SRS/SBRT Case Studies: Gamma Knife for Brain (and Spine?)

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Conflicts of Interest

Research support: Elekta Instruments, AB

Educational objectives

1. Understand the differences in indications and dose/fractionation strategies for intracranial SRS and spine SBRT.
2. Describe the different treatment modalities which can be used to deliver intracranial SRS and spine SBRT.
3. Cite the major differences in treatment setup and delivery principles between intracranial and spine treatments.
4. Identify key critical structures and clinical dosimetric tolerance levels for spine SBRT and intracranial SRS.
5. Understand areas of ongoing work to standardize intracranial SRS and spine SBRT procedures

Gamma Knife Principles and Design

Gamma Knife as an Intracranial SRS Platform

Hypofractionated Gamma Knife

Gamma Knife as a Spine SRS Platform

Conclusions

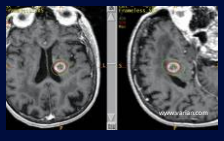
Dosimetric goal of radiosurgery

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

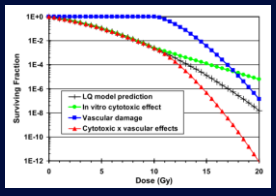
SRS radiobiology may be different

In-vitro cell survival > LQ model predicts for SRS

But clinically SRS performs better than LQ model predicts

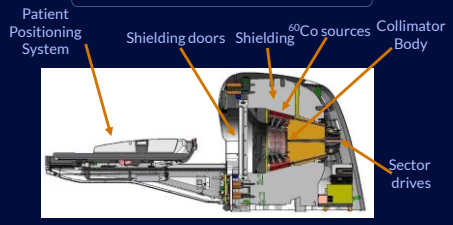
Microvascular damage has been shown to occur at doses > 10Gy.

SRS biological effect may involve DNA damage + vascular damage



The Linear-Quadratic Model is Inappropriate to Model High Dose per Fraction Effects in Radiosurgery
J. Kirkpatric, J. Meyer, L.B. Marks
Semin Rad Onc. 18(4), 2008.

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

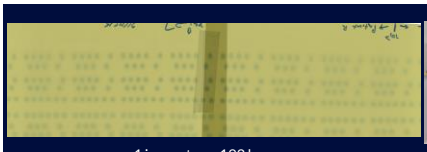
Generate high dose gradients by spreading out energy

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

Distributing the energy over many cross-firing beams generates the steep dose gradients

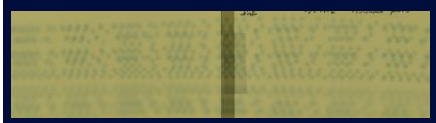
Model C: 201 beams / isocenter Perfexion: 192 beams / isocenter
Not uncommon to have 10-20+ isocenters to create an irregular shape

Image courtesy of Elekta, AB



1 isocenter = 192 beams

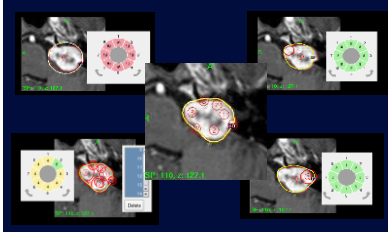
Radiochromic film placed at radial distance away from isocenter allows resolution of individual beams



3 isocenters = 3x192 = 576 beams

Y.B. Cho et al., Med Phys 37(3), 2010.

Gamma Knife treatment planning process



Total dose distribution is a sum of one more isocenters, or "shots"

Center of each shot is a location that will dwell at isocenter of GK for calculated time

Planning is fast – a requirement when a patient is waiting with a frame

Plans are classically prescribed to the 50% isodose line to maximize gradient

Frames for localization and immobilization

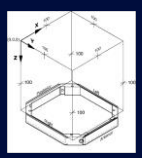
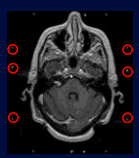


Image courtesy of Elekta



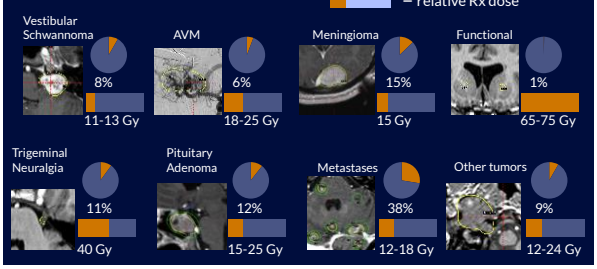
The frame defines the coordinate system and immobilizes patient

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)

What to treat and what dose?



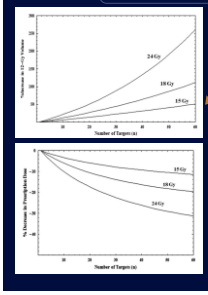
Organs at risk and dose limits

Critical Structure	Dose Limit
Anterior optic pathway	8 Gy (to ~0.01 cc of structure)
Brainstem	12 Gy to a significant volume (30% or so)
Skin	~ 10-12 Gy
Lenses	2 Gy maximum
Cranial Nerves in Cavernous Sinus	TBD
Cochlea	TBD, maybe as low as 5 Gy

Dose limit data is sparse and is based mainly on class III evidence

Sheehan, et al., in Controversies in Stereotactic Radiosurgery, J. Sheehan, P. Gerszten ed., Thieme, 2014.

Factors involved in choosing a dose



- Indication
- Tumor volume (RTOG 90-05)
- Prior RT/SRS
- Tumor vs resection cavity
- Location
- Number of tumors treated

A small reduction in dose can help keep the volume of normal brain at predictive dose levels (such as 12Gy) constant with increasing # tumors treated.

A. Sahgal, et al., IJROBP 78, 2010.

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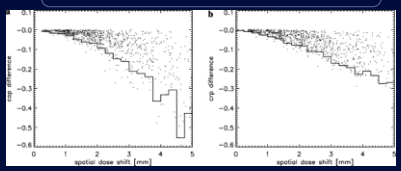
- Conclusions

Always be aware of uncertainty!



Change in obliteration probability (AVMs)

Change in control probability (mets)

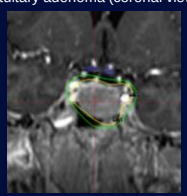
Impact of target point deviations on control and complication probabilities in stereotactic radiosurgery of AVMs and metastases.

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

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

The brain is often short on space

Pituitary adenoma (coronal view)



Parasellar anatomy

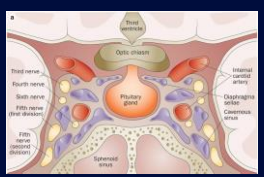
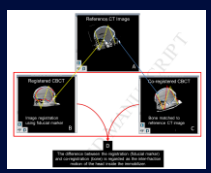


Image from Di Ieva, et al., Nat Rev Endorinology 10, 2014.

Frames have very low uncertainty



- SRS frames provide for low setup uncertainty and robust immobilization.
- But…practically limits treatment to single fraction.
- Looks more invasive than it really is.

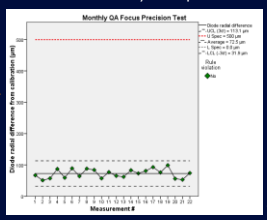
	Setup Error							Intrafraction Error						
	Translation (mm)				Rotation (°)			Translation (mm)				Rotation (°)		
	LR	AP	CC	Vector	LR	AP	CC	LR	AP	CC	Vector	LR	AP	CC
Mean	-0.19	0.08	-0.35	0.40	-0.14	-0.03	0.10	-0.03	-0.03	-0.03	0.05	-0.05	-0.03	-0.01
SD	0.32	0.29	0.50	0.66	0.25	0.19	0.20	0.05	0.18	0.12	0.22	0.30	0.20	0.09

Li, et al., IJROBP 2016.

The mechanics of the Gamma Knife have low uncertainty

Site-diode tool (Focus Precision Tool) used to locate radiation isocenter

Control chart: Monthly focus precision results



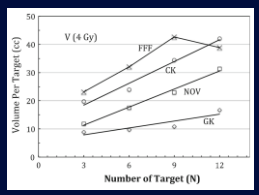
Radial difference from calibration position

Control limit (3σ) determined from first 5 measurements

Gamma Knife has small low-dose spillage

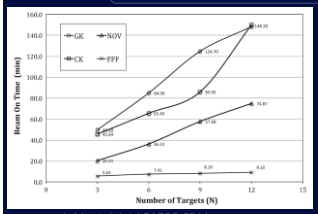
Low-dose spillage in normal brain tends to be lower with Gamma Knife SRS and other multi-isocentric techniques. But….treatments can be lengthy.

Single-isocenter VMAT is designed for speed. Tradeoff (at the moment) is low-dose spillage.



L. Ma, et al., Variable dose interplay effects across radiosurgical apparatus in treating multiple brain metastases, Int J CARS 9, 2014.

The tradeoff is in time to treat!



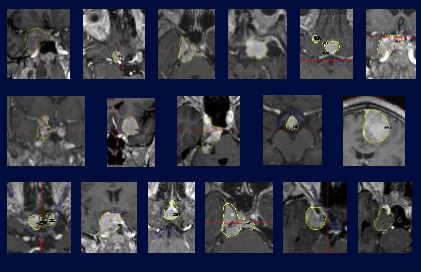
Multi-isocenter techniques: Beam-on time scales with # targets treated

Single-isocenter VMAT: Treatment time stays constant regardless of number of lesions

L. Ma et al., Int J CARS 9, 2014.

But remember….beam-time is not the same as total procedure time!

Sometimes cases are tricky…



The first try: Gamma Knife Extend System

Reference measurements taken at time of CT imaging

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

How does Extend perform?

Author	Device	Setup displacement mm (SD)
Sweeney, et al. (1998)	Biteblock + vacuum assist	<1.02*
Rosenberg, et al. (1999)	GTC frame	1.1(0.6)#
Ryken, et al. (2001)	Mask + optically-tracked biteblock	0.16(0.04)†
Baumert , et al. (2005)	Mask + Bite block	2.2 (1.1)‡
Minniti et al. (2010)	Relocatable frame + upper jaw support	0.5(0.4) ‡
Ruschin, et al. (2010)	Extend prototype	1.0^ / 1.3†
UVA Series	Extend clinical system	0.64(0.25)^

* fiducials vs. surface landmarks; # orthogonal radiograph landmarks;
† fiducials vs CBCT; ‡ simulation CT vs. QA CT; ^ probe/depth measurements

A better idea for hypofractionated Gamma Knife

Gamma Knife ~~Perfexion~~ ~~Plus~~ *Icon*

- CBCT image guidance
- Optical motion tracking and gating
- Compatible with G-frame, and thermoplastic mask

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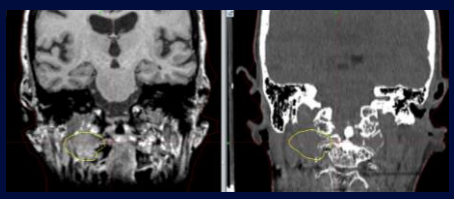
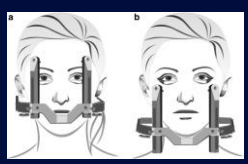
We already do Gamma Knife for spine – sort of



C1-C2 level brain metastasis

Immobilization is the basic technical problem



Fixation of frame at the maxilla can allow treatments lower than C2.
Still need reliable methods to immobilize C-spine.

Tripathi et al., Acta Neurochir, 2016.

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Conclusions

The Gamma Knife was designed specifically around the requirements for intracranial radiosurgery.

It balances high accuracy and precision with efficient workflow.

As indications have changed, Gamma Knife has attempted to adapt.

While upper cervical spine is within reach, immobilization remains a significant technical hurdle.

Thank You!

Thomas Jefferson's Rotunda at the University of Virginia