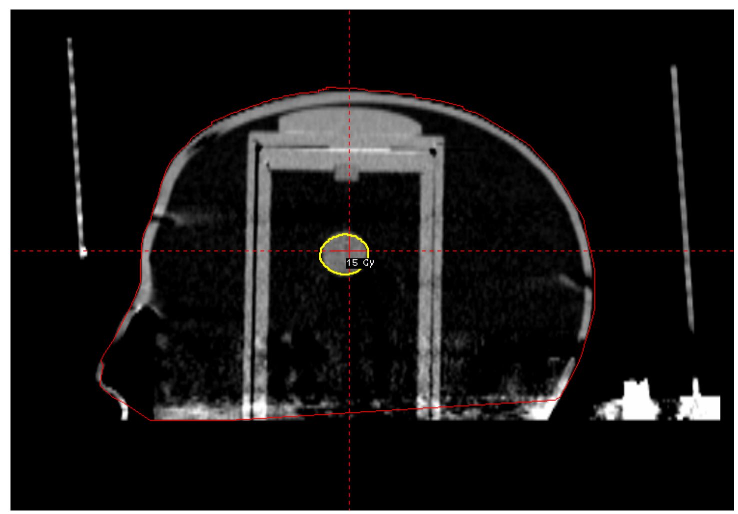
http://www.nrc.gov/materials/miau/med-use-toolkit/perfexion-guidance.pdf

Output dose rate

- Only time you don't know the Gamma Knife dose rate is at initial commissioning and reload
- Probably the most important measurement you take
- There is no single standard for GK output calibration (TG-21, TG-51, IAEA TRS398, etc.)
- Use multiple methods and compare
- Watch for report of TG 178

BE CAREFUL!!!!





Quality Assurance (Perfexion)

Daily	Monthly	(Semi) Annually
-Radiation monitors	-Output check	-Surveys
-Survey meters	-Timer check	-Wipe tests
-NRC postings	-Linearity check	-Film tests
-Alarms	-Diode checks	-Other mechanical checks
-Interlocks	-Power supply	-TPS checks
-Basic morning QA test	-Clearance check tool	

History of the Gamma Knife

Design and Physical Principles

Treatment Procedures

Acceptance/Commissioning/QA

Recent/Future Developments

New: Convolution algorithm

$$\text{Dose}(r) = \iiint \text{TERMA}(\rho \cdot r')\,\text{Kernel}(\rho \cdot (r - r'))\,d^3(r')$$

- Allows correction for tissue inhomogeneity
- Requires a calibrated CT scan

CIRS Model 062 electron density phantom
http://www.cirsinc.com/products?show=modality&id=24

Why consider convolution?

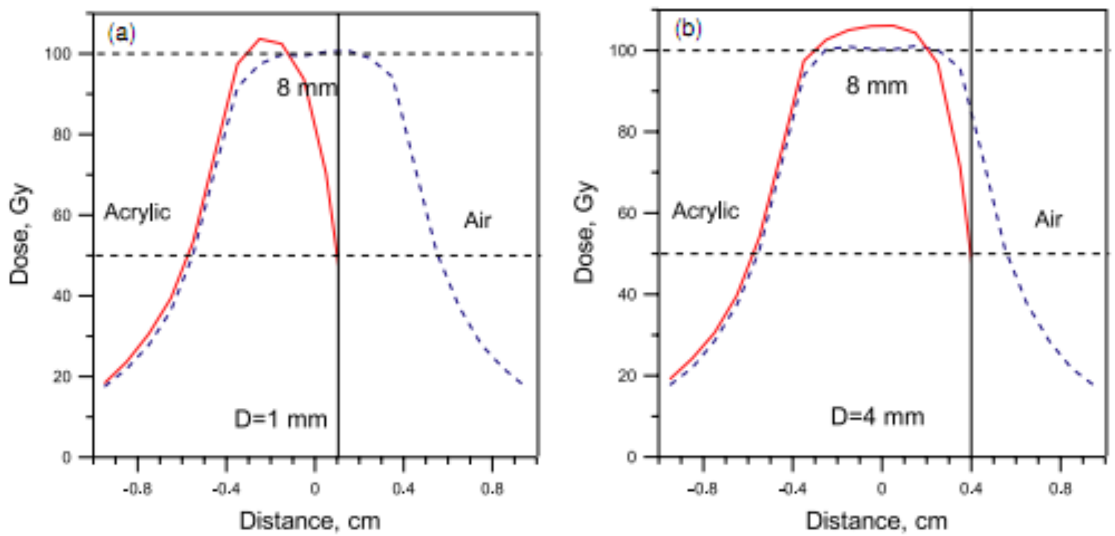


Figure 6. Dose profiles in the direction perpendicular to the air-tissue interface for homogeneous (dashed lines) and heterogeneous (solid lines) phantoms. A collimator of 8 mm is used for computations. The positions of the isocentre were selected at 1 mm (a) and 4 mm (b) from the interface. In the case 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

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.

Fractionated stereotactic radiotherapy with the Leksell Gamma Knife: feasibility study.

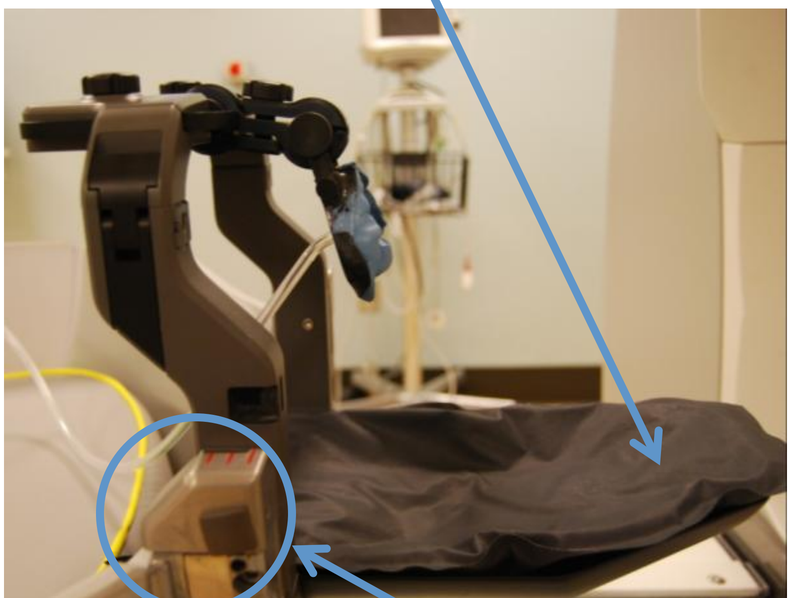
G. Simonová, et. al., Radiother Oncol, 37(2), 1995.

- 48 patients in series
- Frames kept on 2-6 days
- 1 fraction / day

UVA Gamma Knife (patient consented to photo use)

Extend frame system

Vac-loc headrest



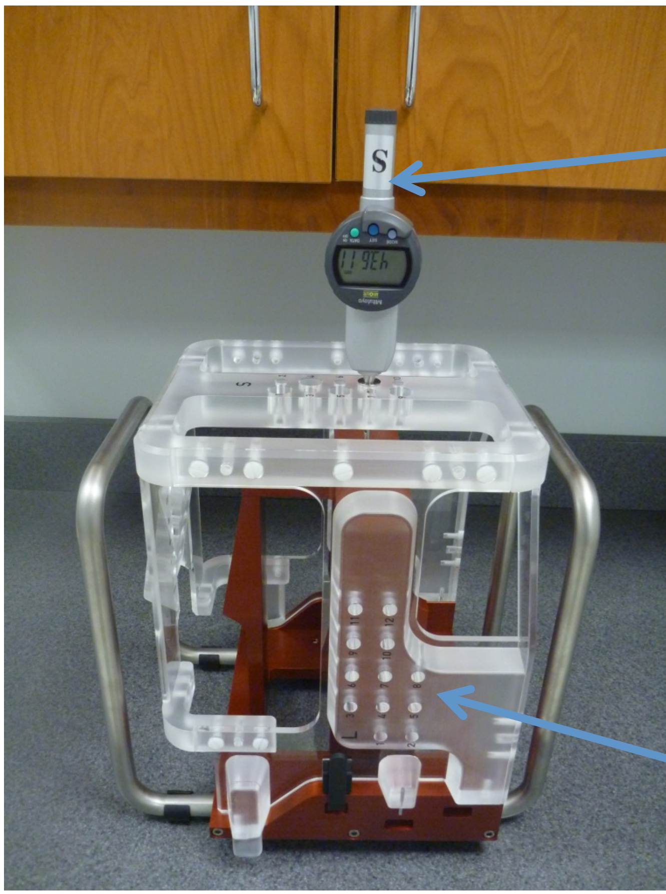
Interface to bed/positioning system

Patient-specific frame

Vacuum tube (to pump)

Mouthpiece

Reposition Check Tool (RCT)

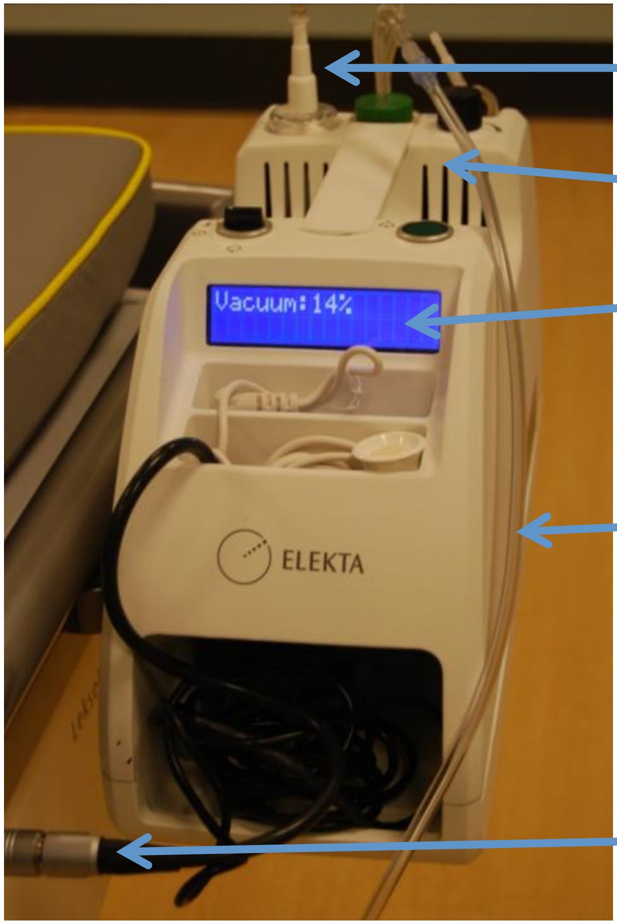


C150XB

- Mitutoyo Corporation
- Resolution: 0.001 mm
- Accuracy: < 0.006 mm
- Repeatability: < 0.002 mm
- We found 0.006-0.06 mm

Reposition check tool (RCT)

Patient Control Unit (PCU)

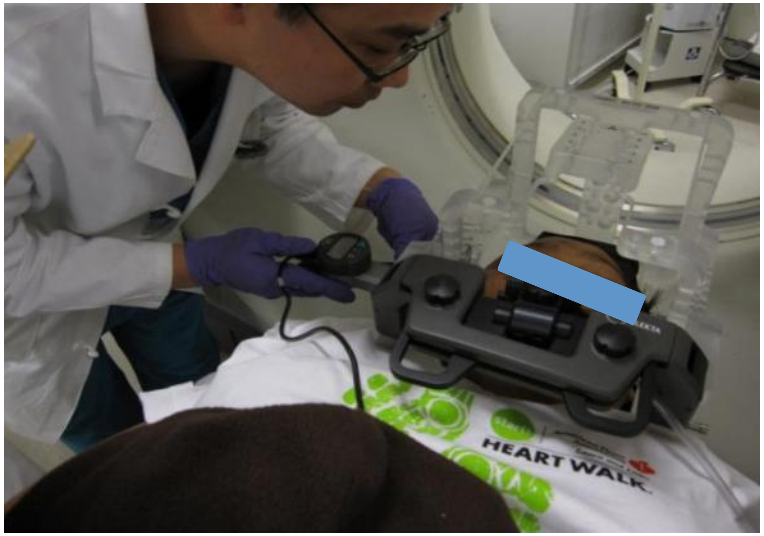


Saliva guard and bacterial filter

Display and controls

Vacuum tube (from mouthpiece)

Interface to Gamma Knife



Reference measurements taken at time of CT imaging

Patient position measured at GK before each fraction. Patient repositioned to match reference measurements.

Gamma Knife Perfexion *Plus*

- CBCT image guidance
- Optical motion tracking and gating
- Compatible with G-frame, Extend Frame, or thermoplastic mask
- Expected release in 2015

Summary | Conclusions

The design of the Gamma Knife was in direct response to specific requirements of intracranial radiosurgery.

After almost 50 years of development, it remains an elegant solution to the problem.

Future developments will further decrease treatment uncertainty and add treatment flexibility.

References

Historical

Leksell, L. 1951. The stereotactic method and radiosurgery of the brain. *Acta Chir. Scand*. 102:316–9.

Stereotactic Radiosurgery and Stereotactic Body Radiation Therapy, S. Benedict, D, Schlesinger, S. Goetsch, B. Kavanagh, editors, CRC Press, Jul 2014.

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Technical

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NRC Leksell Gamma Knife Perfexion – Licensing Guidance, http://www.nrc.gov/materials/miau/med-use-toolkit/perfexion-guidance.pdf

M. Ruschin et. al., “Performance of a novel repositioning head frame for gamma knife perfexion and image-guided linac-based intracranial stereotactic radiotherapy”, IJROBP 78(1), 2010.

C. Lindquist, I. Paddick, “The Leksell Gamma Knife Perfexion and comparisons with its predecessors”, Neurosurgery, 61(3 Suppl), 2007.

Acknowledgements

Steve Goetsch, Ph.D., FAAPM – Provided many historical figures

Thomas Jefferson's Rotunda at the University of Virginia