Overview of Gamma Knife Radiosurgery

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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

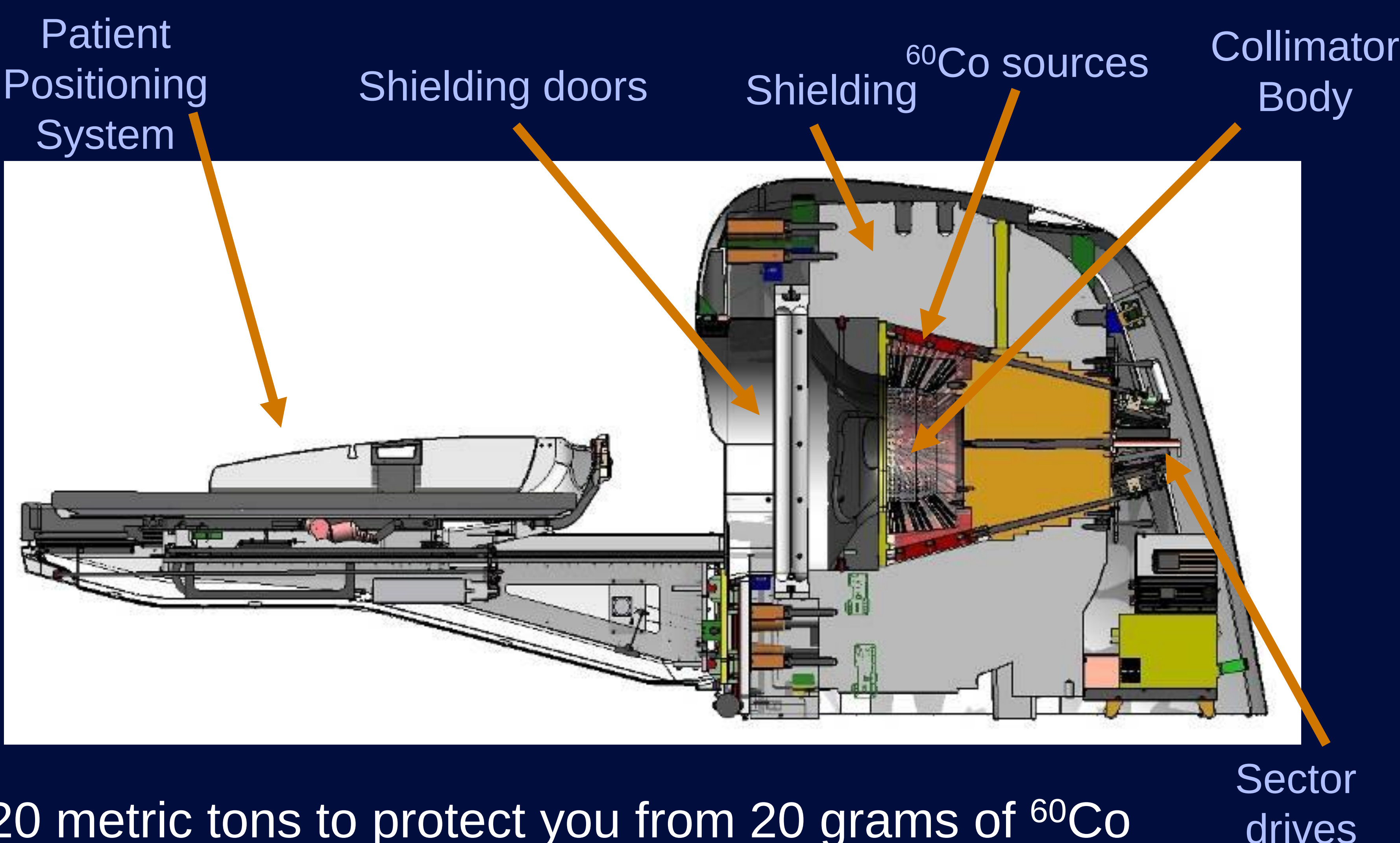
Gamma Knife Model C

Shielding doors

Collimator helmet

Treatment bed

Gamma Knife Perfexion



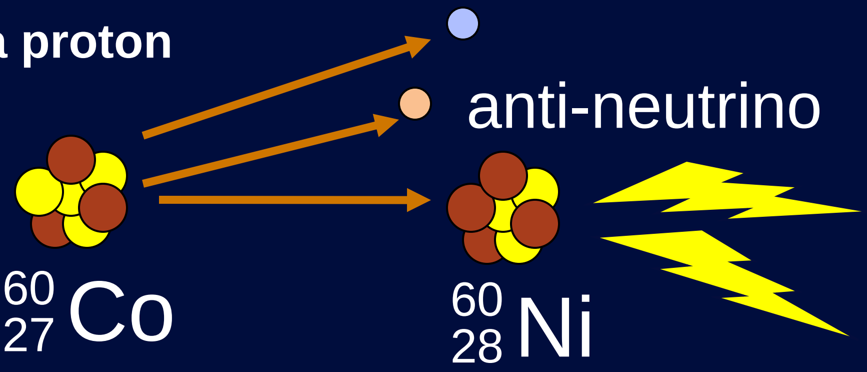
~20 metric tons to protect you from 20 grams of ^{60}Co

^{60}Co-Powered

β- decay: a neutron converts into a proton

e- (β particle)

$T_{1/2}$ = 5.26 years



γ1 = ***1.17 MeV***

γ2 = ***1.33 MeV***

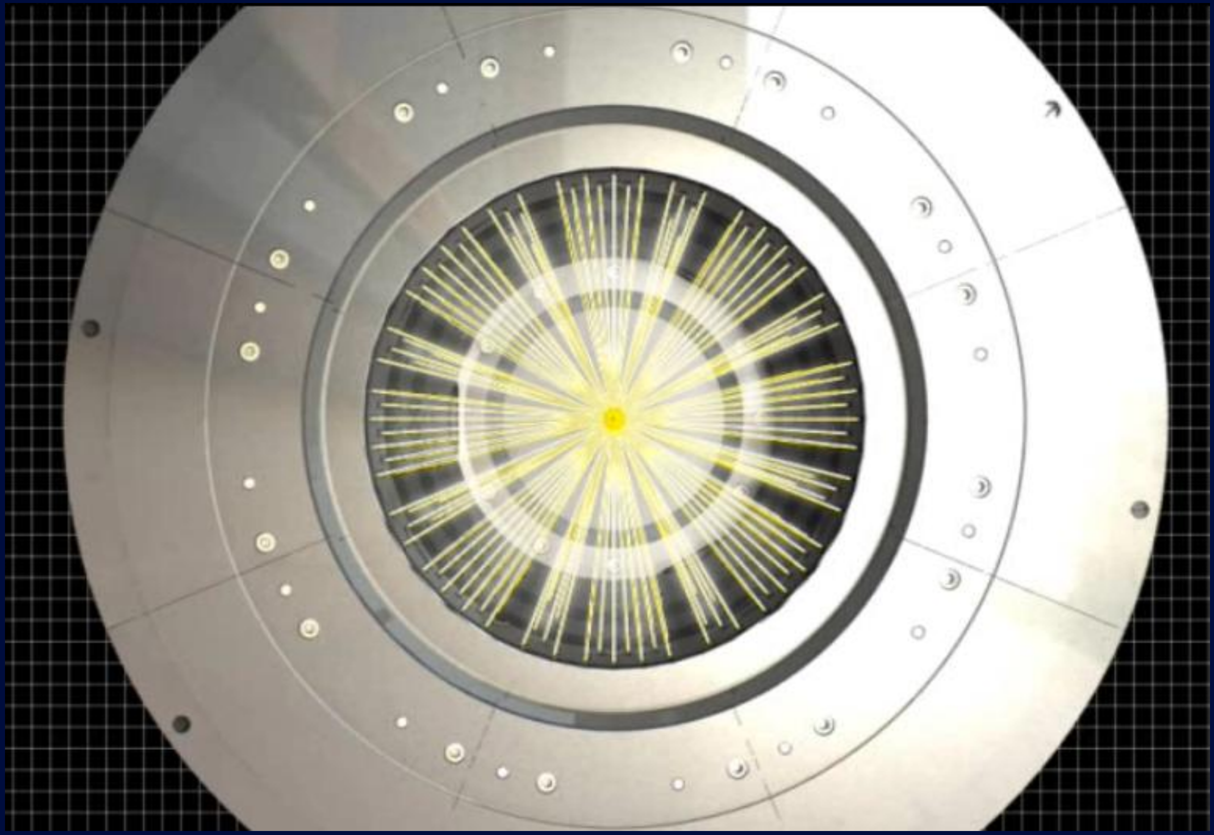
^{60}Co decay is a very stable photon source

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

Superposition of Beams



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

Stereotactic Targeting

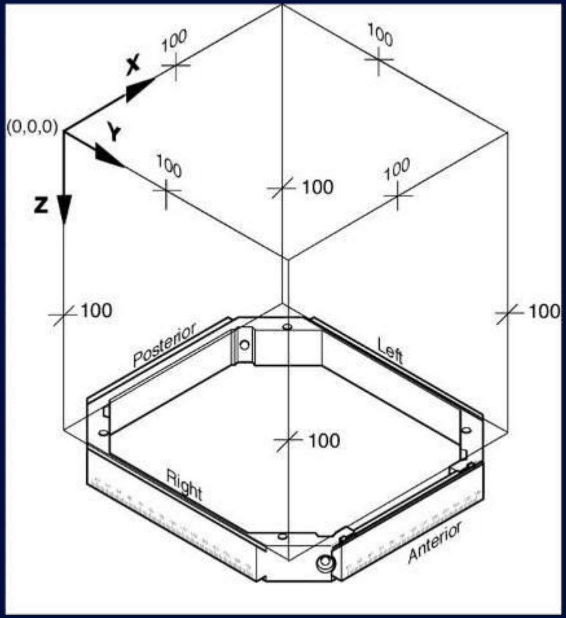


Image courtesy of Elekta

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)

Model C Collimator Characteristics

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

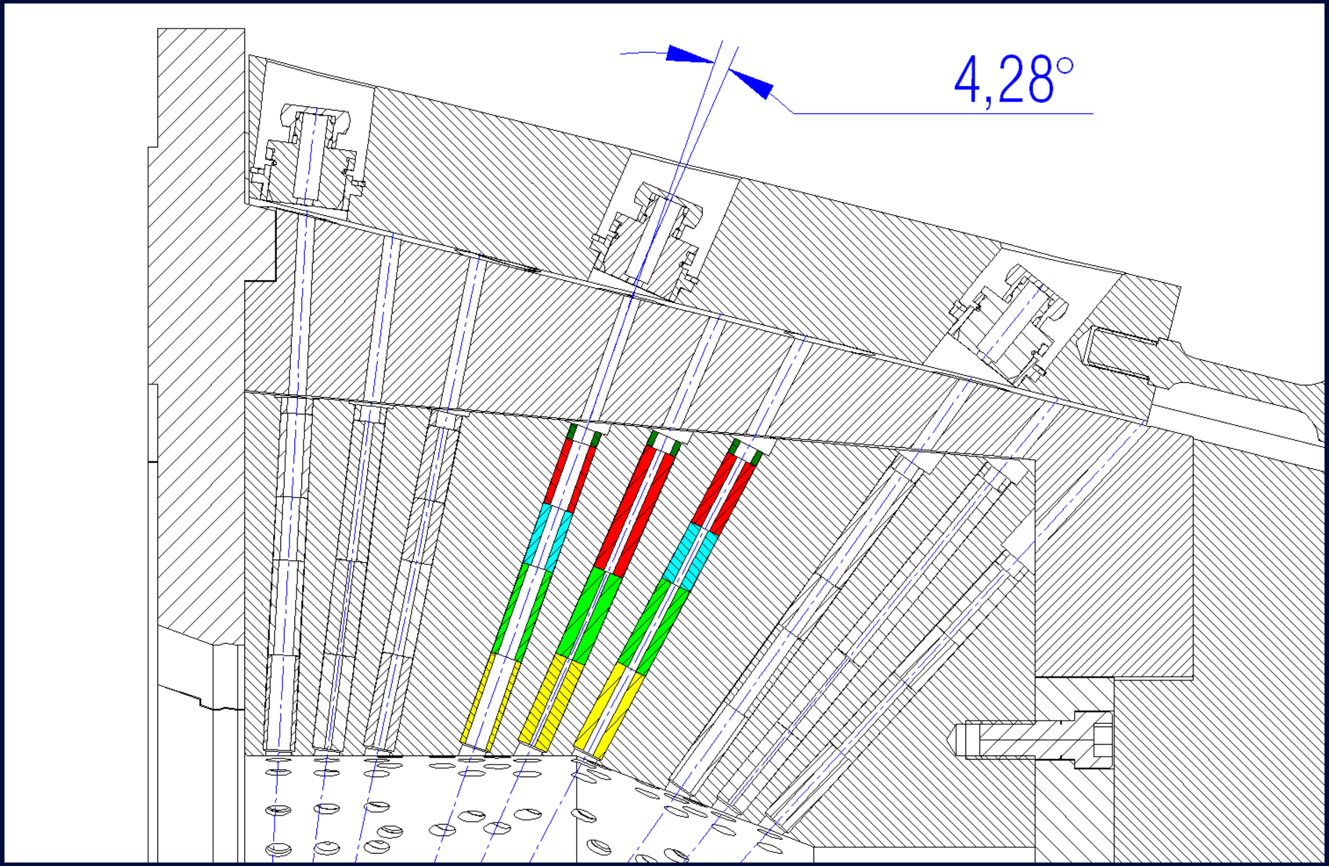
Perfexion collimator system

Beam channels are not all the same source to focus distance

Sources are angled relative to the collimators – 2D profiles

4mm / 8mm / 16mm and blocked collimator positions

Also a home position when not in use

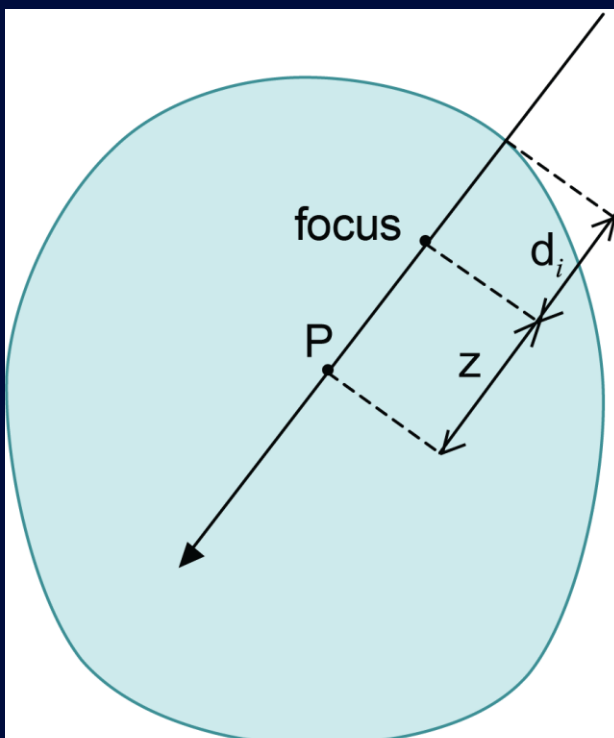


15 base beam configurations

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

TMR10 – The basic dose model

$$\dot{D}_i(P) = \dot{D}_{calibration,16} \times \frac{1}{192} \times of_i \times e^{-\mu_0 (d_i - R_{calibration})} \times \frac{e^{-\mu_1 z}}{\left(1+\frac{z}{R_{vsf,i}}\right)^2}$$



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

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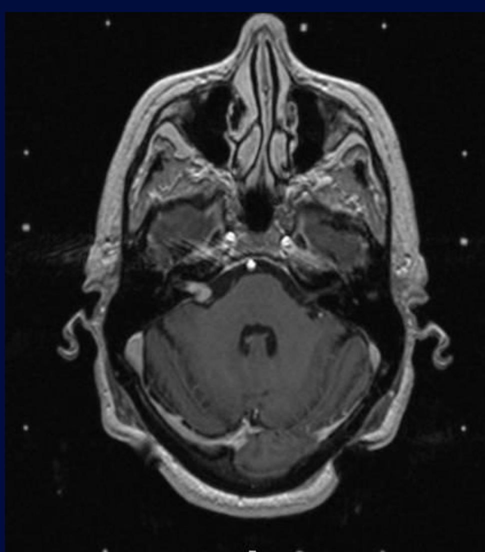
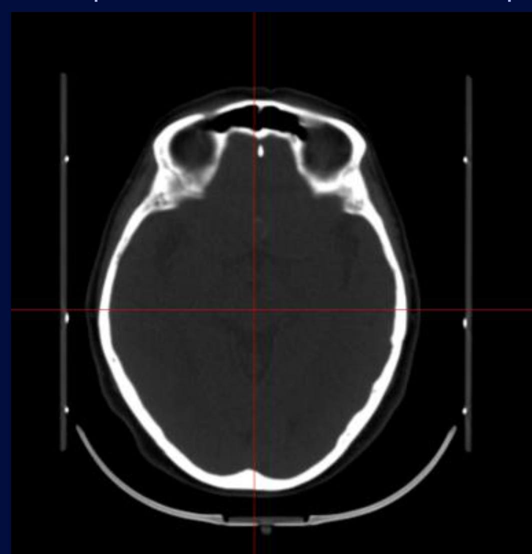
Treatment Planning Imaging

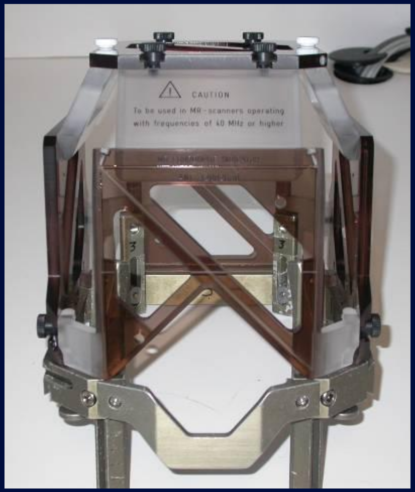
Typical imaging protocols:

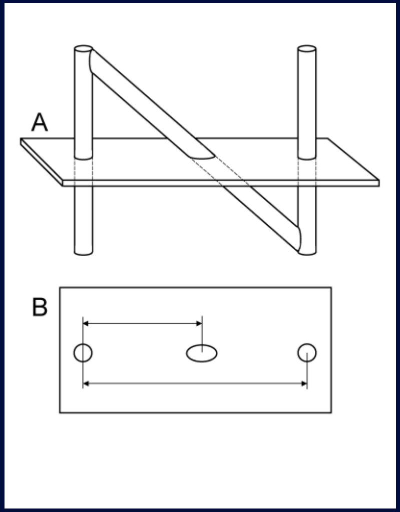
Solid tumors	AVMs	Skull-base and pituitary
T1-weighted MR + contrast	Biplane DSA T1-weighted MR + contrast MRA	T1-weighed MR + contrast T2 CISS or SPACE T1-weighted + fat saturation

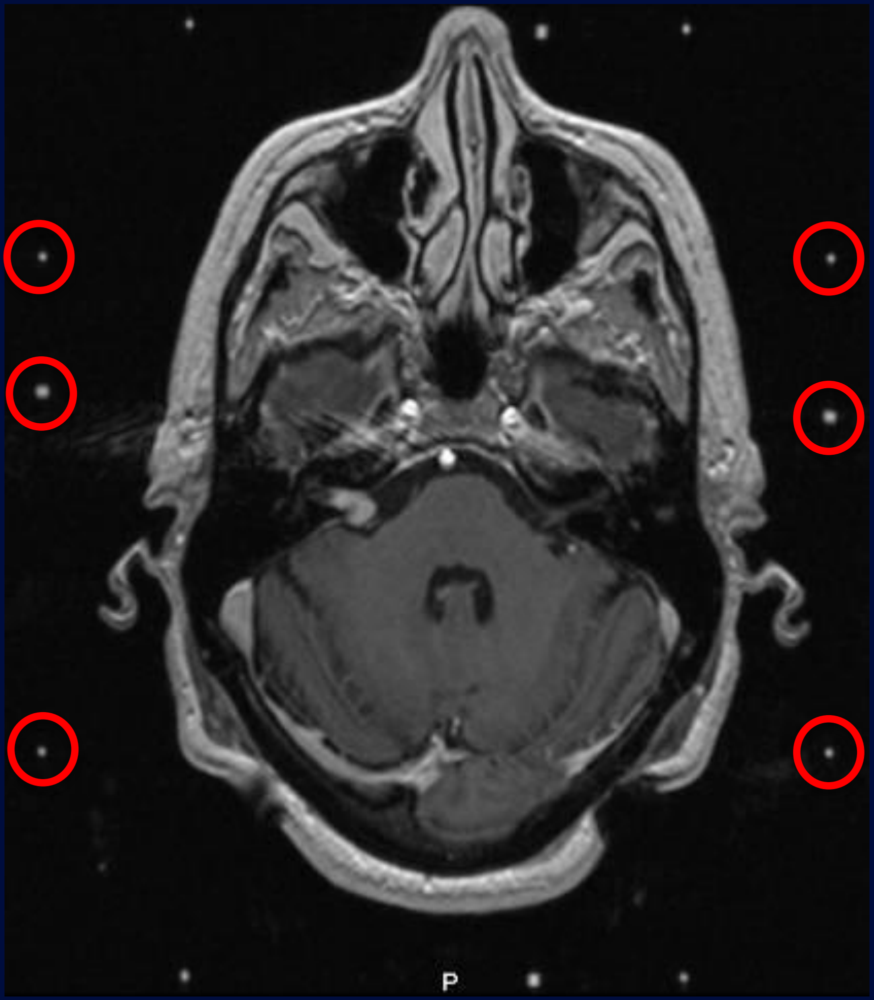




Stereotactic Fiducials

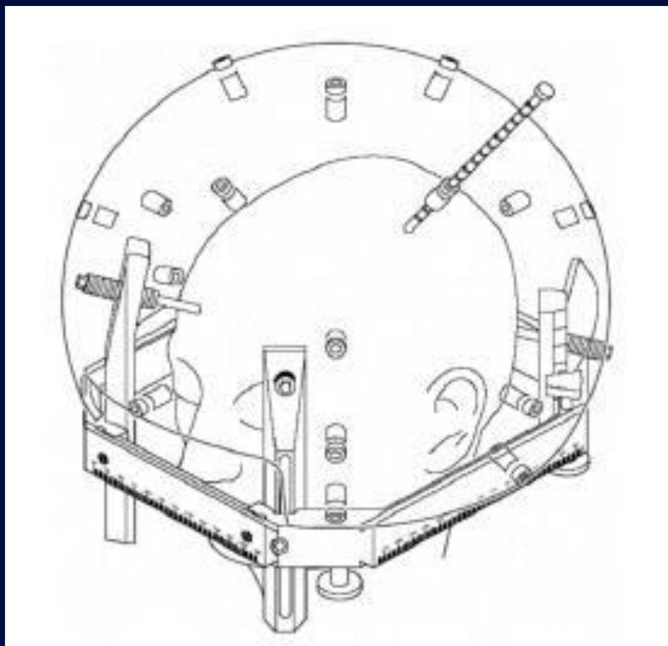


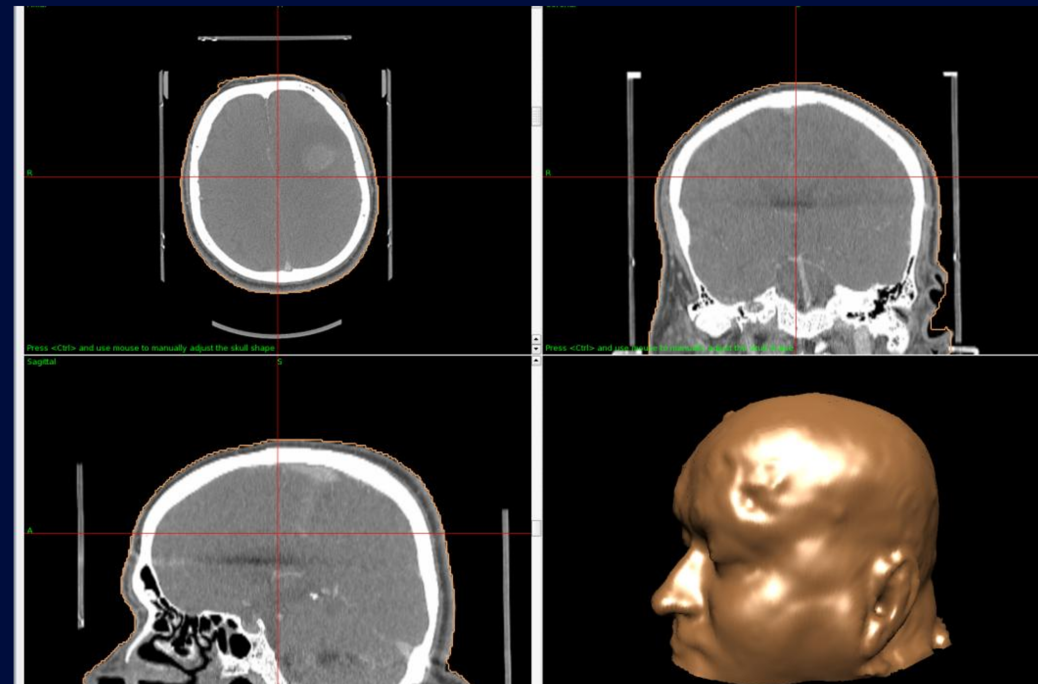




Brown R A, et al. (2013) The Origin of the N-Localizer for Stereotactic Neurosurgery. Cureus 5(9)

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

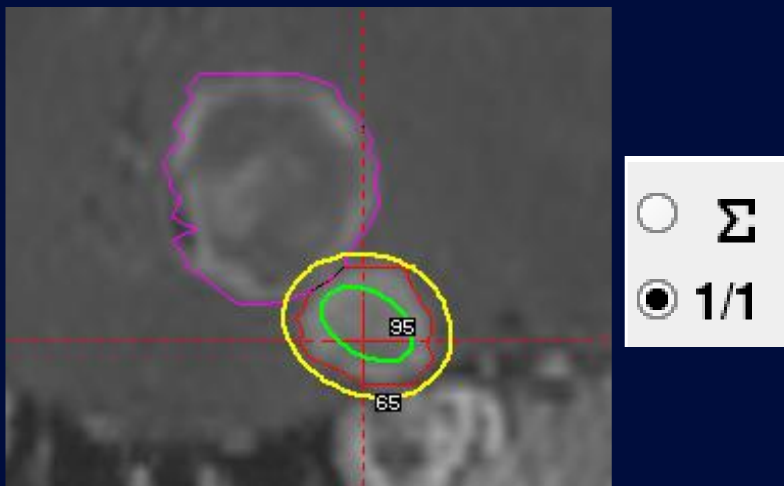
Target/Dose Matrix Definition

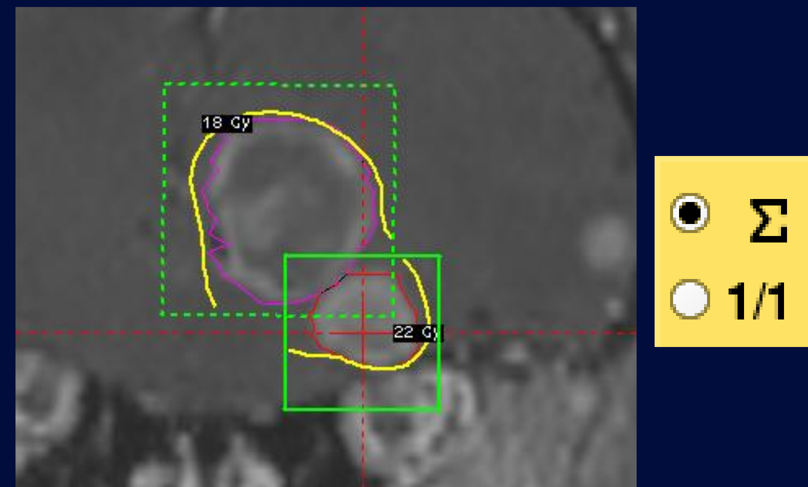
Targets

Target	Shots	Prescription dose	Ref point dose	Max dose
C:lpostf1	1	22.0 Gy at 60 % (36.7 Gy at 100%)	36.7 Gy	36.7 Gy
D:lmedialpostf	1	24.0 Gy at 80 % (30.0 Gy at 100%)	30.0 Gy	30.1 Gy
E:rfrontalps1	1	20.0 Gy at 50 % (40.0 Gy at 100%)	40.0 Gy	40.0 Gy

New | Edit | Delete | Set Dose | View | Close | Help

Single Target vs All Target Modes





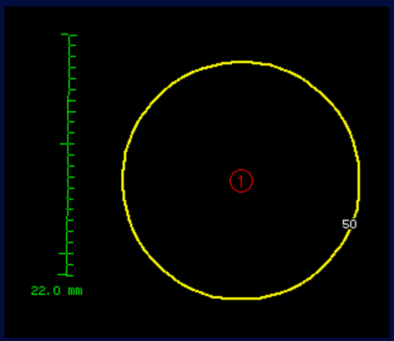
Single target mode: only shots from current target contribute to isodose lines shown. Dose in % of maximum dose in target.

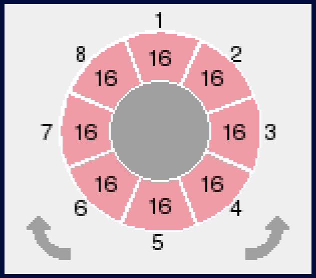
All target mode: All shots in plan from all targets contribute to isodose lines shown. Dose in units of Gy.

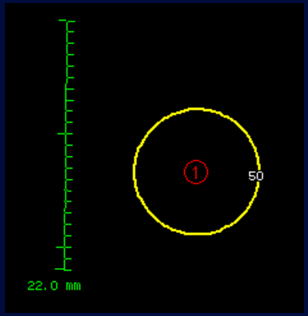
For targets that are close together, there can be significant differences!

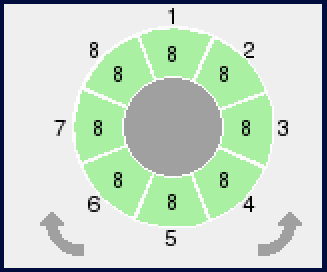
Model Perfexion: Basic Isocenter Parameters

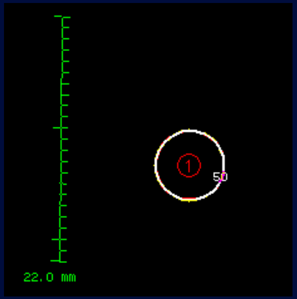
Base configurations

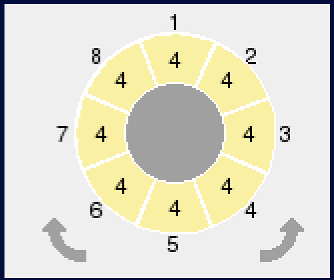




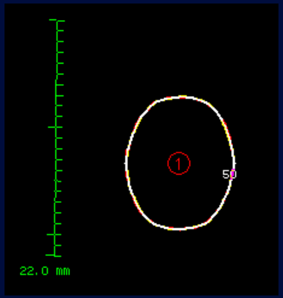


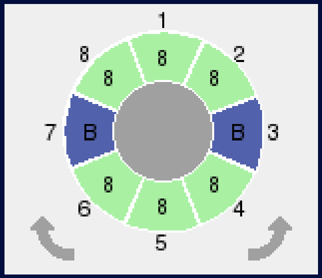


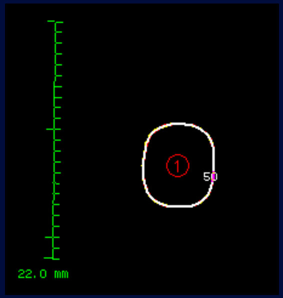


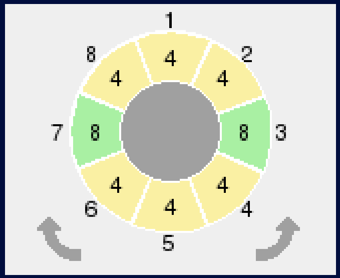


Composites and blocking

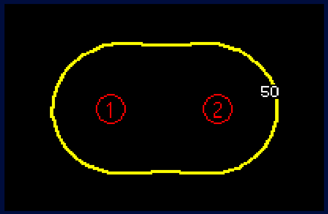








Weighting



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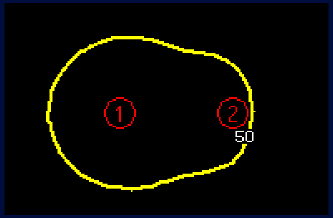
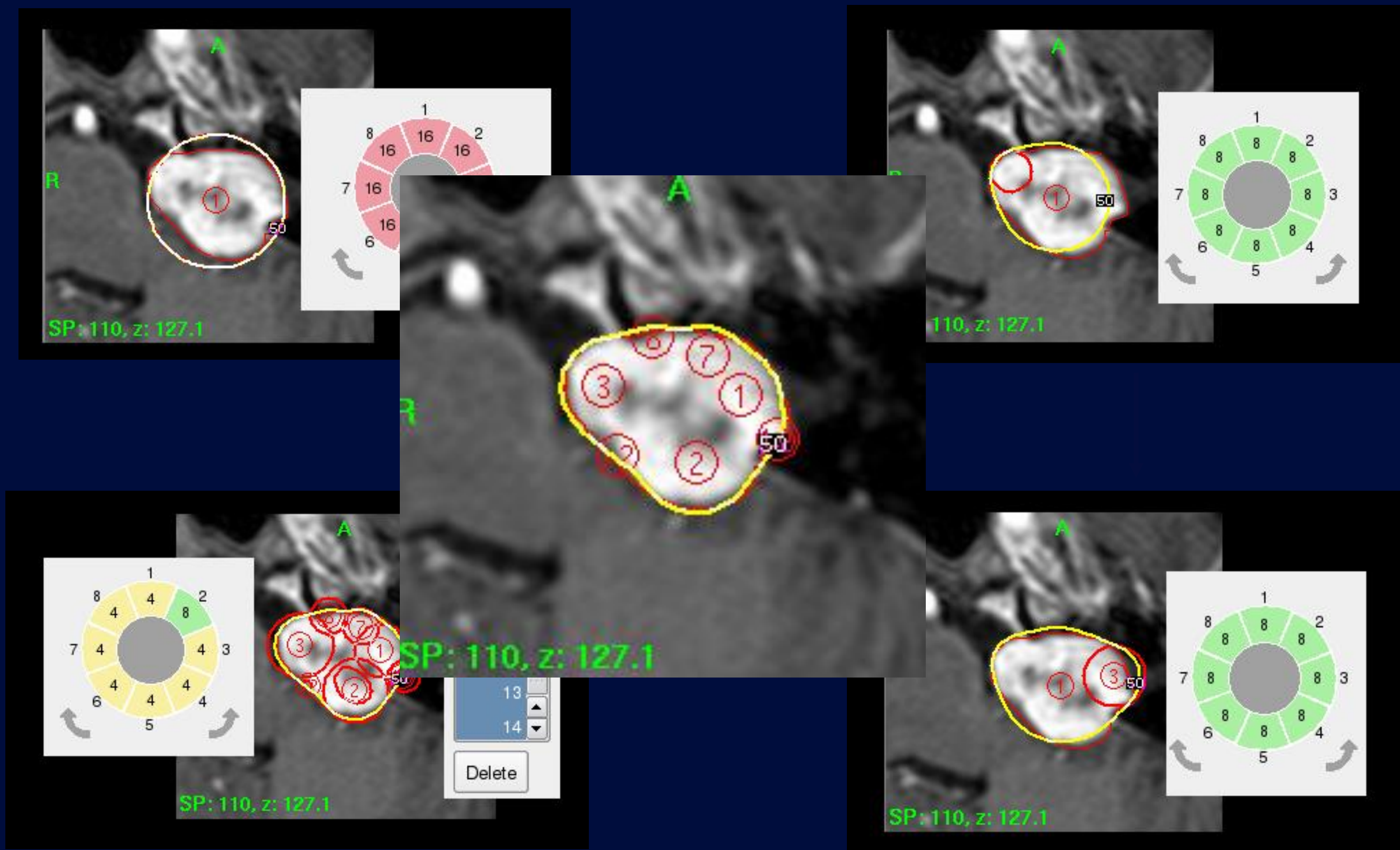


1.0 / 0.5

Defining a Dose Distribution



Doses are usually prescribed to 50% isodose line

Gamma Angle

90°

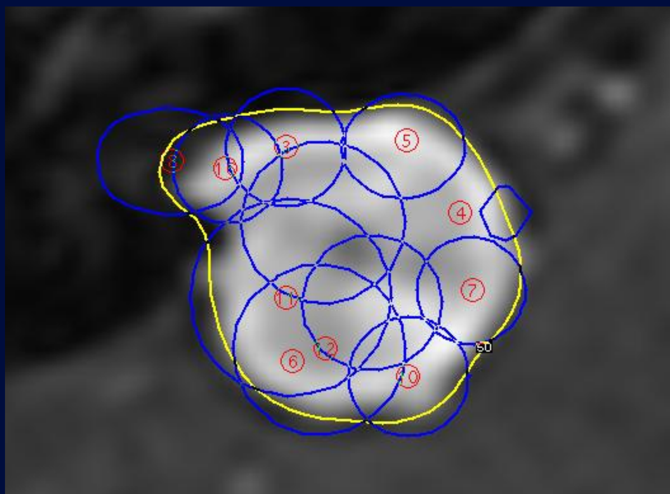
70°

Gamma angle rotates head around x-axis.

Used to avoid collisions

Sometimes to lower dose to critical structures

A plan boils down to this….



Run 1 (90 degrees)

Run-Step	Shot	X [mm]	Y [mm]	Z [mm]	Collimator [sectors 1-8]								Time [min]	Notes
1-1	A13	74.8	75.7	114.4	8	8	8	8	8	8	8	8	2.59	
1-2	A4	76.0	80.7	117.3	4	4	4	4	4	4	4	4	2.85	
1-3	A7	76.9	76.7	121.3	4	4	4	4	4	4	4	4	2.85	
1-4	A9	77.7	80.7	123.8	4	8	8	8	4	B	B	B	4.25	
1-5	A5	73.8	84.5	121.5	B	B	4	4	4	4	4	B	6.66	
1-6	A14	69.9	80.5	123.9	8	8	8	8	8	8	8	8	2.59	
1-7	A3	67.6	84.4	121.5	4	4	4	4	4	4	4	4	1.97	
1-8	A8	61.7	83.9	121.4	B	4	4	4	B	B	B	B	9.18	
1-9	A16	64.3	83.4	120.4	4	4	4	4	4	4	4	4	2.23	
1-10	A15	70.1	81.2	117.6	4	8	8	8	4	4	4	4	2.74	
1-11	A2	70.3	76.4	114.8	4	4	4	4	4	4	4	4	2.81	
1-12	A11	67.1	76.7	119.2	8	8	8	8	8	8	8	8	2.56	
1-13	A6	67.2	73.4	118.5	4	4	4	4	4	4	4	4	2.79	
1-14	A10	73.3	72.4	120.5	4	4	4	4	4	4	4	4	2.82	
1-15	A12	69.4	74.0	123.7	8	8	8	8	8	8	8	8	2.57	
1-16	A1	72.3	76.3	124.2	8	8	8	8	8	8	8	8	2.59	

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).

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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

PI = Prescription Isodose

CI = 1.0 represents perfect conformity

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

Gradient Index

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

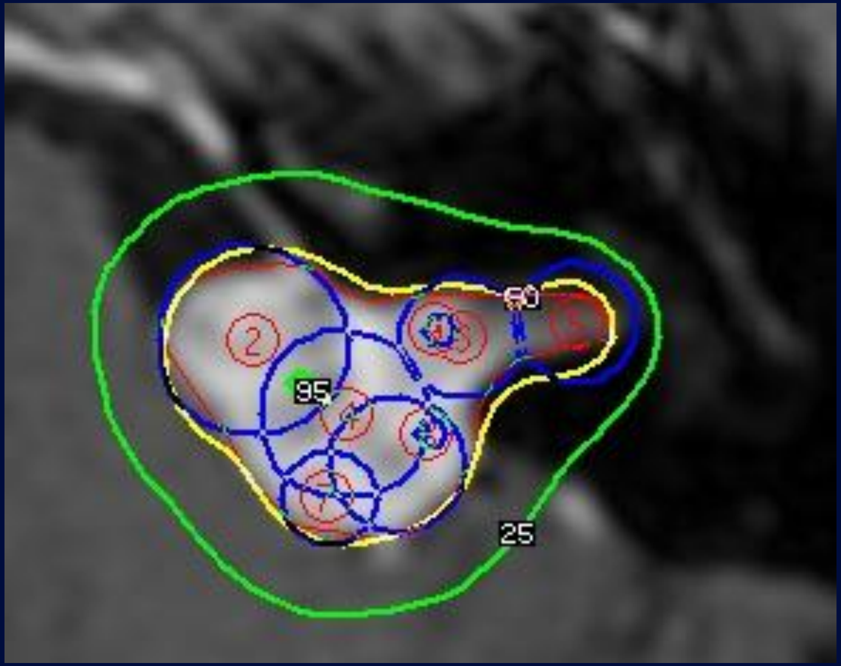
Measures how quickly dose is dropping outside of target:

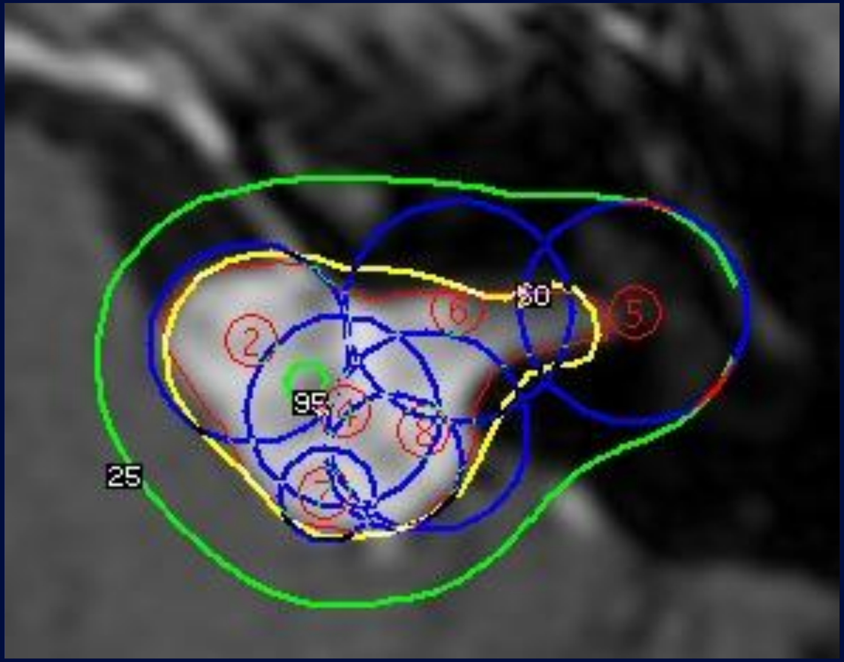
Example: If prescription isodose is at 60%, measure volume of 30% / 60%

GI < 3.0 is “good” dose falloff

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

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!

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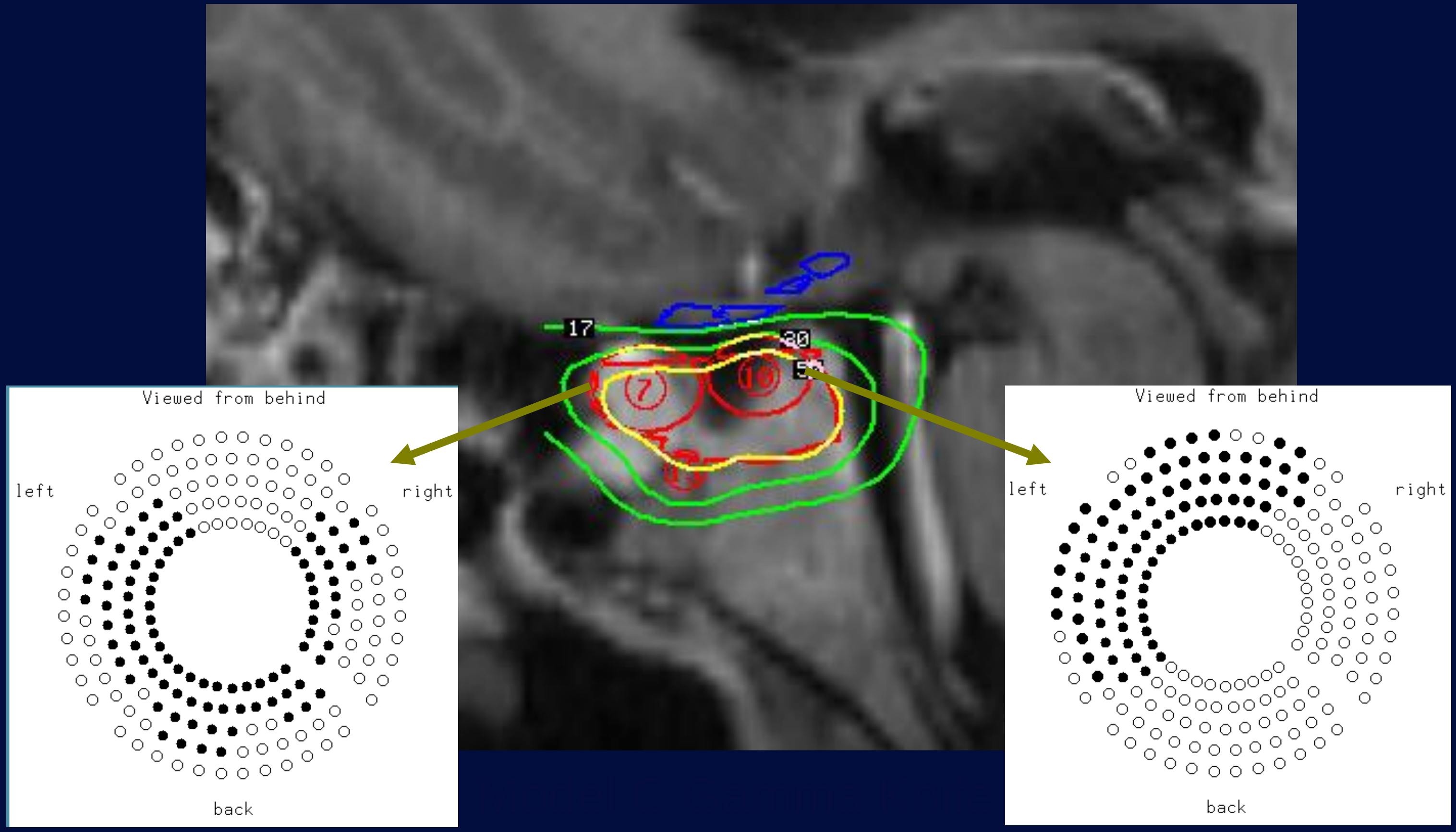
“Advanced” Features

Shielding - Protecting Critical Structures

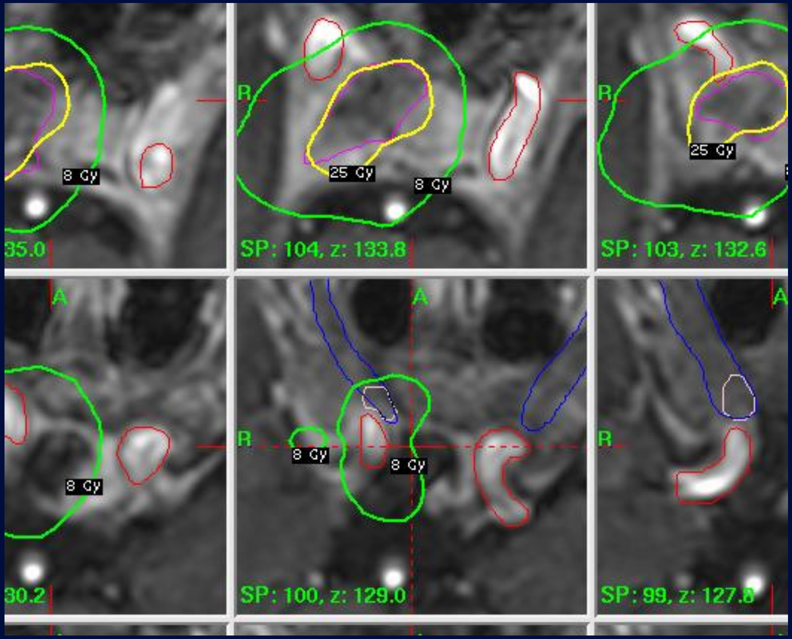
- Combinations of plug patterns are applied to one or more isocenters
- Example: Isocenter #7 has a different optimal plug pattern than isocenter #10



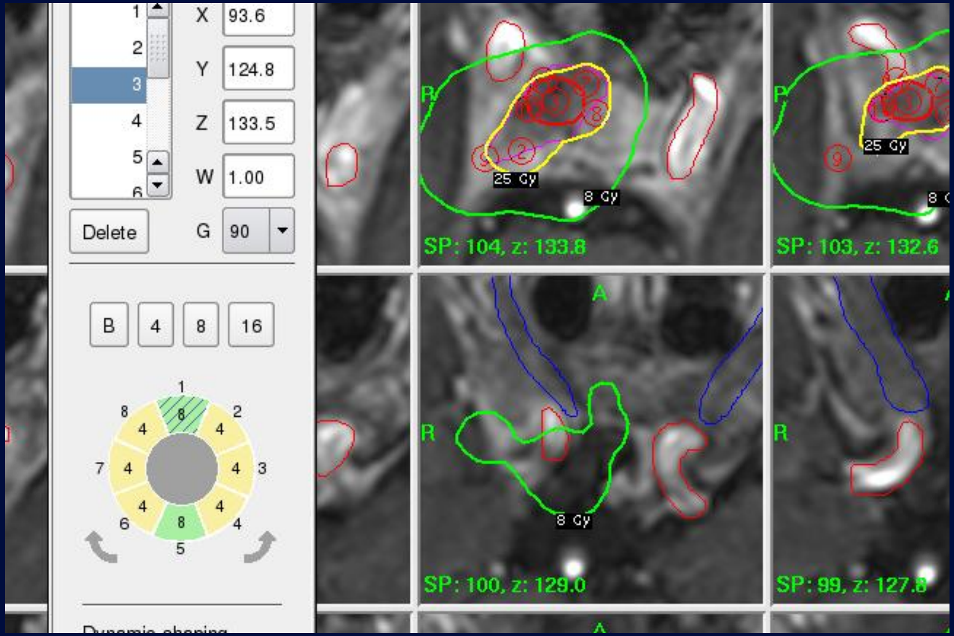
Shielding on Perfexion

- 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

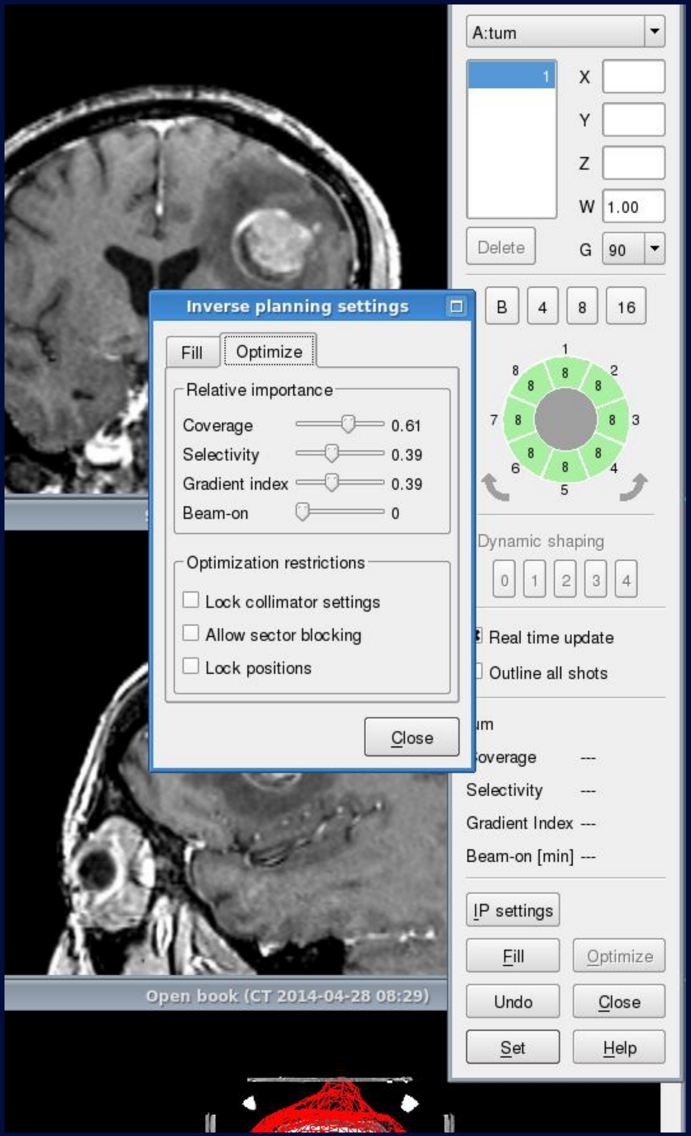
Before



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

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

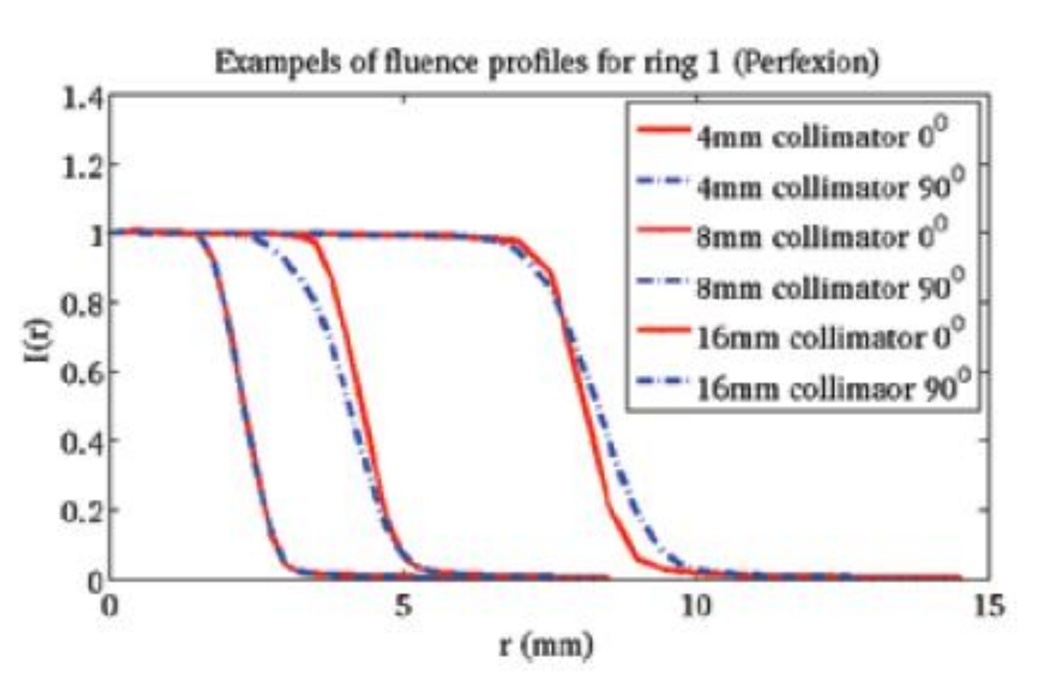


Figure 1. Examples of fluence profiles for Perfexion. The profiles for the 4 mm collimator are symmetric in different directions while the profiles for the 8 and 16 mm collimators are asymmetric.

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

Whitepaper, The Convolution algorithm in Leksell GammaPlan 10, Elekta, AB, 2010.

Acknowledgements

Thomas Jefferson’s Rotunda at the University of Virginia