Strategies and Technologies for Cranial Radiosurgery Planning: Gamma Knife

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Conflicts of Interest

Research support: Elekta Instruments, AB

Educational objectives

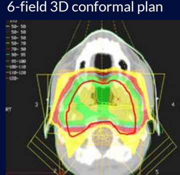
1. Introduce the basic physical principles of intracranial radiosurgery and how they are realized in the treatment planning paradigms for Gamma Knife and Linac radiosurgery.
2. Demonstrate basic treatment planning techniques.
3. Discuss metrics for evaluating SRS treatment plan quality.
4. Discuss recent and future advances in SRS treatment planning.

GK Planning Overview

- Treatment Planning Preparation
- Treatment Planning Techniques
- Treatment Plan Evaluation
- Physics Considerations

Dosimetric goal of radiosurgery

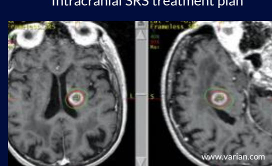
6-field 3D conformal plan



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

Relies on differential biology

Intracranial SRS treatment plan



Relies on differential targeting

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

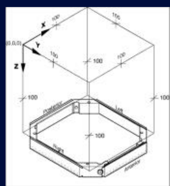



Image courtesy of Elekta

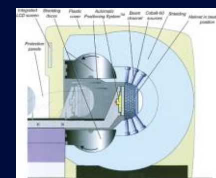
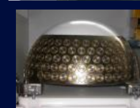
The frame defines the coordinate system and immobilizes patient

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

All coordinates are positive – no sign mistakes

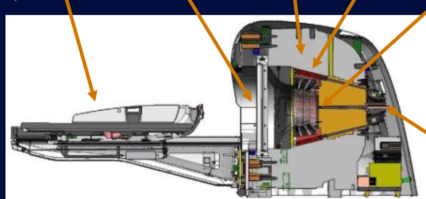
Center of the system is considered to be (100, 100, 100) (mm)

Gamma Knife model C / 4C

Kondziolka, et al., Gamma Knife Radiosurgery: Technical Issues, Textbook of Stereotactic and Functional Neurosurgery

Gamma Knife Perfexion



A single 36 Ci source yields a dose rate of ~480 mSv/hr at 1 meter!

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

Georgia registry of radioactive sealed sources and devices, 2001

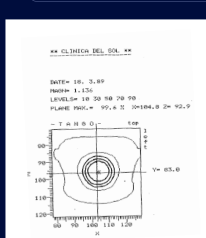
Goal for treatment planning

Image courtesy of Elekta Instruments, AB

Create instructions to move the patient relative to the isocenter of the Gamma Knife so the focus point of the beams creates a conformal dose distribution.

Style of treatment planning reflects the requirement to manage 192 (or 201) beams at a time.

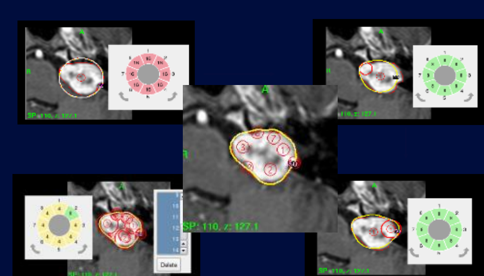
Evolution of treatment planning



Tango treatment planning system
Buenos Aires,
plan circa 1989

KULA treatment planning system
Elekta, AB, plan circa 1994

The basic planning process



Total dose distribution is a sum of one more isocenters, or "shots"
Plans are classically prescribed to the 50% isodose line

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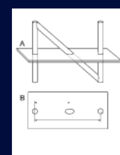
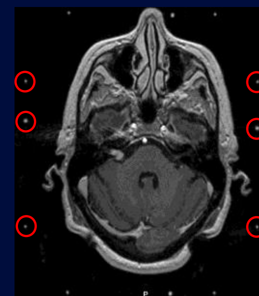
Stereotactic fiducials

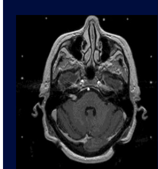


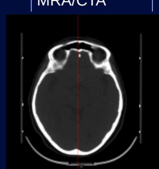


Brown R A, et al. (2013) The Origin of the N-Localizer for Stereotactic Neurosurgery. Cureus 5(9)

Imaging for treatment planning

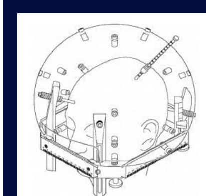
Solid tumors	AVMs	Skull-base and pituitary
T1-weighted MR + contrast (MPRAGE)	Biplane DSA T1-weighted MR + contrast MRA/CTA	T1-weighed MR + contrast T2 CISS or SPACE T1-weighted + fat saturation



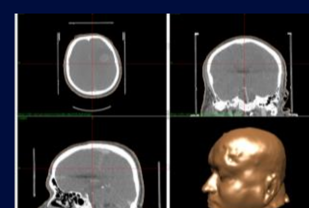


Critical to establish a robust imaging QA program for SRS!

External head contour



Manual head contour measurement

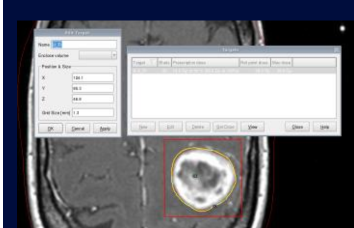


Semiautomatic segmentation from CT

Used to calculate SSD and depth of each beam

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

Targets –a.k.a. "dose matrices"



- 31x31x31 calculation grid
- Variable resolution
- Used to group a collection of shots
- Isodose curves displayed only in dose grid
- Allows separate prescription per target

Uncertainties with large dose matrices

4mm isocenter

Grid spacing	Max. Error (%)	Mean Error (%)
0.5 mm	1.1	0.30
1.0 mm	3.8	0.84
1.5 mm	7.5	1.7
2.0 mm	15.0	3.3
2.5 mm	35.1	7.8

Non-published data - Ian Paddick, MSc MIPEM, Medical Physics Ltd.

- GK Planning Overview
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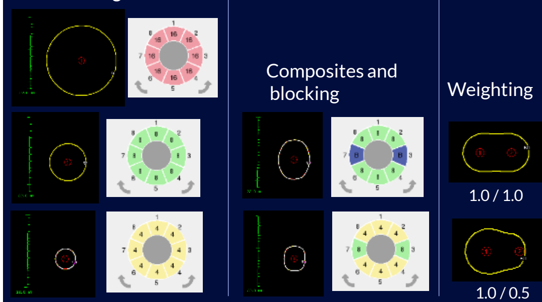
GK Perfexion: Basic isocenter parameters

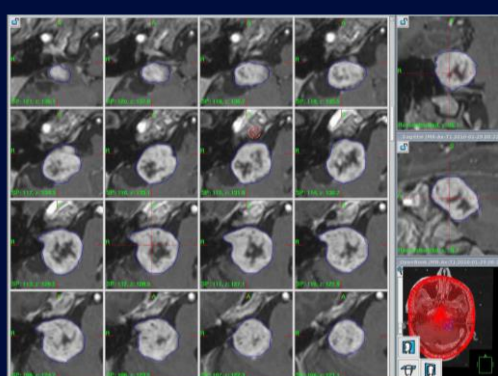
Base configurations

X, Y, Z coordinates

Composites and blocking

Weighting

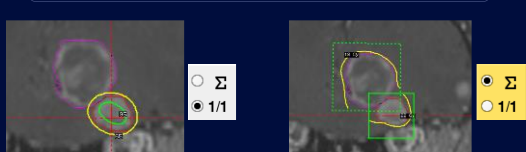




Planning multiple targets

Each target is ideally planned in its own dose matrix
Prescription for each dose matrix can be set individually

Single target vs all target modes



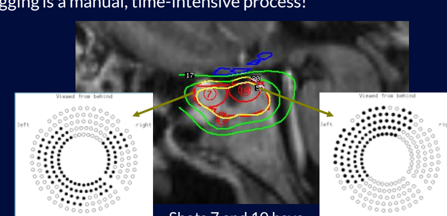
Single target mode: only shots from current target contribute to isodose lines shown. Dose in % of maximum dose in target.

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!

Protecting Critical Structures (model C/4C)

Combinations of plug patterns are applied to one or more isocenters
Different isocenters will have different optimal plugging patterns
Plugging is a manual, time-intensive process!



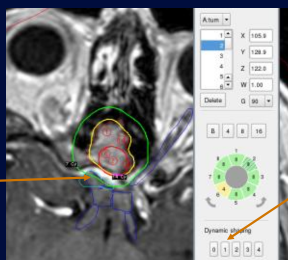
Shots 7 and 10 have different plugging requirements

Protecting critical structures (Perfexion)

Define risk structures near OARs you wish to shield

Planning system will block sectors with beams intersecting risk structures

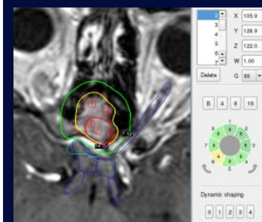
Shielding to reduce dose to optic pathway



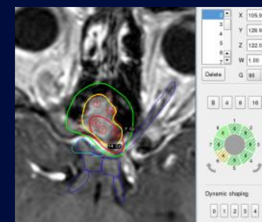
Shielding Level 1

Cross-hatched sectors are what system will shield

Set these to blocked yourself to preserve the pattern if you are dealing with multiple OARs



Shielding Level 2

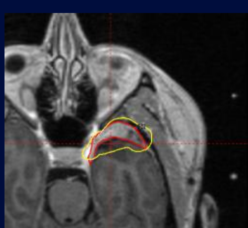


Shielding Level 3

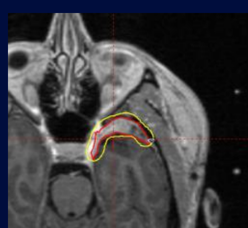
Shielding on Perfexion is automated

Overuse of shielding can significantly increase beam time

Shielding for shaping dose

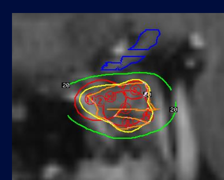


Plan without shielding



Plan with shielding

Use of the gamma (head) angle



$\gamma=90^\circ$

$\gamma=70^\circ$

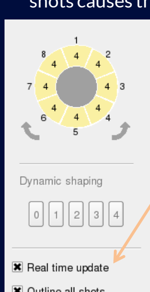
Gamma angle rotates head around X (left/right) axis

Manual technique usually used to avoid collisions of frame or patient with Gamma Knife

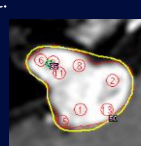
Sometimes can be used to lower dose to critical structures

Isocenter distribution effects

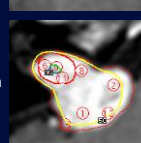
Display the 95% isodose line to understand why grouping shots causes the isodose lines to contract.



Real time update makes this easy to see!

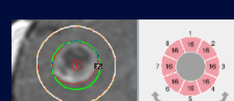


Effect of increased weight on shot 9

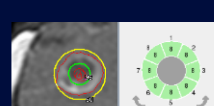


Superimposing shots

Superimposing and weighting shots of different sizes can give you all of the sizes in-between



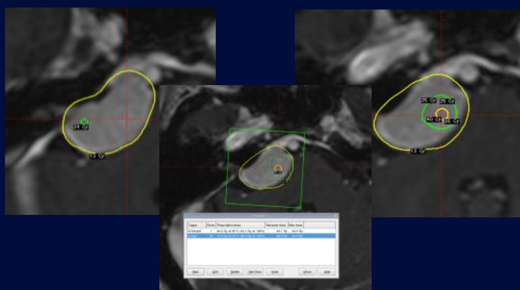
16 mm isocenter



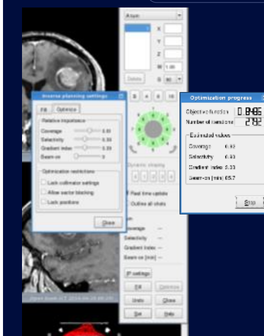
16 mm isocenter (weight 1.0)
8 mm isocenter (weight 2.0)

"Dose painting" hotspots

Use nesting dose matrices to manually place hotspots

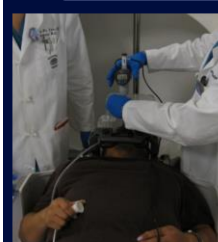


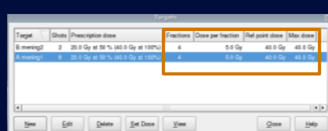
"Inverse" Planning



- Automatically fills a volume with isocenters
- Optimizes against plan metrics such as coverage, conformity, dose falloff, and beam time
- Does NOT use dose/volume constraints
- Plan can be manually adjusted via typical forward-planning techniques

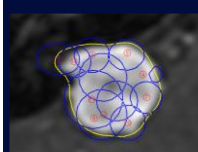
Extend System multifraction GKRS





- Treatment planning follows same basic process as single-fraction SRS
- Can set total dose or per-fraction dose + number of fractions
- Delivery of each fraction managed at control console

In the end 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 coordinates, collimator configurations, and dwell times.

Each coordinate is a point in the patient's head that is moved to machine isocenter for the specified dwell time/collimator configuration.

Total # beams = 192 (or 201) x number of locations (unless sectors are blocked).

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Conformity Index

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

Volume of PI → Overtreatment Ratio

Volume of Target → Undertreatment Ratio

PI = Prescription Isodose

CI = 1.0 represents perfect conformity

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

Gradient Index

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

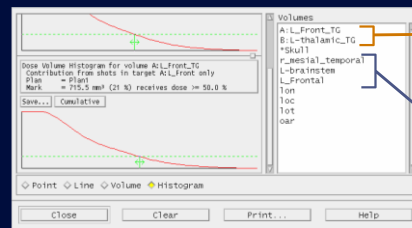
Measures how quickly dose is dropping outside of target:

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

The numbers are from the DVHs



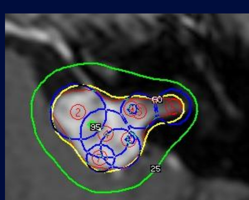
Dose Matrix DVHs

Target (GTV/CTV) DVHs

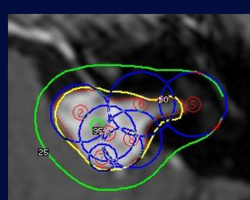
Dose Volume Histograms provide information on treatment volume, tumor volume, and tumor coverage

Requires that you contour! Not always the case in SRS!

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!

GK Planning Overview

Treatment Planning Preparation

Treatment Planning Technique

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Physics Considerations

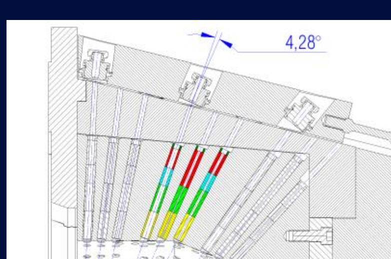
Perfexion collimator system

Beam channels are not all the same source to focus distance

Sources are angled relative to the collimators – 2D beam profiles

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

Also a home position when not in use

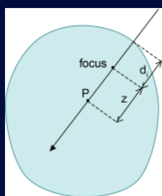


15 base beam configurations

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

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



Whitepaper, A new TMR dose algorithm in Leksell GammaPlan, Elekta, AB, 2010.

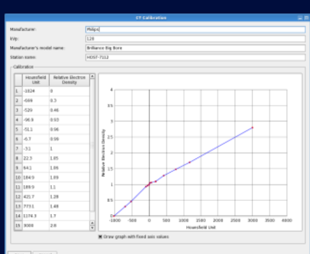
- d_i: depth of beam i
- z: depth from focus to calc point
- $R_{vsf,i}$: virtual source to focus distance for beam i
- of_i: output factor for beam i
- μ_0: attenuation coefficient of primary photon fluence (0.00633mm^{-1})
- μ_i: virtual attenuation coefficient of beam i (contribution of photon-electron interactions at z)
- $R_{calibration}$: source to focus for calibration phantom
- $\dot{D}_{calibration,16}$: base dose rate

Important TMR 10 approximations

- Treats the brain as a homogeneous ball of water – no heterogeneity correction
- Ignores build-up region effects
- Uses a poor approximation of the skull shape
- These are all minor issues inside the brain
- FAST – works well with Gamma Knife workflow

Convolution algorithm

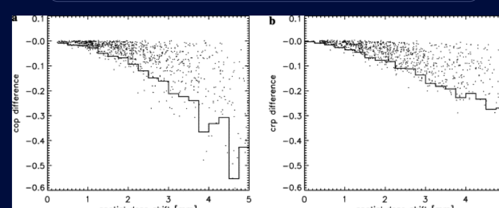
$$\text{Dose}(\mathbf{r}) = \iiint \text{TERMA}(\rho \cdot \mathbf{r}')\text{Kernel}(\rho \cdot (\mathbf{r} - \mathbf{r}'))d^3(\mathbf{r}')$$



- Allows for tissue heterogeneity correction
- Requires calibrated CT imaging for treatment planning
- 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.

Always be aware of uncertainty!



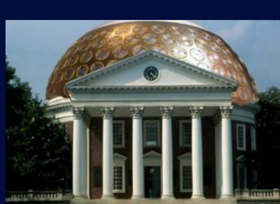
Change in obliteration probability (AVMs) | Change in control probability (mets)

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.

Acknowledgements



Thomas Jefferson's Rotunda at the University of Virginia