Re-irradiation techniques: Gamma Knife

A technical and clinical overview

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Conflicts of Interest

None

(but a presentation about anything Gamma Knife® is almost by definition vendor-specific)

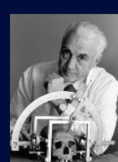
What is Gamma Knife radiosurgery?

Gamma Knife re-irradiation scenarios

What makes re-irradiation difficult?

Evolution of Gamma Knife for re-irradiation

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.

1967: The first "Gamma Knife"

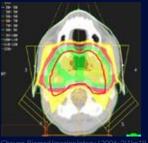
Lars Leksell and Ladislau Steiner at the Karolinska Institute

Tony DeSalles and Catherine Gilmore (past president of Elekta) with the original Gamma Knife after it moved to UCLA (1982, picture circa 1993)

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

What makes radiosurgery different?

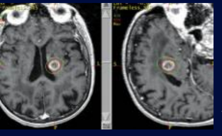
6-field 3D conformal plan



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

Relies on differential biology

Intracranial SRS treatment plan



www.varian.com

Relies on differential targeting

Spreading out energy is the key to SRS

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

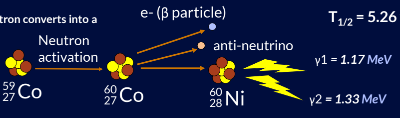
Spreading the energy out generates steep dose gradients that concentrates dose on the target

Model C: 201 beams / isocenter

Perfexion: 192 beams / isocenter

Image courtesy of Elekta, AB

Gamma Knife: powered by nature



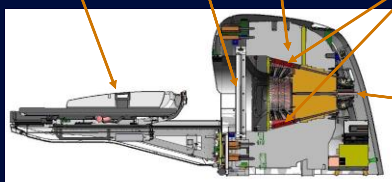
^{60}Co decay is a very stable photon source

Sources are usually in pellet-form, triple-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. Decay figure originally by Håkan Nordström, Elekta AB

Gamma Knife Perfexion/Icon: internal view



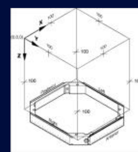
~20 metric tons to protect you from 20 grams of ^{60}Co

Note: Image of a Perfexion. Icon has the same internal configuration

Images: Elekta Instrument, AB

How do you know where you are aiming?

The traditional method!



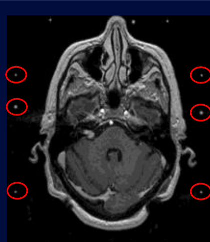
The frame defines a targeting coordinate system.

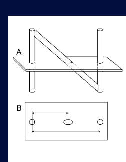
Coordinate system origin is to the right, superior, posterior of the patient's head.

All coordinates are positive – no sign mistakes.

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

Stereotactic fiducials



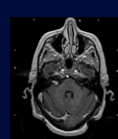


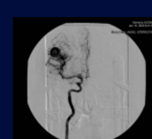
Brown R A, et al. (2013) The Origin of the N-Localizer for Stereotactic Neurosurgery. Cureus 5(9)

Imaging for treatment planning

Typical imaging protocols

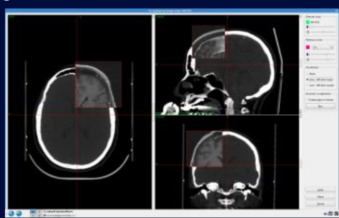
Solid tumors	AVMs	Skull-base and pituitary
T1-weighted MR + contrast	Biplane DSA T1-weighted MR + contrast MRA	T1-weighed MR + contrast T2 CISS or SPACE T1-weighted + fat saturation



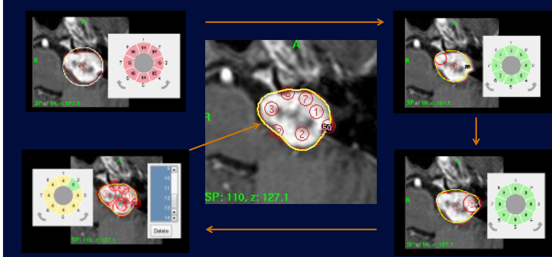


Non-stereotactic imaging

Co-registration allows use of PET, advanced MRI sequences

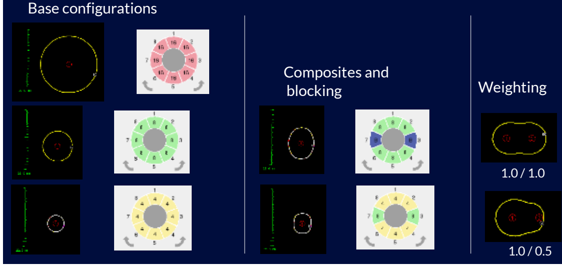


Treatment planning today….

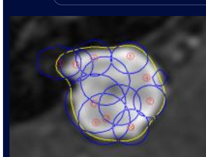


Doses are traditionally prescribed to 50% isodose line

Basic treatment building-blocks



But in the end a plan is simple to describe



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 brachytherapy treatment planning.
Each location is a coordinate to position that location at radiation isocenter.
Total # beams = 192 x number of locations (unless sectors are blocked).

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Gamma Knife re-irradiation scenarios

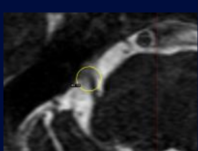
What makes re-irradiation difficult?

Evolution of Gamma Knife for re-irradiation

Re-irradiation of same site

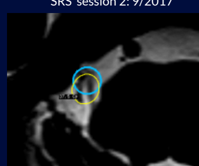
Repeat treatment for trigeminal neuralgia

SRS session 1: 2/2012



40 Gy->50%

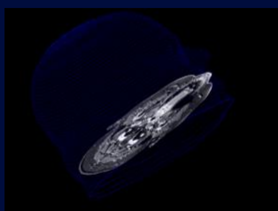
SRS session 2: 9/2017



37.5 Gy - > 50%
(shielded to protect brainstem)

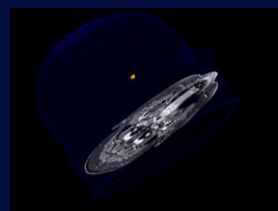
Re-irradiation for new tumors

One brain, multiple radiosurgeries



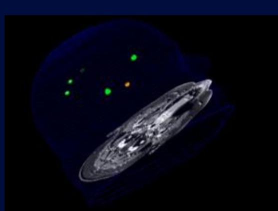
Date	# tumors	Vol 12Gy (cc)	Skull mean dose (Gy)

One brain, multiple radiosurgeries



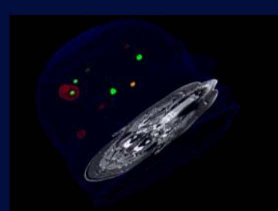
Date	# tumors	Vol 12Gy (cc)	Skull mean dose (Gy)
7/2013	1	0.6	0.1

One brain, multiple radiosurgeries



Date	# tumors	Vol 12Gy (cc)	Skull mean(SD) dose (Gy)
7/2013	1	0.6	0.1 (0.3)
10/13	5	3.4	0.4 (0.8)

One brain, multiple radiosurgeries



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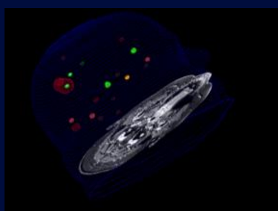

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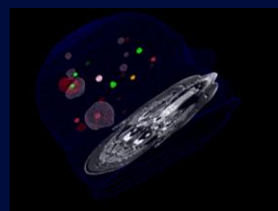

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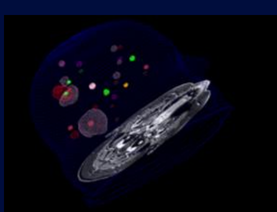
5/14	11	5.1	0.6 (0.9)
6/15	8	43.8	1.4 (2.3)

9/2014 - WBRT (30 Gy in 10 fractions)

One brain, multiple radiosurgeries



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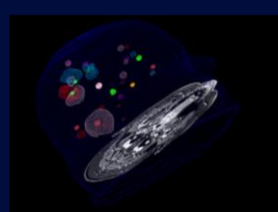
One brain, multiple radiosurgeries



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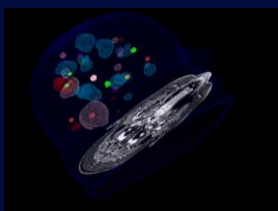
One brain, multiple radiosurgeries



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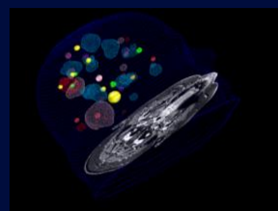
7/15	4	2.0	0.2 (0.5)
10/15	6	14.6	0.6 (1.4)
2/16	9	46.2	1.6 (2.3)

9/2014 - WBRT (30 Gy in 10 fractions)

One brain, multiple radiosurgeries



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55 tumors, 9 SRS procedures, 3 years
Still alive as of 8/2018!

9/2014 - WBRT (30 Gy in 10 fractions)

Geographical fractionation

Staged AVM radiosurgery

Pediatric patient, prior embolization x 2, aborted embolization #3

SRS session 1: 3/2014

13.5 Gy - > 50%
$V_{13.5Gy}$ = 14.6 cc
V_{12Gy} = 17.1cc

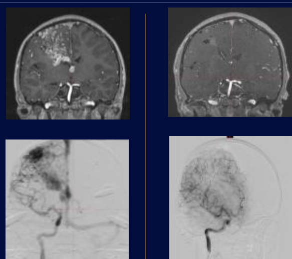
SRS session 2: 4/2014

13.5 Gy - > 50%
$V_{13.5Gy}$ = 8.9 cc
V_{12Gy} = 10.8 cc

Staged AVM radiosurgery

MRI: date of 1st GKSRS

Followup MRI: 6/2017



Angio: date of 1st GKSRS

Followup Angio: 3/2018

Complete obliteration confirmed via MR (6/2017), angio (3/2018)

Dose fractionation (sometimes with prior SRS)

A bit of an extreme case….

Recurrent pituitary macroadenoma / prolactinoma

Other therapies:

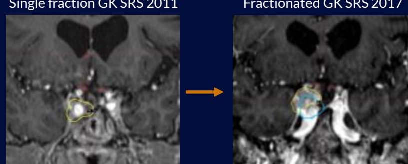
post transphenoidal x 4

post fractionated RT (50.4 Gy, 2010)

temozolamide 2012, 2015-2016

Single fraction GK SRS 2011

Fractionated GK SRS 2017



18 Gy->50%
3.3cc Rx volume
0.01cc OP: 6.3 Gy (RON)

20 Gy->50% in 5 fractions
5.0cc Rx volume
0.01cc: 18.7 Gy (RON)

Some clinical references (I'll spare the details…)

Year	Author(s)	Journal	Clinical setting
2002	A. Bhatnagar, et al.	IJROBP 53 (3)	Primary and metastatic tumors
2012	K. Park, et al.	Neurosurgery 70 (2)	Repeat trigeminal neuralgia
2015	C. Helis, et al.	Neurosurgery 77 (5)	Repeat trigeminal neuralgia
2015	S. Lonneville, et al.	Surg Neurol Int 28(6)	Repeat vestibular schwannoma
2017	R. Kotecha et al.	Neurosurgery 80 (6)	Repeat SRS for multiply recurrent brain metastases
2017	A. Ilyas, et al.	J. Clinical Neuroscience 43	Volume-staged AVMs
2018	G. Mehta, et al.	J. Neurooncology	Multicenter repeat SRS Cushing's

Note: This is not (and is not meant) to be complete! This is a physics talk after all!

What is Gamma Knife radiosurgery?

Gamma Knife re-irradiation scenarios

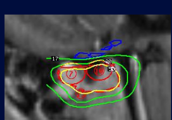
What makes re-irradiation difficult?

Evolution of Gamma Knife for re-irradiation

Radiosurgery is hard.

Uncertainty makes it harder.

SRS/SBRT often has difficult constraints



Brain SRS: Pituitary adenoma
(optic pathways within few mm)

Spine SRS: (spinal cord within few mm)

High doses per fraction, small # fractions
Fields that must conform to anatomy
Inhomogeneous dose within tumor

Sharp dose gradients outside target:
10%-25%/mm (Gamma Knife)
>10%/mm (linac)

Extremely high requirements for accuracy and precision!

What happens if you really mess up

The New York Times

THE RADIATION BOOM
By WALT BOGDANICH

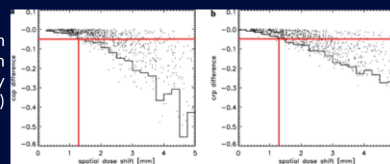
A Pinpoint Beam Strays Invisibly, Harming Instead of Healing
Published: December 28, 2010

Radiation Offers New Cures, and Ways to Do Harm
Published: January 23, 2010

More likely…this sort of thing can happen:

You can miss your target…

Change in obliteration probability (AVMs)

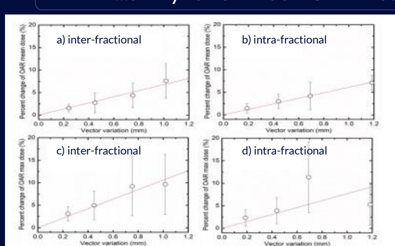


Change in remission probability (mets)

Spatial dose deviation (mm) from intended target

Treuer H, Kocher M, Hoevels M, et al., Radiother Oncol, , 2006 Oct;81(1):25-32.

…and you can hit an OAR instead.



Change in mean OAR dose vs positioning deviation

Change in max OAR dose vs positioning deviation

Kim et al., Inter- and intrafractional dose uncertainty in hypofractionated Gamma Knife radiosurgery, JACMP, 17(2), 2016.

Radiosurgery is hard.

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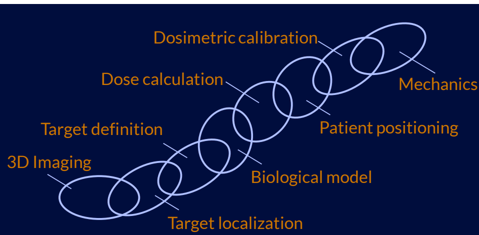
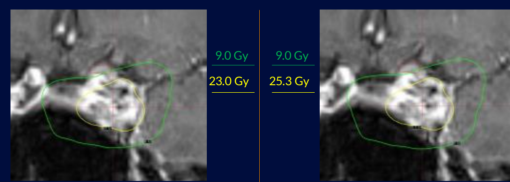


SRS/SBRT has a complex uncertainty chain

A. Mack, H. Czempiel, H-J Kreiner, et. al., Med Phys 29(4), 2002

Procedural uncertainty = isodose uncertainty

What difference does a 10% change in dose make?



Prescription = 23.0 Gy
D_{max} to left optic nerve = 9.0 Gy
V_{9Gy} = 11.7 cm^3

Prescription = 25.3 Gy
D_{max} to left optic nerve = 10.0 Gy
V_{9Gy} = 13.5 cm^3

Stereotactic frames/fiducials are not perfect…

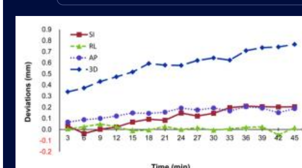
Difference between frame/fiducial and cone-beam CT defined SRS coordinate systems, n=150 frame cases

Shift direction (units)	Absolute Mean Shift	Median Shift	Standard Deviation	Range
Pitch (degrees)	0.14	-0.02	0.19	-0.71 to 0.63
Yaw (degrees)	0.16	0.05	0.21	-0.5 to 0.83
Roll (degrees)	0.12	0.02	0.15	-0.37 to 0.51
Left-right (mm)	0.29	-0.12	0.35	-1.29 to 0.82*
Anterior-posterior (mm)	0.24	-0.21	0.19	-0.59 to 0.33
Superior-inferior (mm)	0.24	0.13	0.27	-0.69 to 0.91

* 3 cases exceeded 1.0 mm translational difference, all in the left-right direction (-1.05, -1.13, -1.29 mm)

S. Dutta, et al., IJROBP, in-press, 2018

…and neither are thermoplastic masks.



CyberKnife intrafraction motion vs time. n=50 patients. 2-mm thermoplastic mask immobilization.

Thermoplastic masks are (possibly) more convenient than an SRS frame.

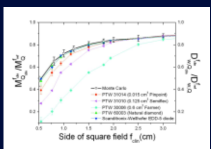
Tradeoff is masks have higher setup and intrafractional uncertainty.

Intrafraction shifts have been reported between 0.1 mm and 2.0 mm.

Require some kind of intrafraction motion management to achieve comparable performance to SRS frame.

C-W Wang, et al., Plos One, April 20, 2015

Small fields are difficult to measure

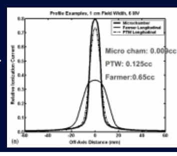


Ratio of absorbed doses vs field size for various detectors + monte-carlo

Charged particle equilibrium assumption no longer valid

Detector itself becomes a prominent source of measurement uncertainty

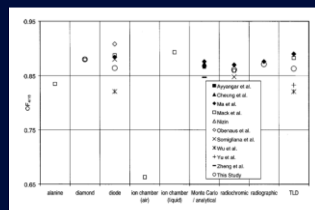
Measured profile with different sized detectors



Volume averaging over detector makes field edge measurements inaccurate

Low, et al., Medical Physics 30(7), 2003.
R. Alfonso, et al., Medical Physics 35(11), 2008.

So independent verification can be hard



Determination of the 4 mm Gamma Knife helmet relative output factor using a variety of detectors (summary of literature)

Note that ion-chamber measurement is well below other detectors.

In some cases, accepted standards for output calibration do not exist (yet).

JS Tsai et al., Med Phys 30(5), 2003.

It can be difficult to decide on a target....

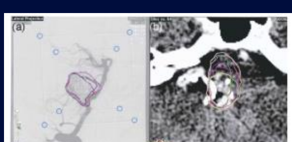


Fig. 1. Contouring variations in a patient with a brainstem arteriovenous malformation. (a) Target volume presented as different colors. All contours were automatically projected on computed tomography images used for further analysis (b).

- 31 AVM patients
- 6 observers contouring on DSA
- Mean AR = 0.45 ± 0.18
- **AR never exceeded 0.6 in any patient!**

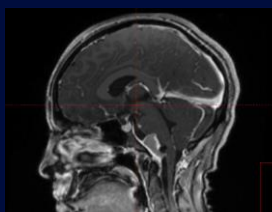
$$\text{Agreement ratio (AR)} = \frac{\text{common overlapping volume}}{\text{encompassing volume}}$$

Stereotactic radiosurgery for brain AVMs: role of interobserver variation in target definition on digital subtraction angiography
Buis, et al., IJROBP 62(1), 2005

....and it can be difficult to localize a target

Does this MR have distortion?

....and it can be difficult to localize a target



Does this MR have distortion?

Sources of MR geometric distortion

System-level

Caused by hardware imperfections

Static-field inhomogeneities
Gradient nonlinearities
Gradient and RF frequency maladjustments
Eddy currents due to gradient switching

Worse on periphery of image
Mostly correctable with vendor-supplied algorithms (gradient coil modeling)

Patient-specific

Caused by magnetic properties of individual patients

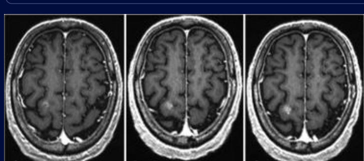
Magnetic susceptibility
Chemical shift

More difficult to correct, but usually smaller in magnitude

Both tend to be worse at higher field strengths and better with higher bandwidth!

J. Weygand, et al., IJROBP 95(4), 2016; A. Fransson et al., Strahlenther Onkol, 2001.

Even subtle timing differences can matter



Scan 1: time of injection
Scan 2: ~10 min delay
Scan 3: ~15 min delay

Scans compared (n=53 studies)	% studies w ≥ 1 new lesion	95% CI	Range of # new lesions
Scan 1:2	35.3%	22.4%-49.9%	1-10
Scan 2:3	21.6%	11.3%-35.3%	1-9
Scan 1:3	43.1%	29.3%-57.8%	1-14

M. Kushnirsky et al., JNS 124, 2016

Re-irradiation makes uncertainties more critical.

What is Gamma Knife radiosurgery?

Gamma Knife re-irradiation scenarios

What makes re-irradiation difficult?

Evolution of Gamma Knife for re-irradiation

Gamma Knife accuracy and precision

Support for multiple fractions

Workflow flexibility

Quantitative imaging

Mechanical accuracy and precision

Linear encoders
Resolution: 0.01 µm
Accuracy over entire length of scale: ± 5 µm

System gets target coordinate and calculates # encoder rotations

↓

Rotational encoder tracks motion

↓

System compares linear encoder to desired position. Must be within tolerance.

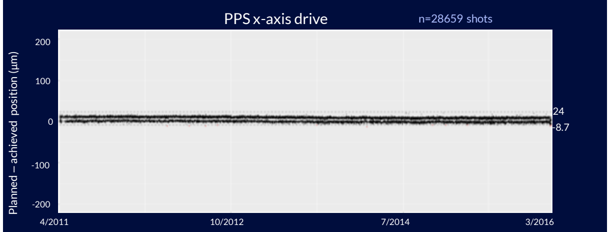
Rotational encoders
2000 pulses per rotation
Pitch on sector screws is 1mm
Resolution: 0.5 µm

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

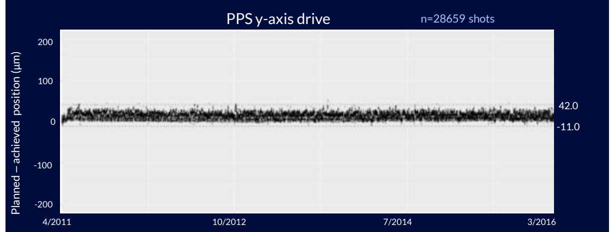
RFP = radiation focus point PPS = patient positioning system (treatment bed)

Planned vs achieved PPS encoder positions



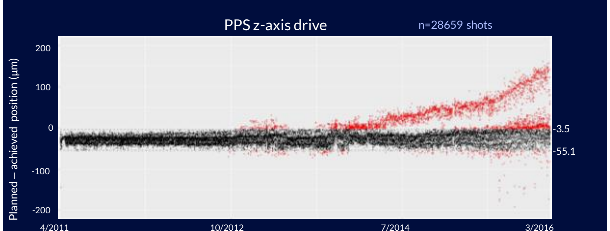
Center: -7.4 µm
Upper Control Limit: 24 µm (+3σ)
Lower Control Limit: -8.7 µm (-3σ)

Planned vs achieved PPS encoder positions



Center: 16.0 µm
Upper Control Limit: 42.0 µm (+3σ)
Lower Control Limit: -11.0 µm (-3σ)

Planned vs achieved PPS encoder positions



Center: -29.3 µm
Upper Control Limit: -3.5 µm (+3σ)
Lower Control Limit: -55.1 µm (-3σ)

Gamma Knife technical fault – 3/2016

Gamma Knife Z drive
(looking up at PPS)

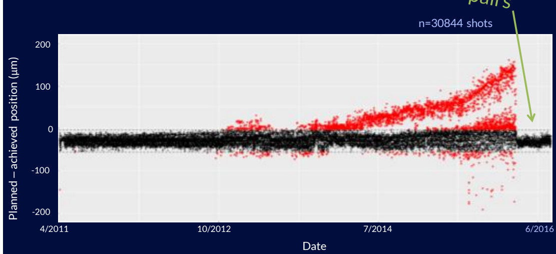
Faulty gearbox spacers

Decayed spacers allowed increase torque on Z-drive gearbox with increasing PPS travel in into the unit.

Torque released tension on drive belt, so bed would stop moving while drive was still moving.

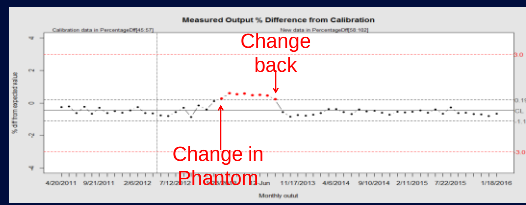
Control system would eventually time out and cause a system fault.

Planned vs achieved PPS encoder positions



Next step is to re-baseline and track prospectively.

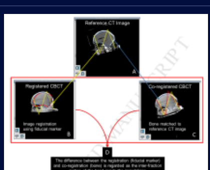
^{60}Co makes for very stable output



Center bias: -0.45%
Upper Control Limit: 0.19% (+3σ)
Lower Control Limit: -1.10% (-3σ)

Regulatory annual limit: ±3.0%

Stereotactic frames help patients to be still



SRS frames provide for low setup uncertainty and robust immobilization.

Practically limits treatment to single fraction.

Looks more invasive than it really is.

	Setup Error Translation (mm)				Rotation (°)			Intrafraction Error 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.

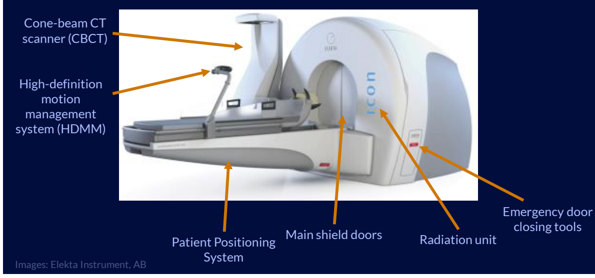
Gamma Knife accuracy and precision

Support for multiple fractions

Workflow flexibility

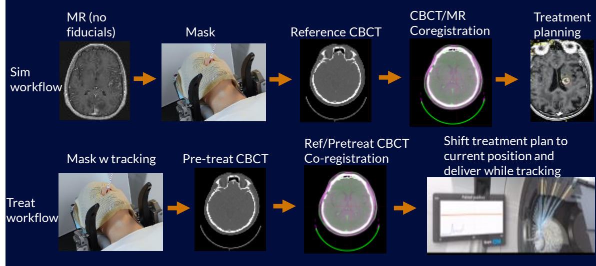
Quantitative imaging

Gamma Knife® Icon™ – external view



Images: Elekta Instrument, AB

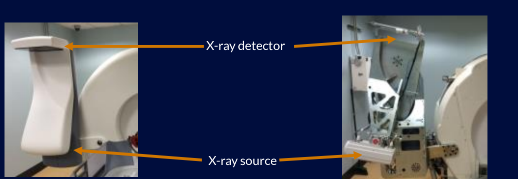
Gamma Knife Icon frameless workflow



MR can be performed with/without mask depending on clinic preference

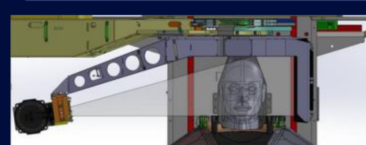
Images: Elekta Instrument, AB

Cone beam CT system



	CTDI 2.5	CTDI 6.3
	2.5 mGy	6.3 mGy
Charge/projection	0.4 mAs	1.0 mAs
Tube current	0.1 mA	0.25 mA
X-ray energy	90 kV	90 kV

Cone beam CT system



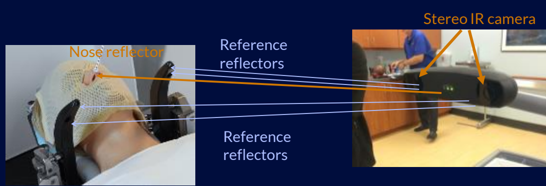
Characteristics	Value
Source to axis distance (SAD)	790mm
Source to detector distance (SDD)	1000mm
Magnification factor	1.27
Reconstructed volume	224 x 224 x 224mm³
Cone beam angle	15°
Fan angle	16°
Scan time	30s
Flex	< 0.2mm

Table 1. The geometric characteristics of the CBCT system.

Components	Properties
Detector	Layers: CsI, TFT(amorphous Si) 780 x 720 pixels (binned mode). Pixel resolution = 0.368 mm
X-ray tube	Energy range: 70-120 kVp. Spot size: 0.6 mm Weight: 17kg

Table 2. Components.

High-definition motion management (HDMM)



The HDMM system tracks the relative position of a marker placed on the patient's nose vs four reference markers built into the mask adapter (on black posts).

UVA Gamma Knife Center

Intra-fraction motion management with GK Icon

A clinical threshold is set for nose marker motion

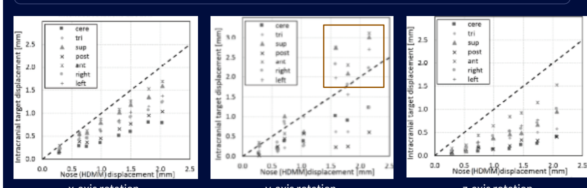
Baseline is established as time-averaged nose marker position during pre-treatment CBCT

System gates on and off if nose marker deviates above line

Re-baseline (CBCT) required if patient remains out of position

UVA Gamma Knife Center

Nose marker tracking seems mostly conservative



x-axis rotation

y-axis rotation

z-axis rotation

For most cases, tumor anatomy will deviate less than the nose marker

G. Wright, et al., JRSBRT 4, 2017

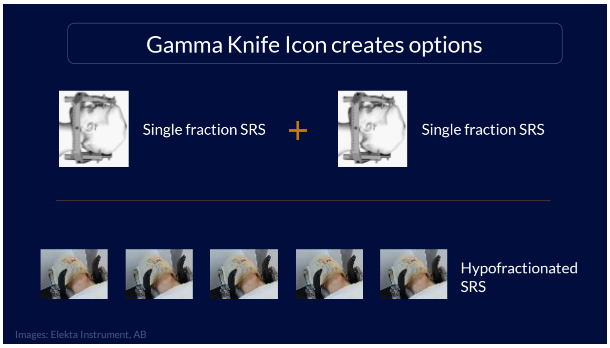
original image from microsoft.com

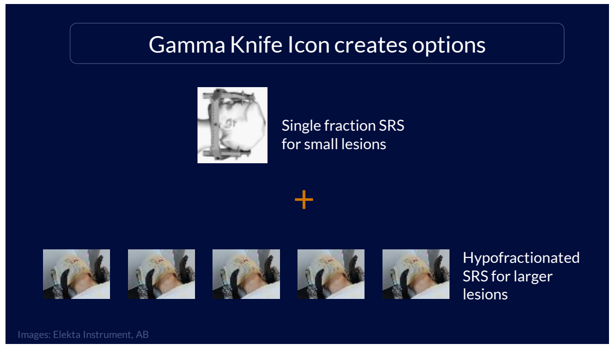
Gamma Knife accuracy and precision

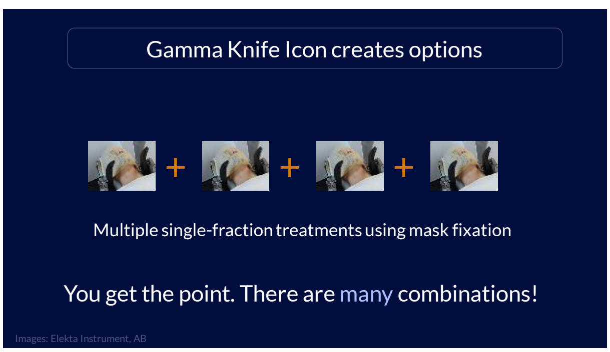
Support for multiple fractions

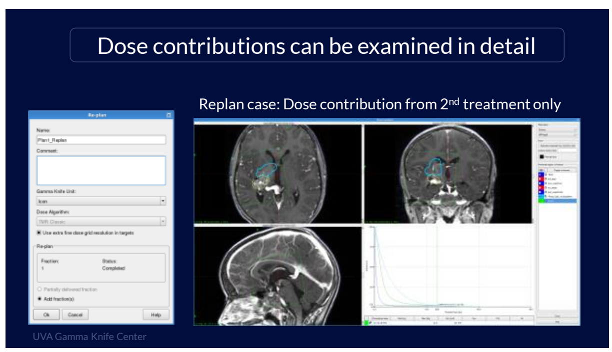
Workflow flexibility

Quantitative imaging


Gamma Knife Icon creates options
Single fraction SRS
+
Single fraction SRS
Hypofractionated SRS
Images: Elekta Instrument, AB


Gamma Knife Icon creates options
Single fraction SRS for small lesions
+
Hypofractionated SRS for larger lesions
Images: Elekta Instrument, AB


Gamma Knife Icon creates options
+
+
+
Multiple single-fraction treatments using mask fixation
You get the point. There are many combinations!
Images: Elekta Instrument, AB


Dose contributions can be examined in detail
Replan case: Dose contribution from 2nd treatment only
UVA Gamma Knife Center

Dose contributions can be examined in detail

Replan case: Dose contribution from both treatments

UVA Gamma Knife Center

Gamma Knife accuracy and precision

Support for multiple fractions

Workflow flexibility

Quantitative imaging

Not specific to Gamma Knife SRS, but important for re-irradiation

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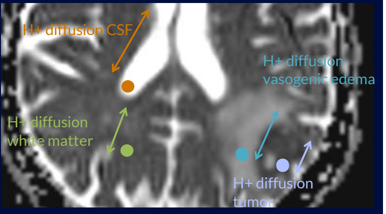
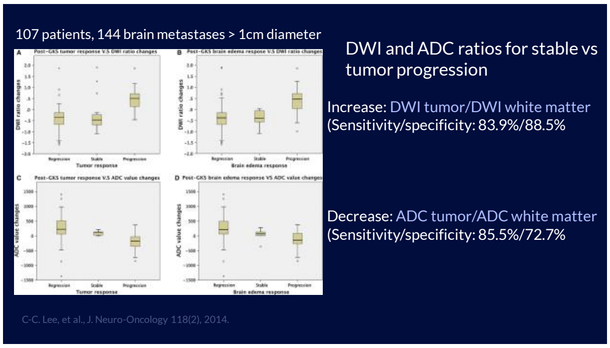
Diffusion-weighted (DWI) imaging

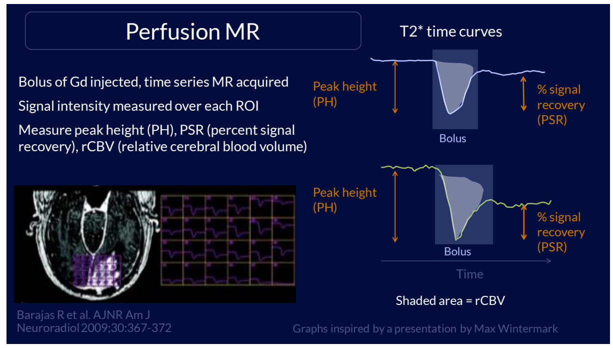
- Indirectly measures the "cellularity" of tissue
- CSF has fewer cells, less restrictive to diffusing H+
- Actively growing tumors have many cells, more restrictive to diffusion.
- Often expressed in terms of an apparent diffusion coefficient (ADC)
- Fractional anisotropy (FA) – measurement of diffusion directionality

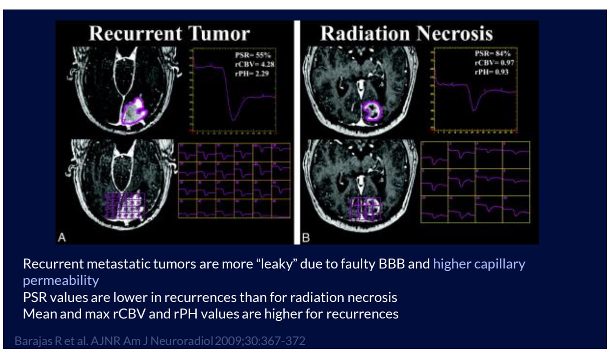


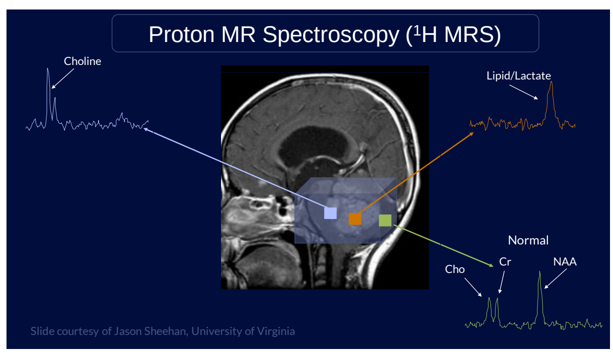
ADC map brain with brain metastasis

Slide adapted from a presentation by Max Wintermark. Images courtesy UVA.

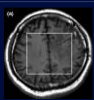
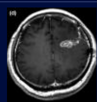
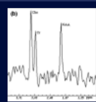
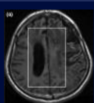
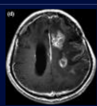
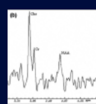

107 patients, 144 brain metastases > 1cm diameter
DWI and ADC ratios for stable vs tumor progression
Increase: DWI tumor/DWI white matter
(Sensitivity/specificity: 83.9%/88.5%
Decrease: ADC tumor/ADC white matter
(Sensitivity/specificity: 85.5%/72.7%
C-C. Lee, et al., J. Neuro-Oncology 118(2), 2014.


Perfusion MR
T2* time curves
Bolus of Gd injected, time series MR acquired
Signal intensity measured over each ROI
Measure peak height (PH), PSR (percent signal recovery), rCBV (relative cerebral blood volume)
Peak height (PH)
% signal recovery (PSR)
Bolus
Peak height (PH)
% signal recovery (PSR)
Bolus
Time
Shaded area = rCBV
Barajas R et al. AJNR Am J Neuroradiol 2009;30:367-372
Graphs inspired by a presentation by Max Wintermark


Recurrent Tumor
Radiation Necrosis
A
B
Recurrent metastatic tumors are more "leaky" due to faulty BBB and higher capillary permeability
PSR values are lower in recurrences than for radiation necrosis
Mean and max rCBV and rPH values are higher for recurrences
Barajas R et al. AJNR Am J Neuroradiol 2009;30:367-372


Proton MR Spectroscopy (¹H MRS)
Choline
Lipid/Lactate
Normal
Cho
Cr
NAA
Slide courtesy of Jason Sheehan, University of Virginia

Radiation injury vs recurrent glioma

	T1 MR w ROI	T1+C MR	MR Spect	Ratio differences
Radiation injury				
Recurrent tumor				>Cho/Cr* >Cho/NAA* <NAA/CR* *p<0.01, n=55

Q. Zeng, et al., J Neurooncol 84(1), 2007

Conclusions

Stereotactic radiosurgery requires careful understanding of procedural uncertainties

Re-irradiation reduces the acceptable uncertainty budget

Gamma Knife radiosurgery assists in re-irradiation scenarios by minimizing the beam-delivery portion of the uncertainty chain

Quantitative imaging can help evaluate when re-irradiation is appropriate

Thank You!

Acknowledgements

University of Virginia
Jason Sheehan
Zhiyuan Xu

Elekta Instrument, AB
Håkan Nordström
Jonas Johansson

And of course the organizers – Thank You!

One-way to get re-irradiated. (Hint: don't do this with a loaded Gamma Knife!)