Strategies and Technologies for Cranial Radiosurgery Planning

MLC-based Linac Radiosurgery

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Disclosure

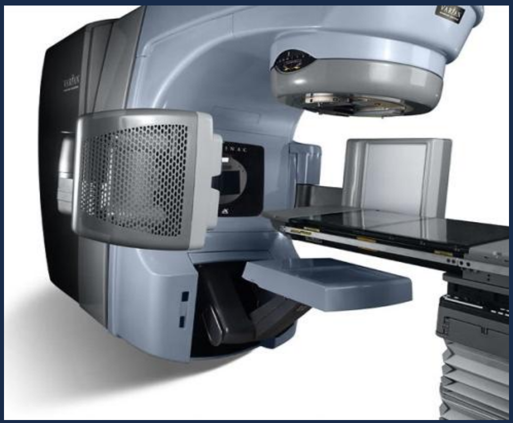
- No conflict of interests to disclose.

Learning Objectives

- Introduce the overview of MLC-based Linac radiosurgery.
- Demonstrate basic treatment planning techniques for MLC based radiosurgery
- Discuss metrics for evaluating SRS treatment plan quality.

Overview

BrainLAB m3



Varian Trilogy

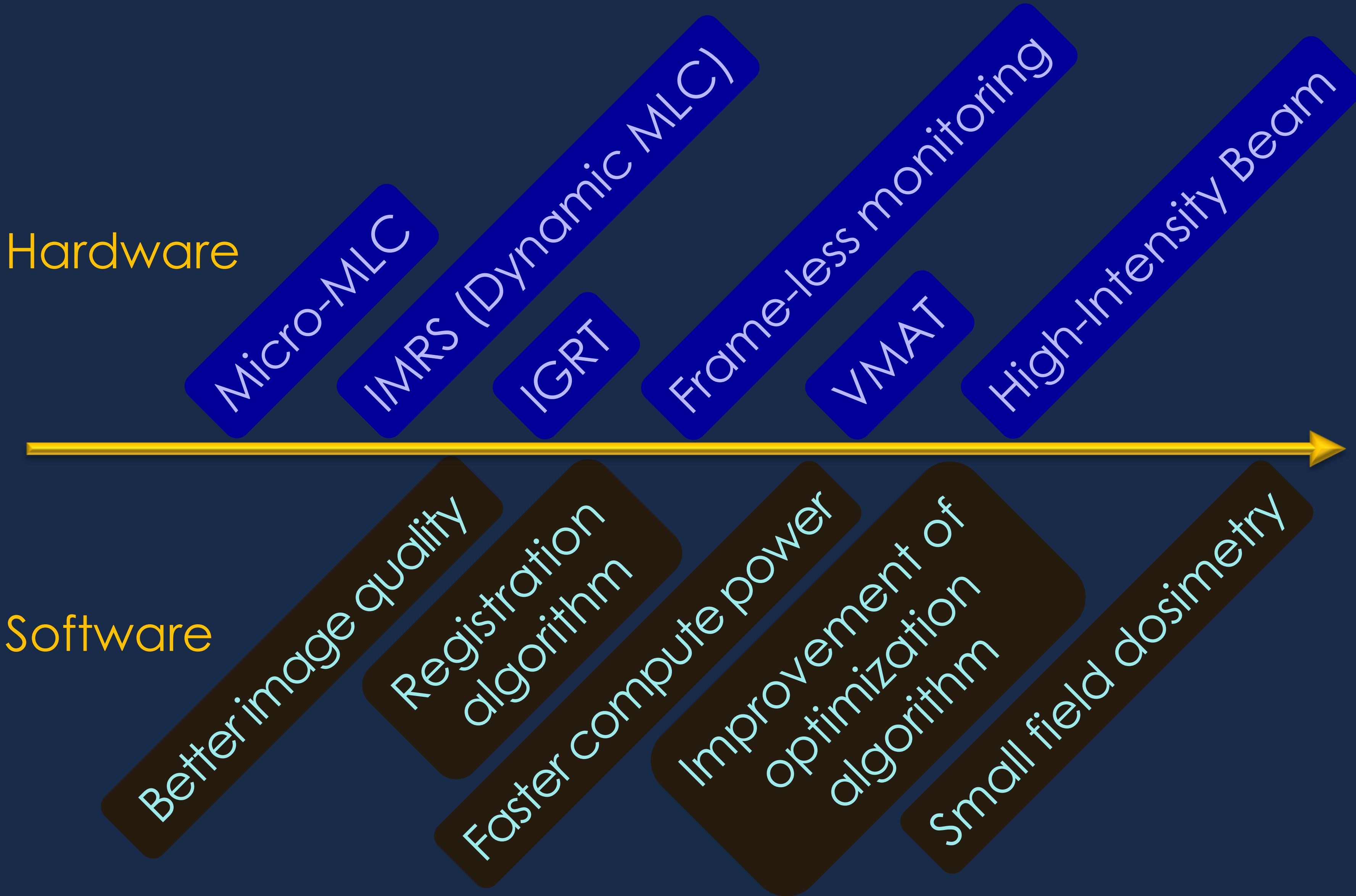
Elekta Axesse

Novalis

Varian Edge

Elekta VersaHD

Evolution of technology



MLC based Linac SRS

- Better conformity for irregular target
- Improved dose homogeneity inside the target
- Comparable dose fall-off outside the target
- Less time-consuming treatment planning
- Shorter treatment time
- Linac is not limited for cranial treatment

SAM Question 1.

What is one advantage of MLC-based Linac radiosurgery over other machines?

79%	1. Relatively fast treatment delivery
10%	2. Easy to treat heterogeneous tissues
2%	3. Multiple choices of different cone sizes
3%	4. More accurate delivery
5%	5. Easy forward planning

What is one advantage of MLC-based Linac radiosurgery over other machines?

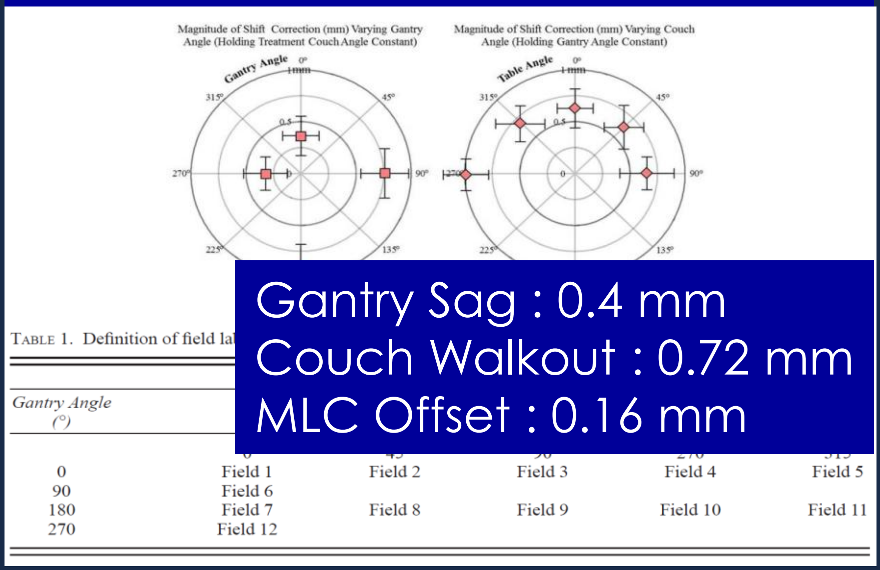
Answer: 1. Relatively fast treatment delivery

Ref: L Ma et al., Variable dose interplay effects across radiosurgical apparatus in treating multiple brain metastases, Int. J CARS, 20 April 2014

Mechanical Stability

- Linac (TG-142)
  - Coincidence of Radiation & Mechanical ISO
    - ±1 mm from baseline
  - Couch position indication tolerance
    - 1mm/0.5 degree

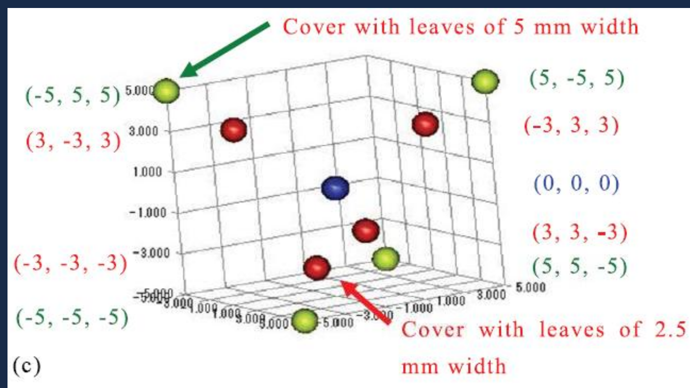
Denton et al., JACMP, 16 (2) 175-188, (2015)

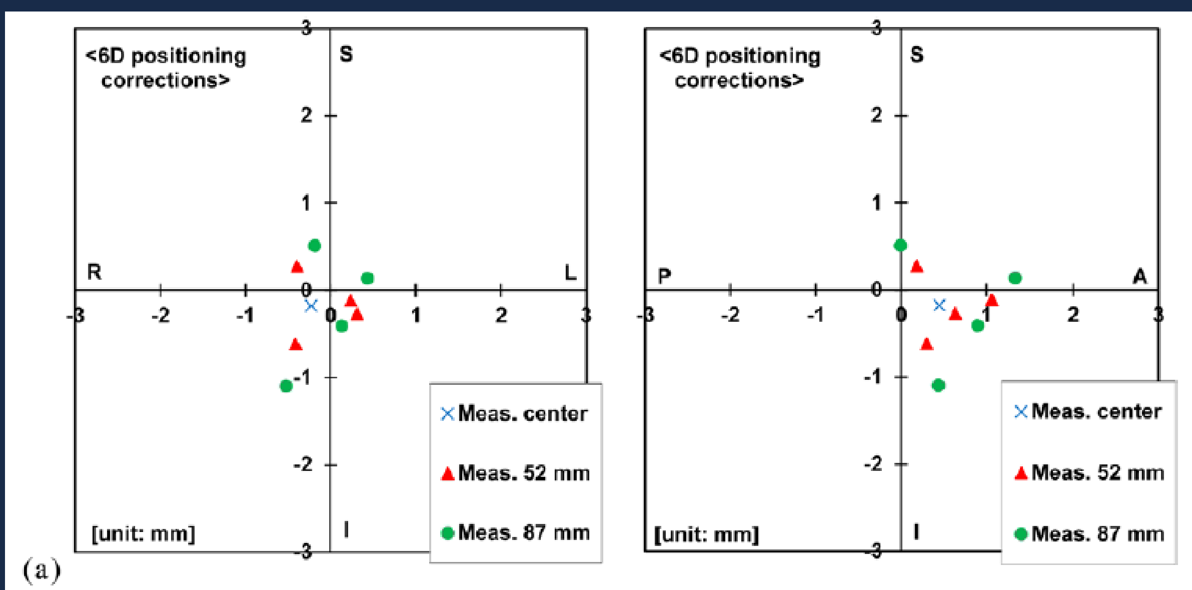


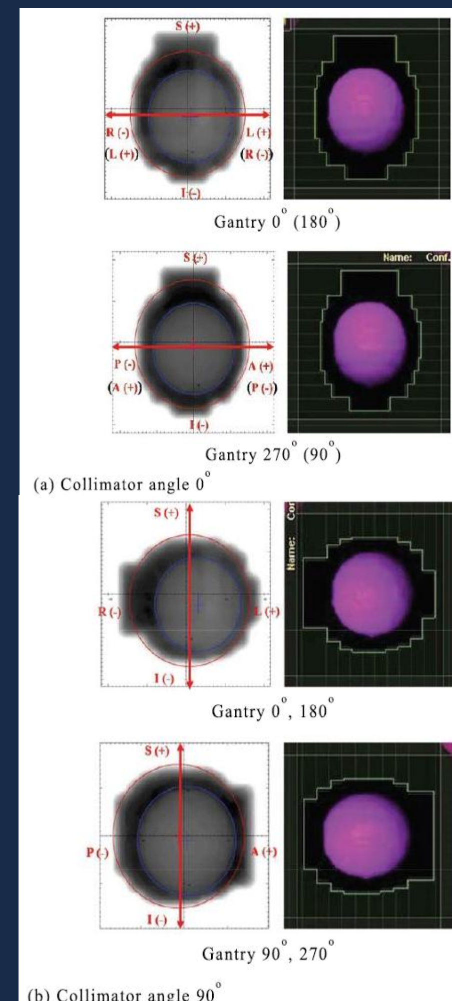
- IGRT (TG-142)
  - KV, MV, CBCT, monitoring image system coincidence
    - ≤ 1 mm
  - Positioning/repositioning
    - ≤ 1 mm

Multiple Metastases

Tominaga et al., Physics in Med. & Biol., **59**, 7753-7766 (2014)







Beam Configuration for Small Field

- Small Field Dosimetry
  - Machine-specific-reference field (msr)
  - Plan-class specific reference field (pcsr)
- Beam Configuration
  - Dosimetry leaf gap
  - Transmission
  - Target Spot Size

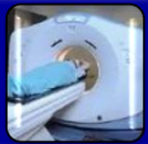
Table 14 Example Values for Target Spot Size Parameters

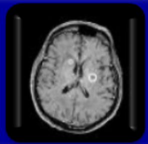
Algorithm / Treatment Unit	Spot Size X-direction [mm]	Spot Size Y-direction [mm]
AAA / Varian treatment unit	0.0 1.0 if MLC in field	0.0 0.0 if MLC in field
Acuros XB / Varian treatment unit	1.0 1.5 if MLC in field	1.0 0.0 if MLC in field
AAA / Elekta Beam Modulator	2.5	0.0
Acuros XB / Elekta Beam Modulator	2.5	0.0
AAA / Other Elekta treatment units	0.0 1.0 if MLC in field	0.0 0.0 if MLC in field
Acuros XB / Other Elekta treatment units	1.0 1.5 if MLC in field	1.0 0.0 if MLC in field
AAA / Siemens treatment units	2.0	2.0
Acuros XB / Siemens treatment units	2.5	2.5

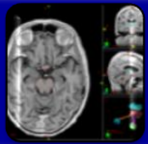
In all cases, fine-tuning of the spot size parameter values can be performed based on matching measurements and calculations.

Eclipse Photon and Electron Algorithms Reference Guide, Dec., 2014, p62

Treatment Planning

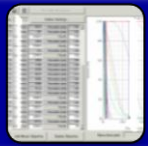

Imaging


Registration


Contouring

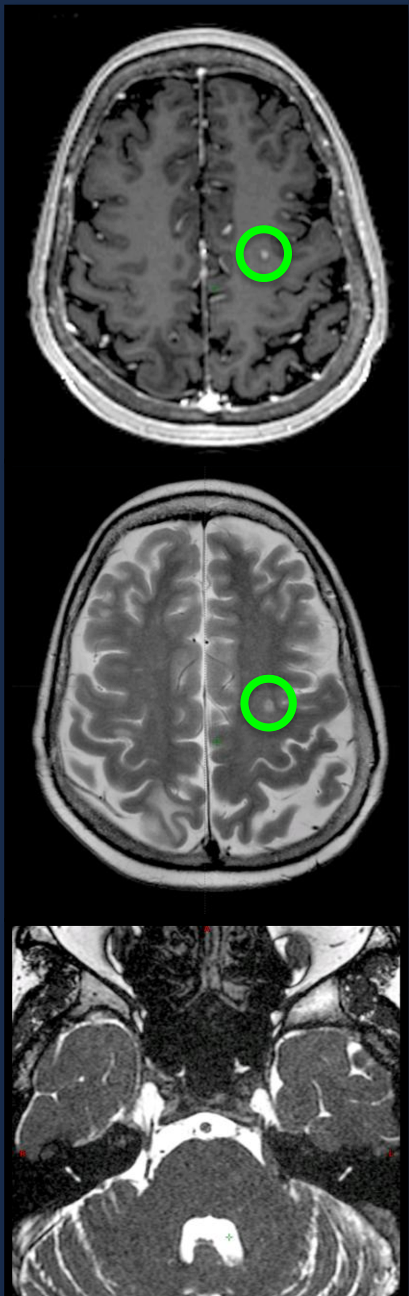

Prescription


Setting up the fields


Optimization


Plan Evaluation

Imaging



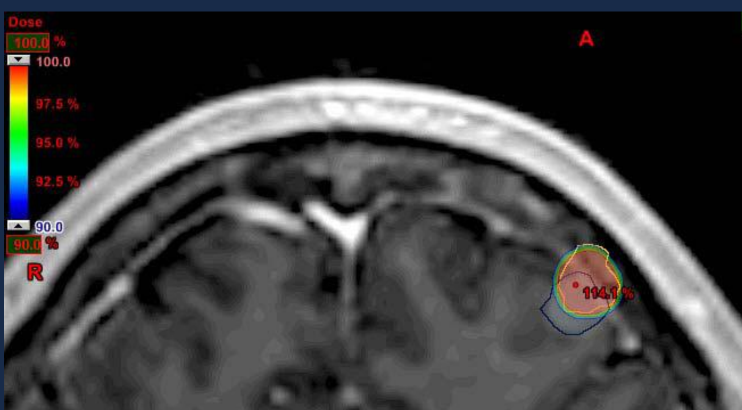
- Metastatic
  - MRI with Gadolinium
    - T1 post contrast (thin slice)
    - Small non-enhancing lesions may be seen on T2
    - T2 Flair showed peritumoral edema
  - CT Head with contrast
    - If MRI unavailable
    - Combine target delineation
- AVM
  - CTA, DSA, MRA
- Trigeminal Neuralgia
  - T1 post, FIESTA

TG-54

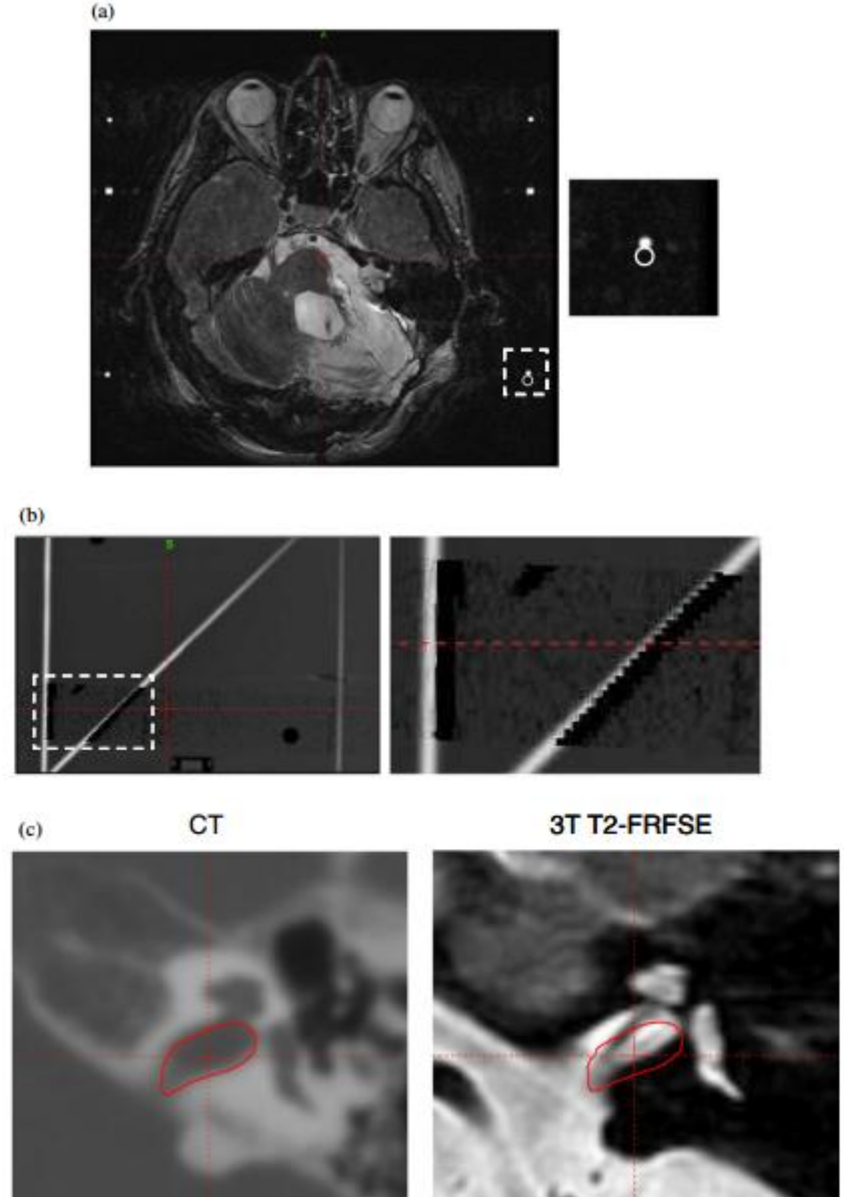
“MRI contains distortions which impede direct correlation with CT data at the level required for SRS”

TG-117

Use of MRI data in Treatment Planning and Stereotactic Procedures – Spatial Accuracy and Quality Control Procedures



Gradient nonlinearity distortion, Siebert et al, ASTRO 2014



B Zhang et al., Phys. Med. Biol. 55 (2010) 6601-6615

...ical impact of geometric distortion of stereotactic references. (a) Stereotactic ...on in MR. (b) Stereotactic reference deviation in sagittal view (subtraction between CT and MR). (c) Displacement of the internal auditory canal (red contour) between CT and MR as a result of stereotactic reference deviation in MR.

Planning CT

- Slice Size (< 1.5 mm)
  - Spatial resolution of Z axis
  - Thick slices: more partial volume averaging.
- FOV (Pixel = FOV/matrix)
  - Smaller is better
- Body
- Immobilizer / Registration
- Target localization

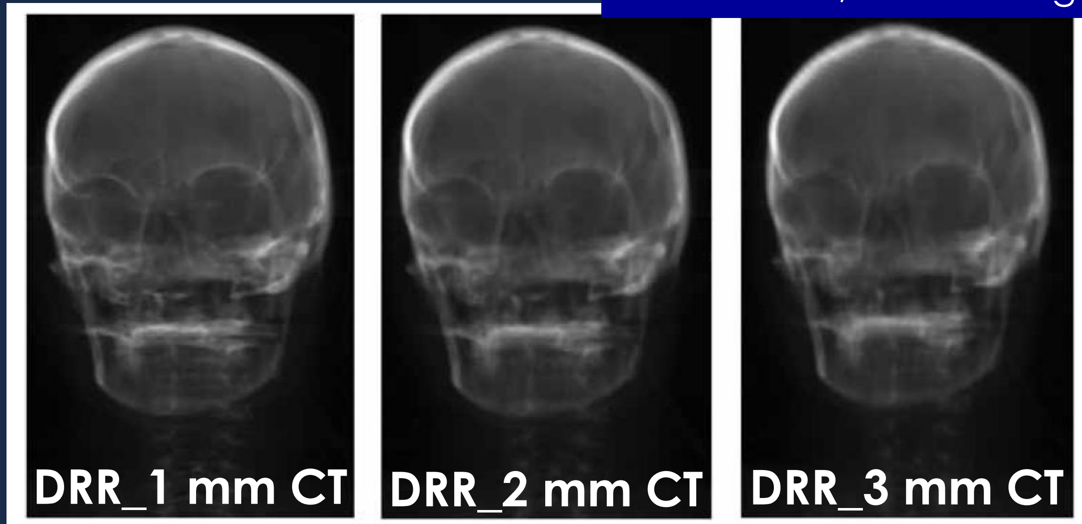
Uncertainty – TG54

TABLE II. Achievable Uncertainties in SRS

Stereotactic Frame	1.0 mm	1.0 mm
Isocentric Alignment	1.0 mm	1.0 mm
CT Image Resolution	1.7 mm	3.2 mm
Tissue Motion	1.0 mm	1.0 mm
Angio (Point Identification)	0.3 mm	0.3 mm
Standard Deviation of Position Uncertainty (by Quadrature)	2.4 mm	3.7 mm

Planning CT - IGRT

Bellon et al., J. Radiosurgery and SBRT, 3, (2014)



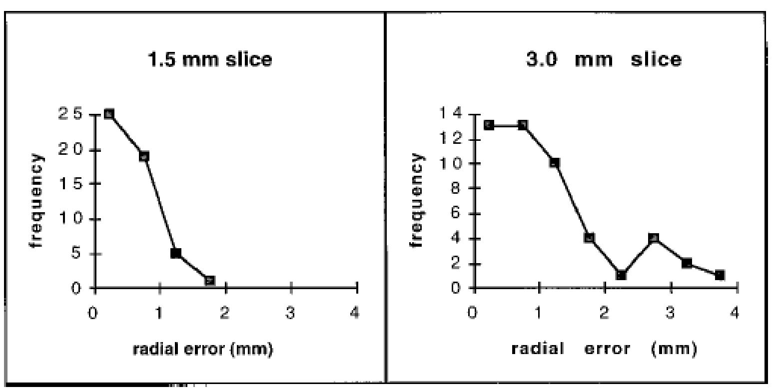
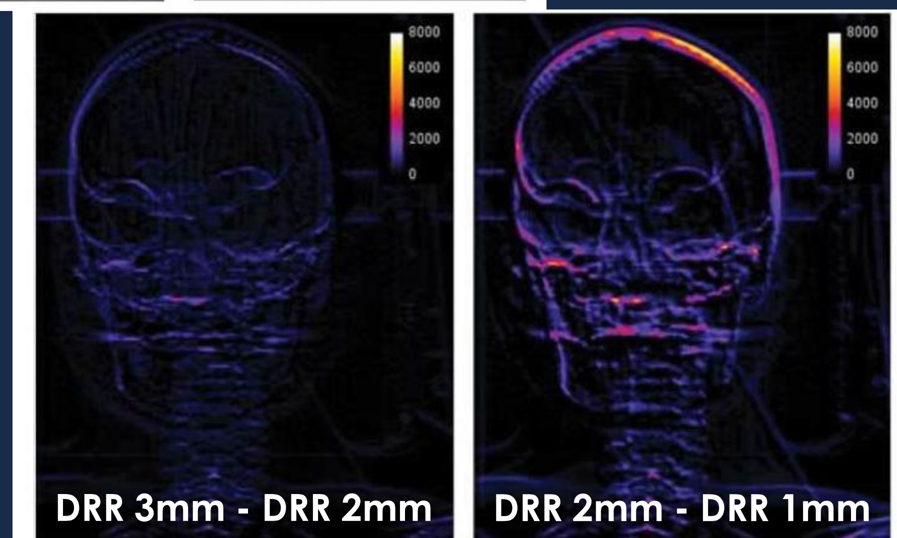


FIG. 4. The distribution of net radial errors in locating a point 10.4 cm from the center of the skull, using the positioning results of the simulations.

Murphy et al., Med. Phys., **26** (2), (1999)



SAM Question 2.

What is the most appropriate imaging modality for target delineation of brain metastases?

1%	1.	Digital subtraction angiography (DSA)
14%	2.	MRI T2 weighted FLAIR
83%	3.	MRI T1weighted + Contrast
0%	4.	Scout image
2%	5.	Computed tomography

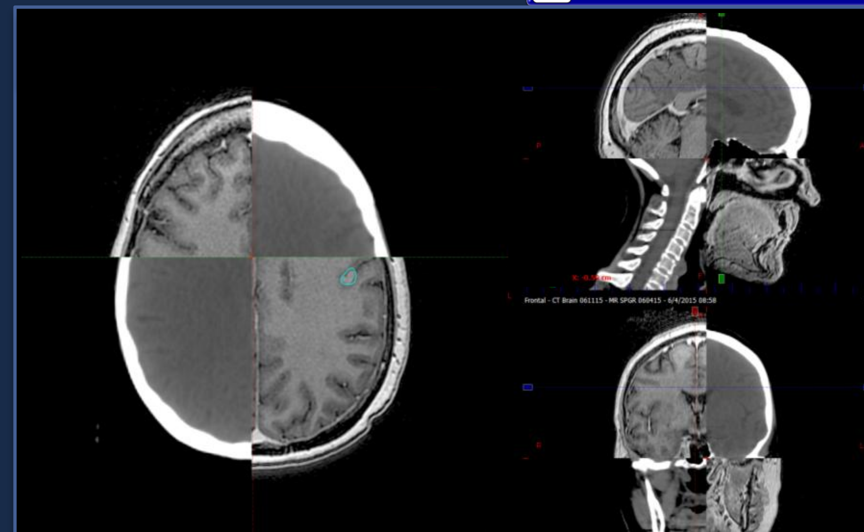
What is the most appropriate imaging modality for target delineation of brain metastases?

Answer: 3. – MRI T1 FS + Contrast

Ref: Kathleen R. Fink, James R. Fink, “Imaging of brain metastases” Surgical Neurology International. Vol.4, s209-s219 (2013)

Registration

CT/CT registration



CT/MR registration

- Benchmark Test for Cranial CT/MR Registration
  K. Ulin et al., IJROBP, **77** (5), 1584-1589 (2010)
  - 45 Institutions and 11 software systems
  - Average error: 1.8 mm
  - MR 2.0 mm Thickness, CT 2.5 mm Thickness
  - Manual registration: significant better result

Registration

- FMEA study of surface image guided radiosurgery (SIG-RS)

TABLE IV. Top ten failure modes ranked by RPN.

Rank	Step	Potential failure modes	Potential cause of failure	Potential effects of failure	O	S	D	RPN
1	31. Contour critical structures	Inaccurate contours	Poor image quality Poor registration Insufficient training	Excessive dose to critical structure	6	8	6	288
1	79. Apply CBCT couch shifts	Inaccurate CBCT–CT registration	Poor image quality Inattention.	Geometric miss	6	8	6	288
3	29. Previous tx CT registered to planning CT	Inaccurate CT–CT registration	Failed to save registration. Registration error	Retreat previous target.	5	8	7	280
4	39. Review OAR statistics	Critical structure doses not checked	Inattention	Excessive dose to critical structure	5	8	6	240
4	29. Previous tx CT registered to planning CT	Not done	Inattention	Retreat previous target	5	8	6	240
4	33. Insert Rx and contour target volumes	Contours accidentally changed by planner	Contours not locked	Underdosing of target volume	6	8	5	240
7	23. Images labeled with acquisition date and technique	Incorrect date label	Transcription error	May cause confusion and/or affect MD decision making	5	6	7	210
8	84. Monitor SIG indicated offsets to ensure patient position is within tolerance	SIG system fails to detect patient movement	SIG system failure	Geometric miss	3	8	8	192
9	59. Ensure SRS QA has been completed (Winston–Lutz, etc.) (P)	SRS QA not checked	Inattention	System out of tolerance	6	6	5	180
9	60. Ensure daily integrated IGRT QA has been performed (P)	IGRT QA not checked	Inattention	System out of tolerance	6	6	5	180

Manger et al., Medical Physics, **42** (5), 2449-2461 (2015)

Contouring

J Neurosurg (Suppl) 117:203–210, 2012

Reliability of contour-based volume calculation for radiosurgery

Laboratory investigation

Lijun Ma, Ph.D.,[1] Arjun Sahgal, M.D.,[4] Ke Nie, Ph.D.,[1] Andrew Hwang, Ph.D.,[1] Aliaksandr Karotki, Ph.D.,[4] Brian Wang, Ph.D.,[3] Dennis C. Shrieve, M.D., Ph.D.,[3] Penny K. Sneed, M.D.,[1] Michael McDermott, M.D.,[1] and David A. Larson, M.D., Ph.D.[1,2]

[1]Department of Radiation Oncology, University of California, San Francisco; [2]Washington Fremont Hospital Gamma Knife Center, Fremont, California; [3]Department of Radiation Oncology, University of Utah, Salt Lake City, Utah; and [4]Department of Radiation Oncology, Sunnybrook Odette Cancer Centre, Princess Margaret Hospital, University of Toronto, Ontario, Canada

- Tested 6 SRS TPS platforms
- Phantom study shows -3.6-22% vol. variation
- Most of platforms & algorithm overestimated
- Large variation: small target < 0.4 cc, near the end slice

Planning Target Volume

Clinical Investigation

Kirkpatrick et al., IJROBP, 91 (1) 100–108, (2015)

Defining the Optimal Planning Target Volume in Image-Guided Stereotactic Radiosurgery of Brain Metastases: Results of a Randomized Trial

John P. Kirkpatrick, MD, PhD,[*,†] Zhiheng Wang, PhD,[*] John H. Sampson, MD, PhD,[*,†] Frances McSherry, MA,[‡] James E. Herndon II, PhD,[‡] Karen J. Allen, ANP,[*] Eileen Duffy, RN, OCN,[*] Jenny K. Hoang, MBBS,[§] Zheng Chang, PhD,[*] David S. Yoo, MD,[*] Chris R. Kelsey, MD,[*] and Fang-Fang Yin, PhD[*]

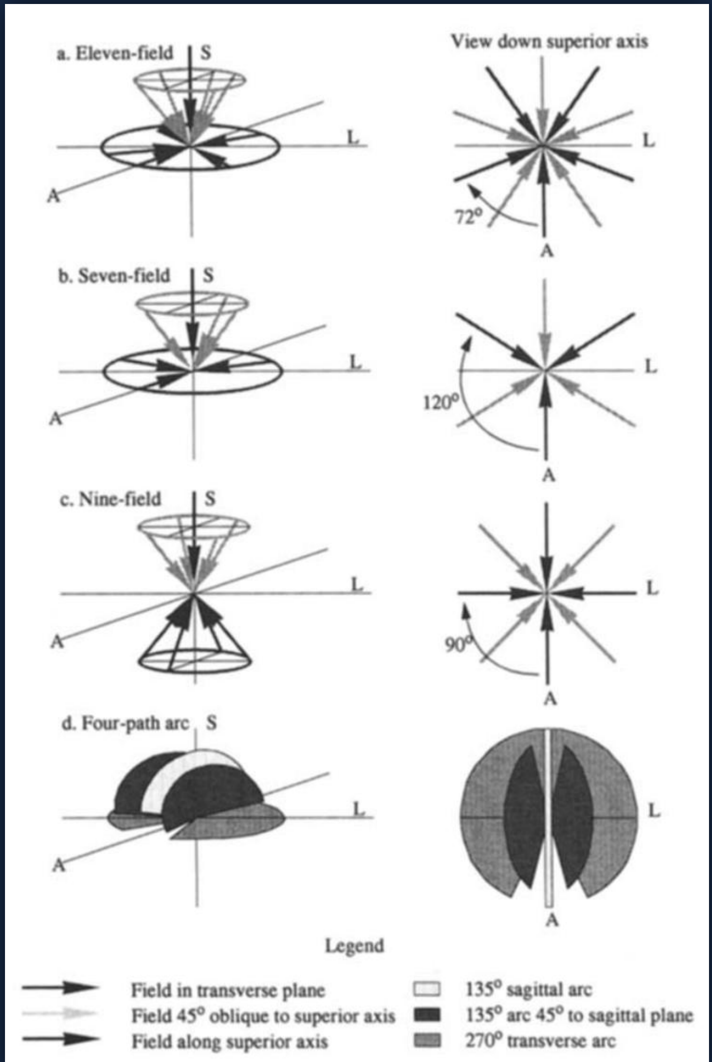
*Departments of *Radiation Oncology, †Surgery, ‡Biostatistics & Bioinformatics, §Radiology, Duke University, Durham, North Carolina*

- Randomized Trial to 1-mm versus 3-mm expansion with IG-SRS
- The local recurrence rate was low for both arms (<10% 12 months after SRS)
- Biopsy-proven radionecrosis was more frequently observed in the 3-mm arm
- Suggest a 1-mm margin is appropriate for IG-SRS

Prescription

- Treatment regimens
  - Target volume (RTOG 90-05)
  - Target location
  - Pre-existing edema
  - Pre-existing neurologic deficit
  - Pathology
  - Previous treatment

Beam Geometry



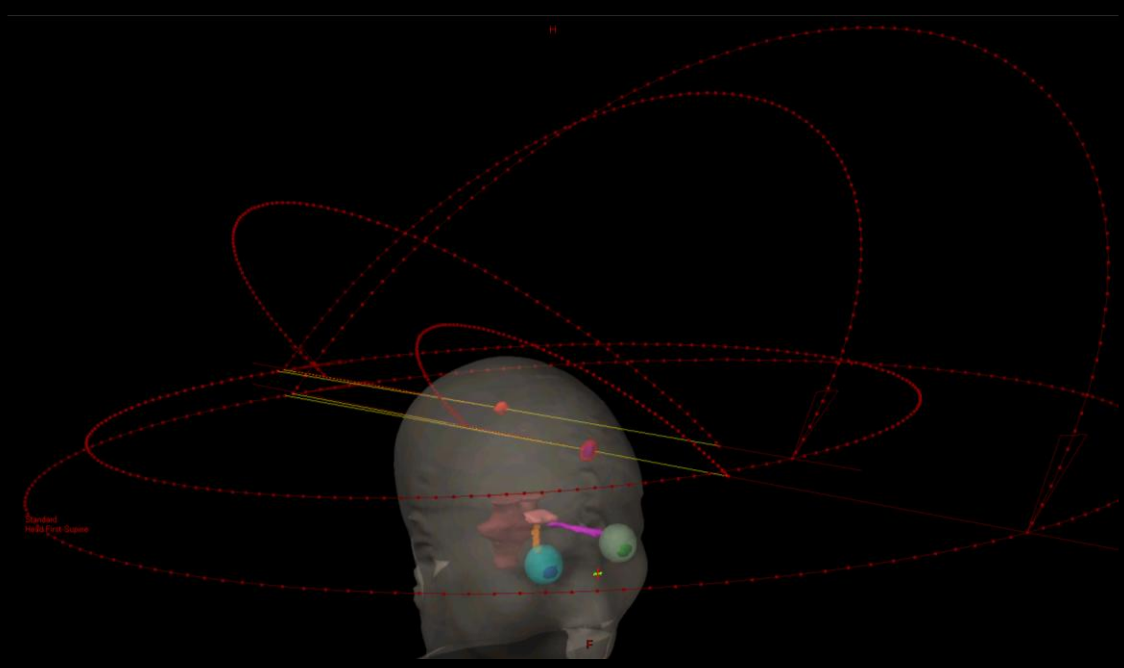
J D Bourland and K P McCollough, IJROBP, 28(2). 471-479, (1994)

- Static , DCA, IMRS, VMAT approach similar solid angle
- Avoid collision
- Reasonable number of beams
- BEV play
- Select isocenter

Multi-met Planning Strategy

Multi-iso approach

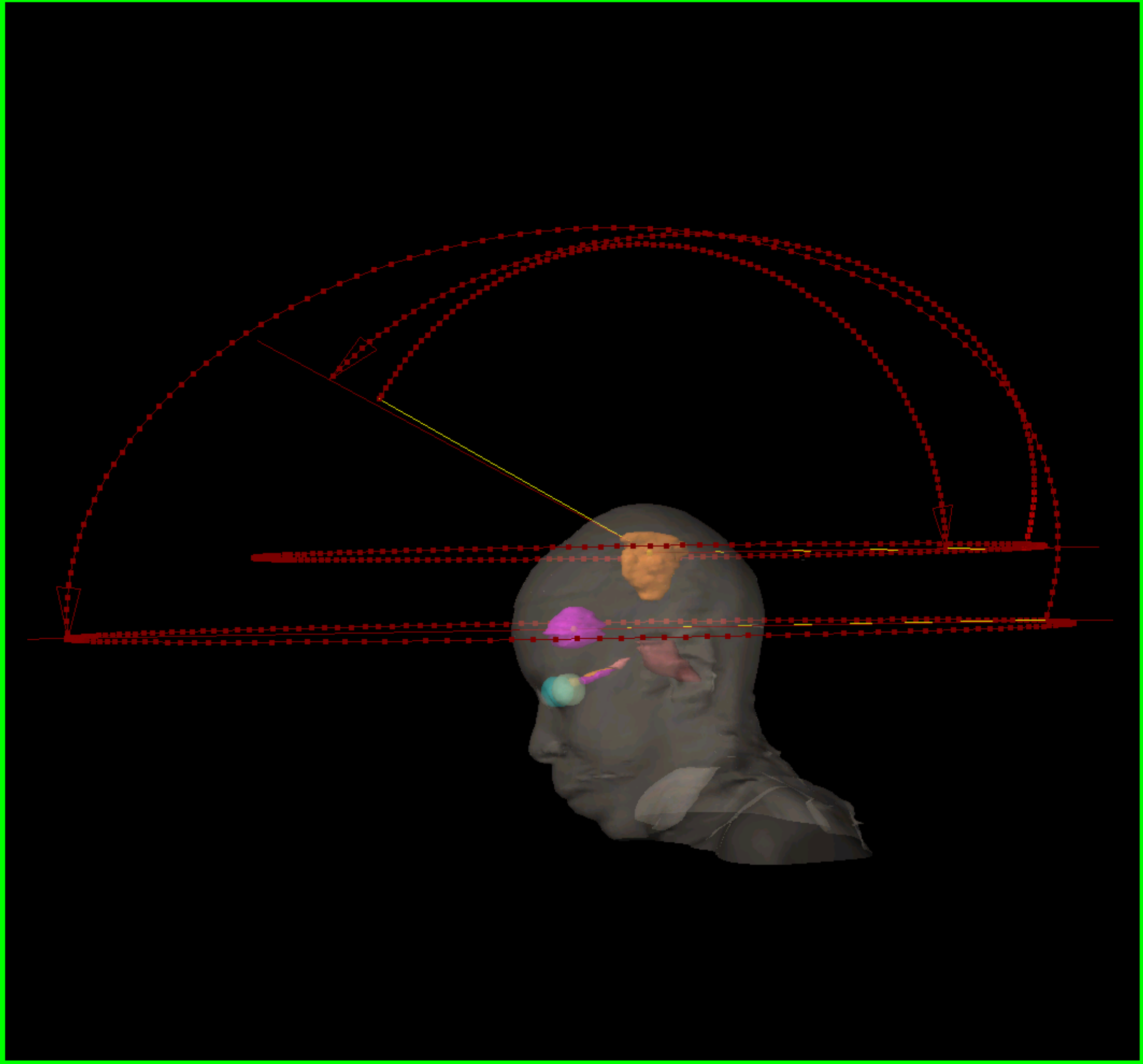
- Relatively easier to achieve good plan quality
- Less influenced by setup uncertainty
- Hard to control sum dose



Multi-met Planning Strategy

Base plan approach

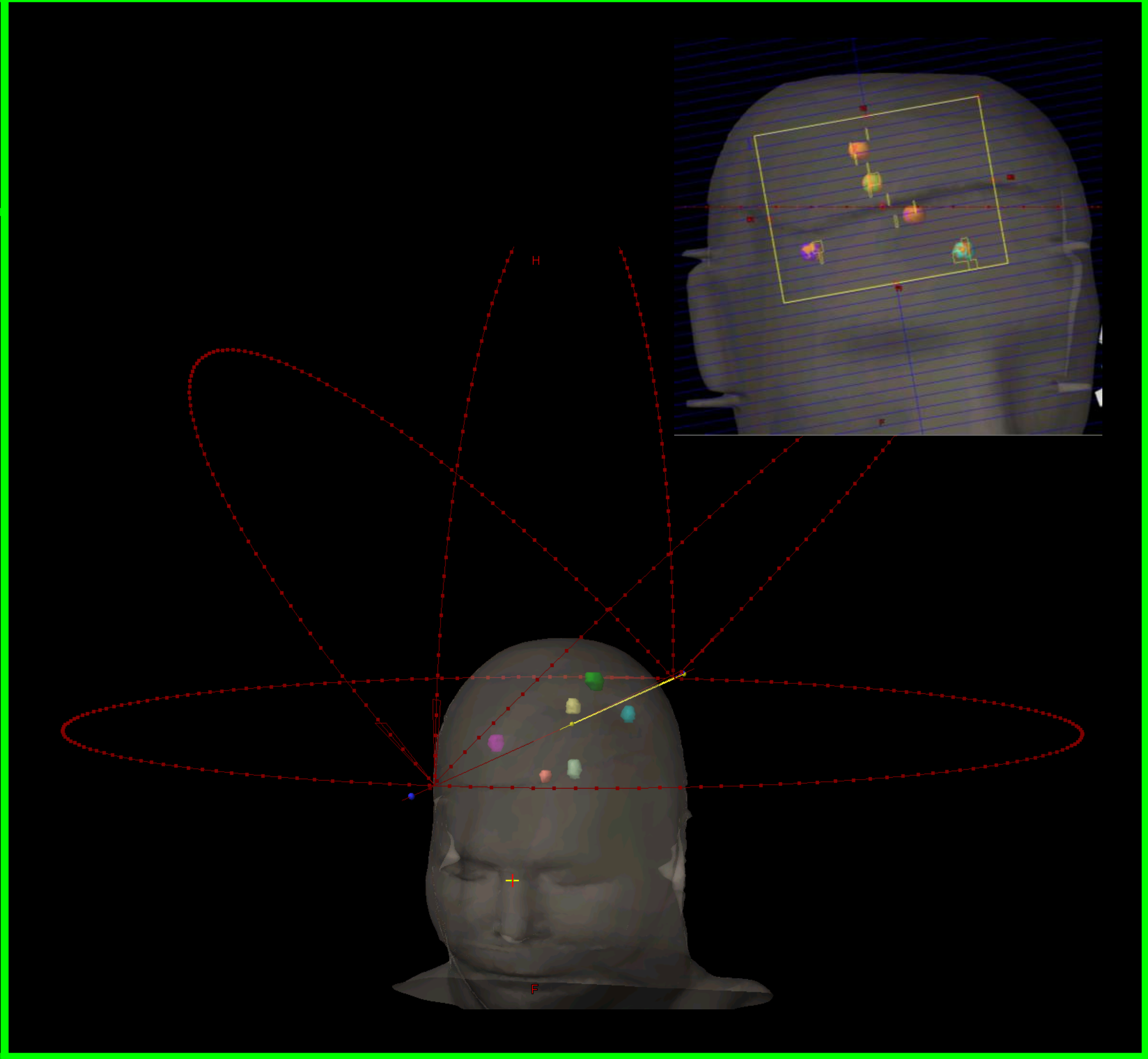
- Contribution dose can be considered during the optimization
- Worse plan quality indices as an individual plan



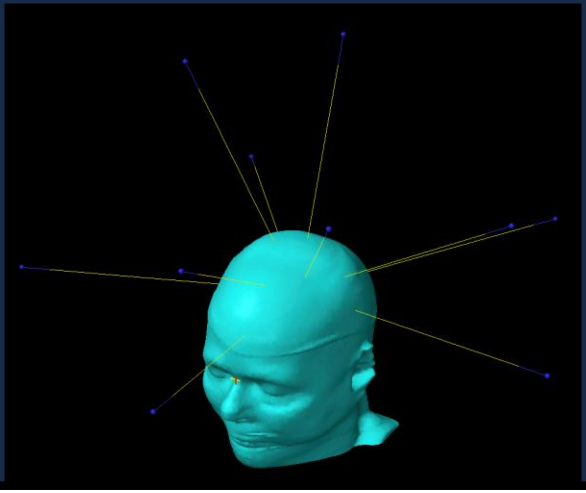
Multi-met Planning Strategy

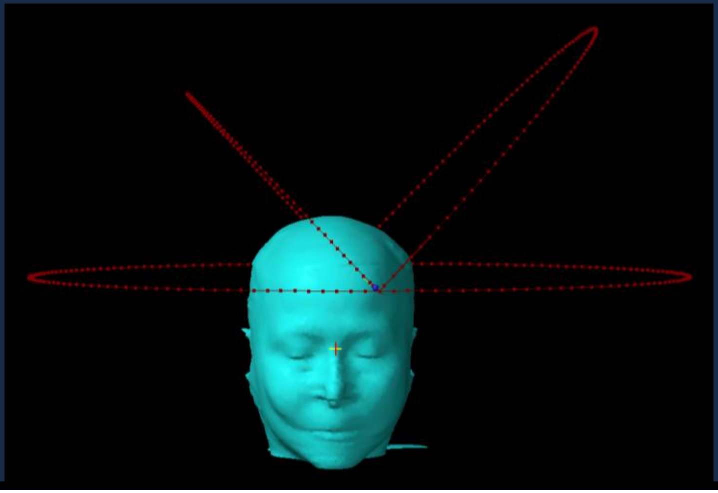
Single-iso approach

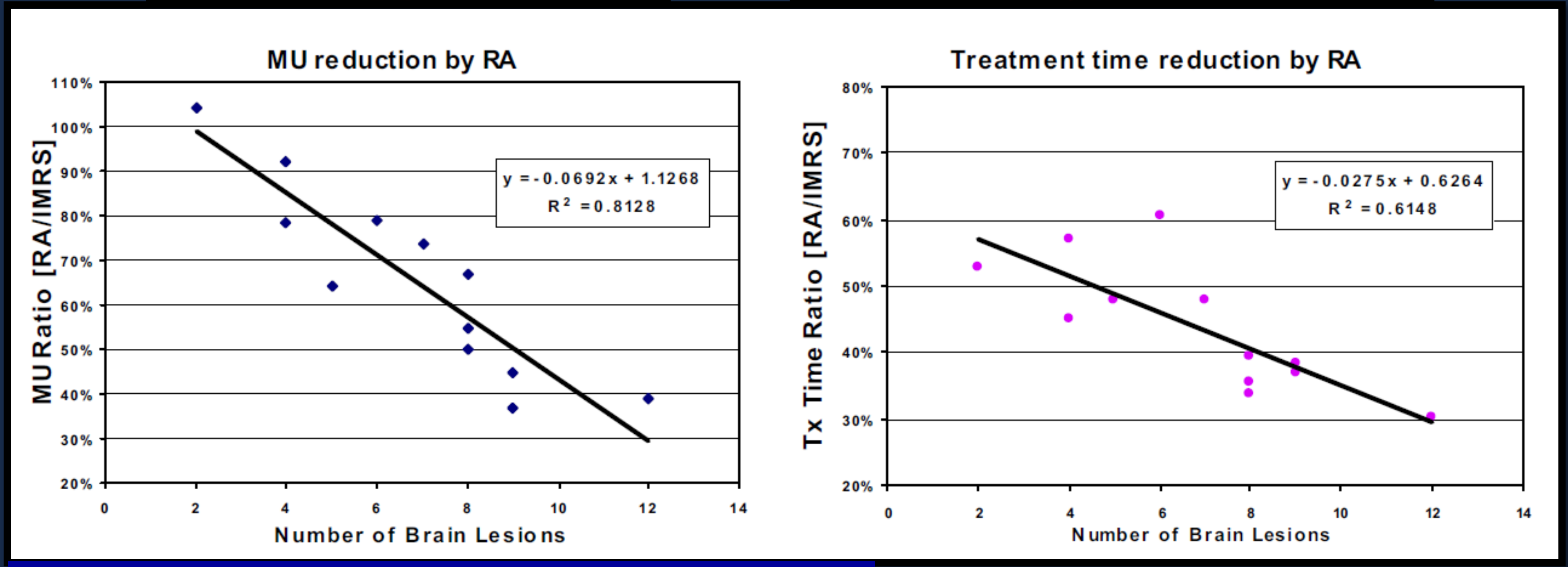
- Need better understanding of planning tools
- Requires accurate patient positioning / monitoring method



IMRS vs. VMAT







JZ Wang et al, Medical Dosimetry 37, 31-36, (2012)

Multiple Metastases

< Island blocking problem>

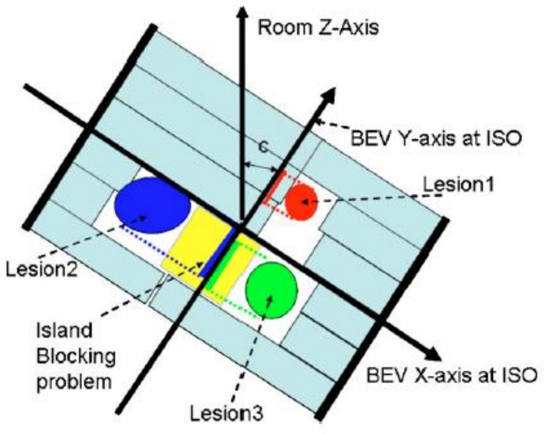


FIG. 1. Schematic beam-eye-view illustration of MLC blocking for an example case with three lesions. The lesions are projected onto the beam *Y*-axis vector. The MLC is unable to block the square region.

< Shadow>

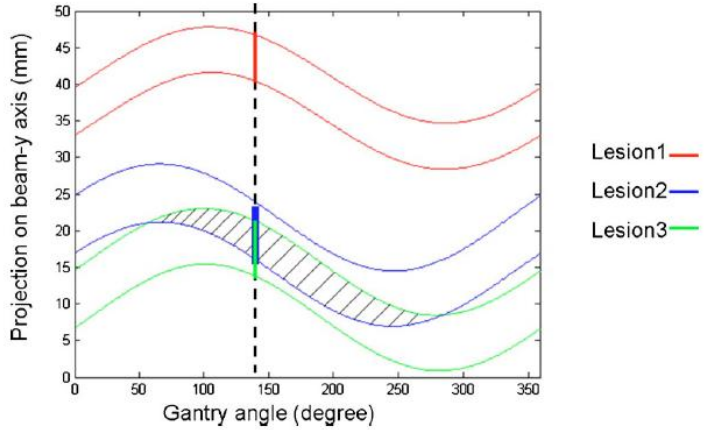
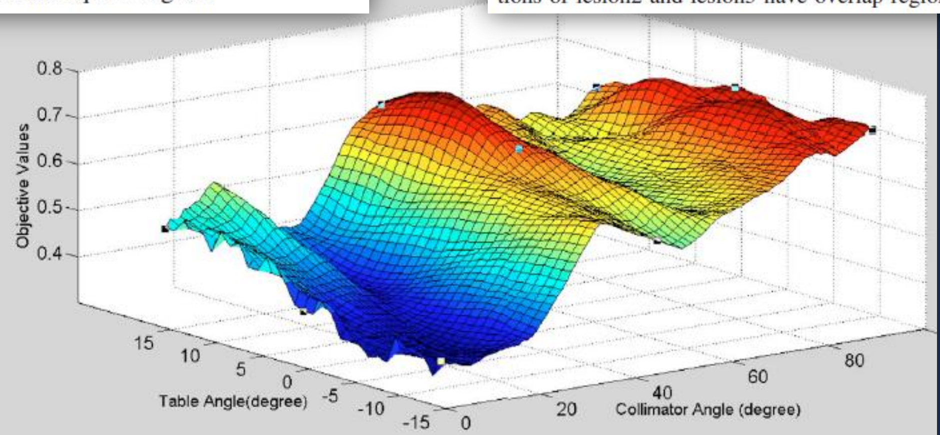


FIG. 2. The sinogram for the three-lesion case. The shadowed region shows the area where two lesions overlap and an island blocking problem is present. The dashed line represents the gantry angle 140°, where the projections of lesion2 and lesion3 have overlap region.



Kang et al., Medical Physics, **37** (8), 4146-4154 (2010)

Plan optimization

- Constraints (GTV, CTV, PTV, OARs)
- NTO or Tuning Structures
- MU constraint
- Optimization resolution
- Calc. grid size

Constraints

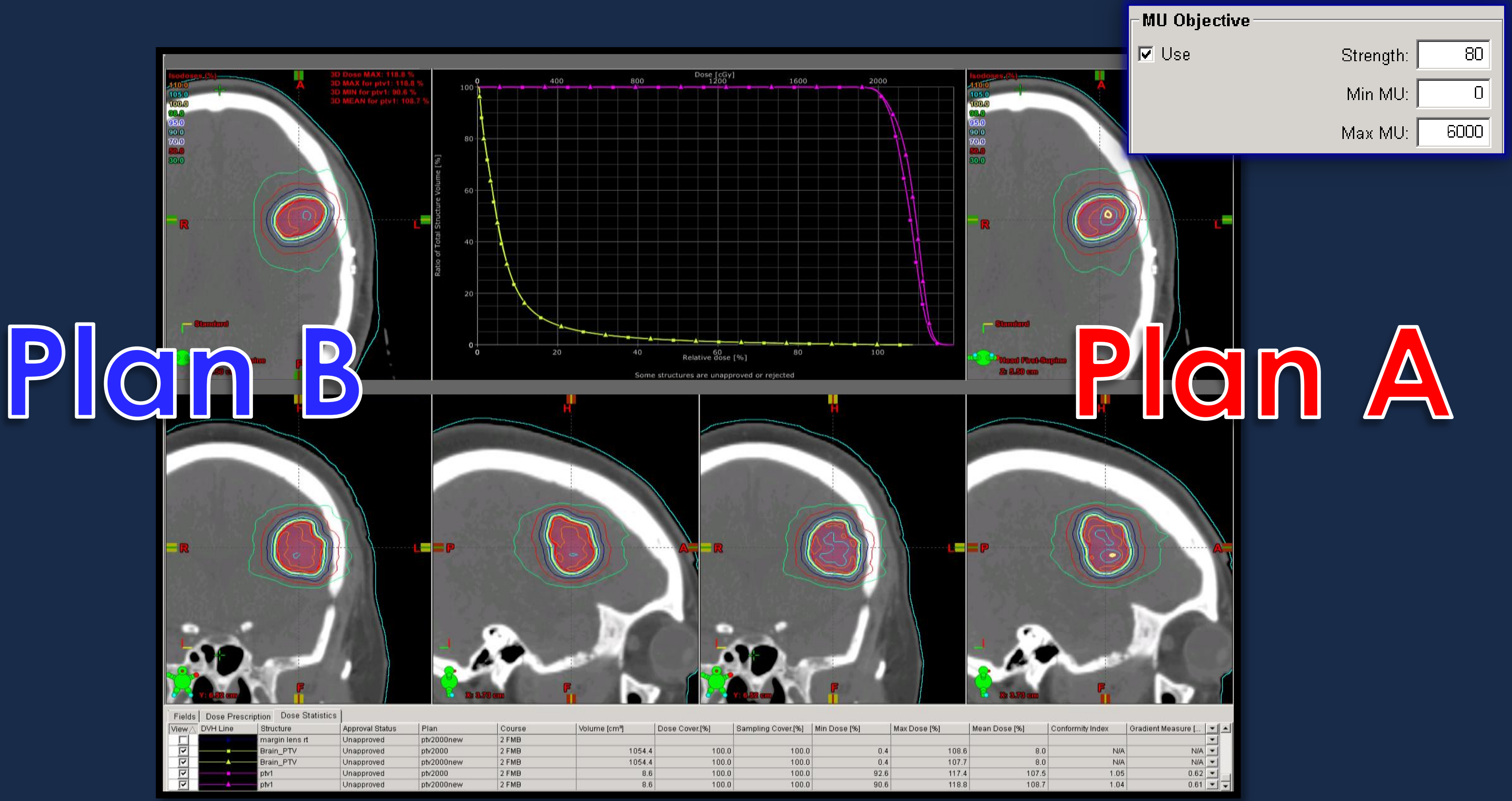
- TG-101

Serial Tissue	Max vol. (cc)	One fraction		Three fraction		Five fraction		End point
		Threshold dose (Gy)	Max point dose (Gy)	Threshold dose (Gy)	Max point dose (Gy)	Threshold dose (Gy)	Max point dose (Gy)	
Optic pathway	<0.2	8	10	15.3	17.4	23	23	Neuritis
Cochlea			9		17.1		25	Hearing loss
Brainstem (not medulla)	<0.5	10	15	18	23.1	23	31	Cranial neuropathy
Spinal cord and medulla	<0.35 <1.2	10 7	14	18 12.3	21.9	23 14.5	30	Myelitis

- Lens Max. dose <10 Gy (1 fx)
- Normal Brain V10 < 12 cc or V12 < 10 cc
- Cranial Nerves (fifth, seventh and eighth CN) 12.5-15 Gy

(Flicker et al., IJROBP 2004)

Plan optimization – MU



Field	Arc 1	Arc 2	Arc 3
Plan A	4116	2105	2105
Plan B	3488 (18% ↓)	1794 (17% ↓)	1794 (17% ↓)

Normal brain dose

Stereotactic radiosurgery for brain metastases: analysis of outcome and risk of brain radionecrosis

Giuseppe Minniti[1,2*], Enrico Clarke[1], Gaetano Lanzetta[2], Mattia Falchetto Osti[1], Guido Trasimeni[3], Alessandro Bozzao[3], Andrea Romano[3] and Riccardo Maurizi Enrici[1]

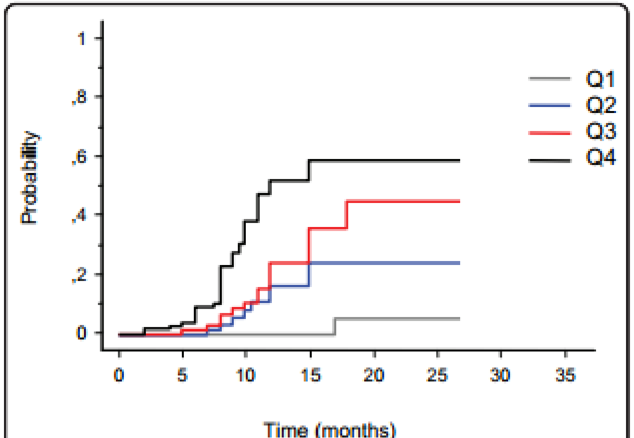


Figure 2 Risk of brain radionecrosis after stereotactic radiosurgery for brain metastases in relation to brain volumes receiving 12 Gy (V12 Gy) stratified for quartiles (Q1-Q4). The risk increased significantly through Q1-Q4, corresponding to V12 Gy < 3.3 cm^3, 3.3-5.9 cm^3, 6.0-10.9 cm^3, and >10.9 cm^3, respectively. The actuarial risk at 1 year was 0% for Q1, 16% for Q2, 24% for Q3, and 51% for Q4

Table 1 Summary of tumor characteristics and treatment parameters

Parameter	No(%)
number of patients	206
median age	62
sex (F/M)	99/107
no of lesions per patient	
1 lesion	126 (61%)
2 lesions	56 (27%)
3 lesions	24 (12%)
histology	
lung	106 (51%)
breast	38 (18%)
melanoma	34 (17%)
others	28 (14%)
tumor location	
frontal	68 (22%)
parietal	78 (25%)
temporal	62 (20%)
cerebellar	43 (14%)
occipital	45 (15%)
brainstem	14 (4%)
radiosurgical dose (Gy)	
20	118 (38%)
18	120 39%)
15-16	72 (23%)
[illegible]	
range	0.2-23.7

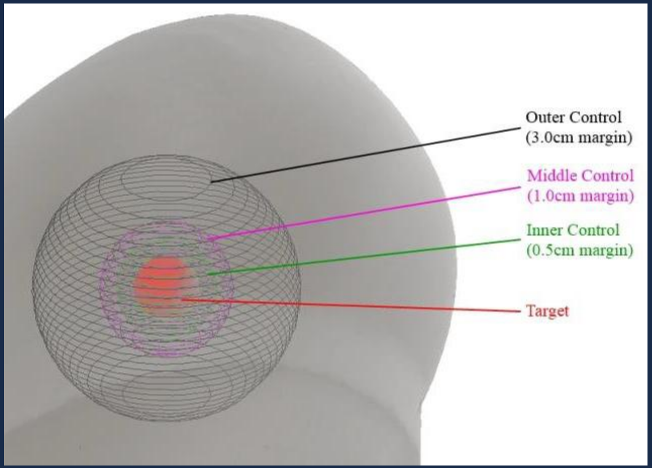
- **V10 and V12 volumes greater than 4.5-7.7 and 6.0-10.9 cc carry >10% risk of symptomatic radiation necrosis , respectively**

G Minniti et al, Radiation Oncology 2011, 6:48

Multi-met optimization

- Optimize individual target
- Single ISO, multiple prescription targets

Tuning Structures



- Individual target(s) (not the composite PTV_total): lower = 100% of the target to receive 102% of prescription, no upper constraint
- **Inner control max dose** = 98% of prescription dose
- **Middle control max dose** = 50% of prescription
- **Outer control max dose** = 40% of prescription

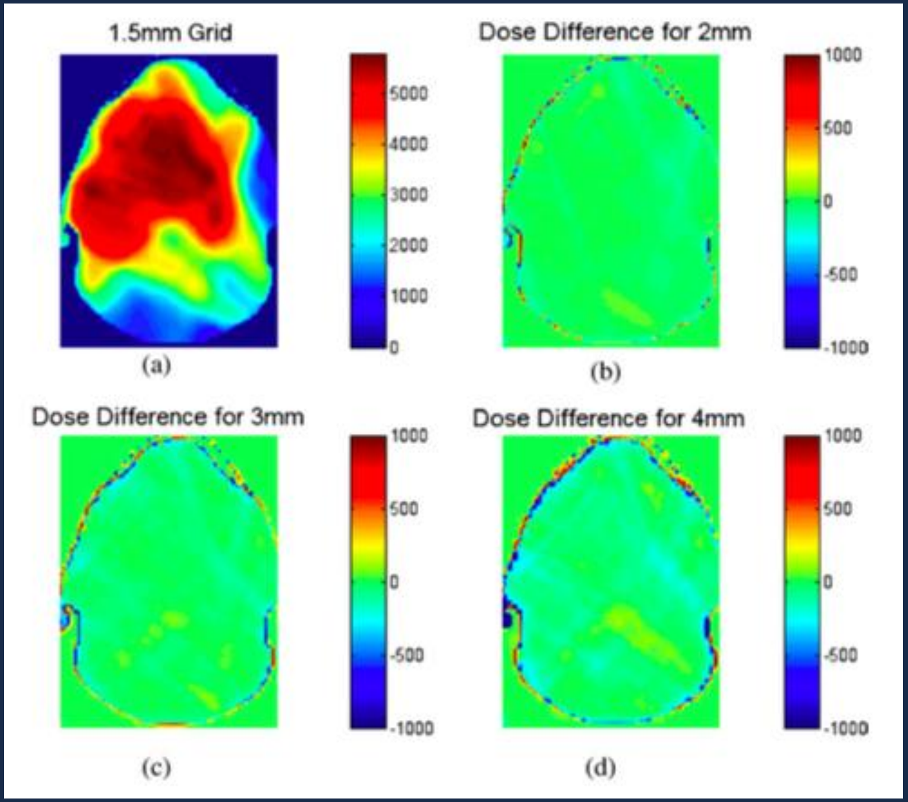
Table 3 Dosimetric indices (15 patients with 1-5 targets)

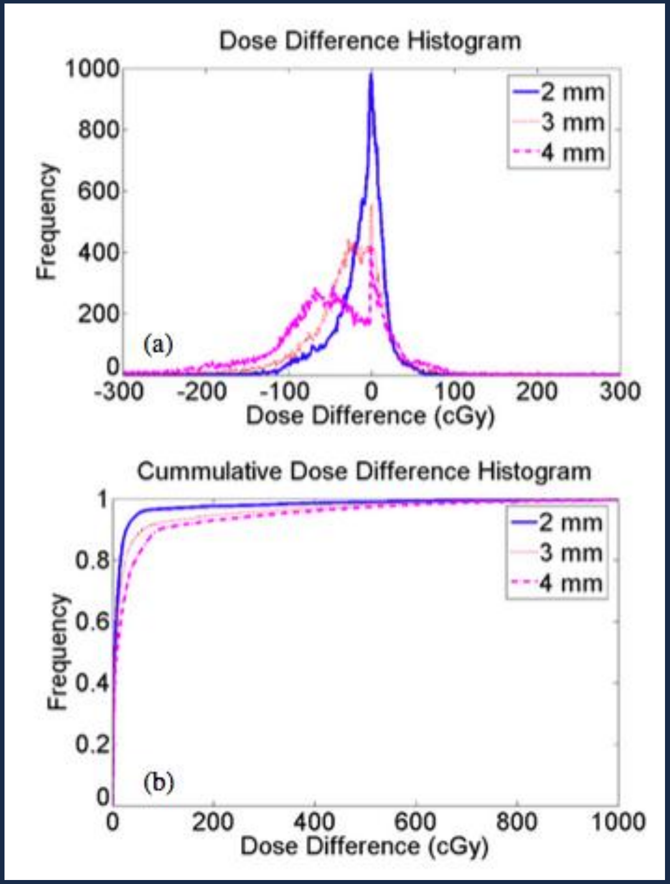
Patient	Target(s)	Target volume (cm^3)	Conformity index	Homogeneity index	Gradient index [a]
Mean		13.17	1.12	1.44	3.34
Standard deviation		13.81	0.13	0.11	0.42
Range		0.43-44.68	0.99-1.49	1.19-1.65	2.53-4.13

[a] Gradient index (GI) is calculated on per-plan basis, with GI = volume of 50% isodose line divided by the volume of the 100% isodose line.

G. Clark et al., Practical Radiation Oncology 2, 306–313, (2012)

Calculation Grid Size

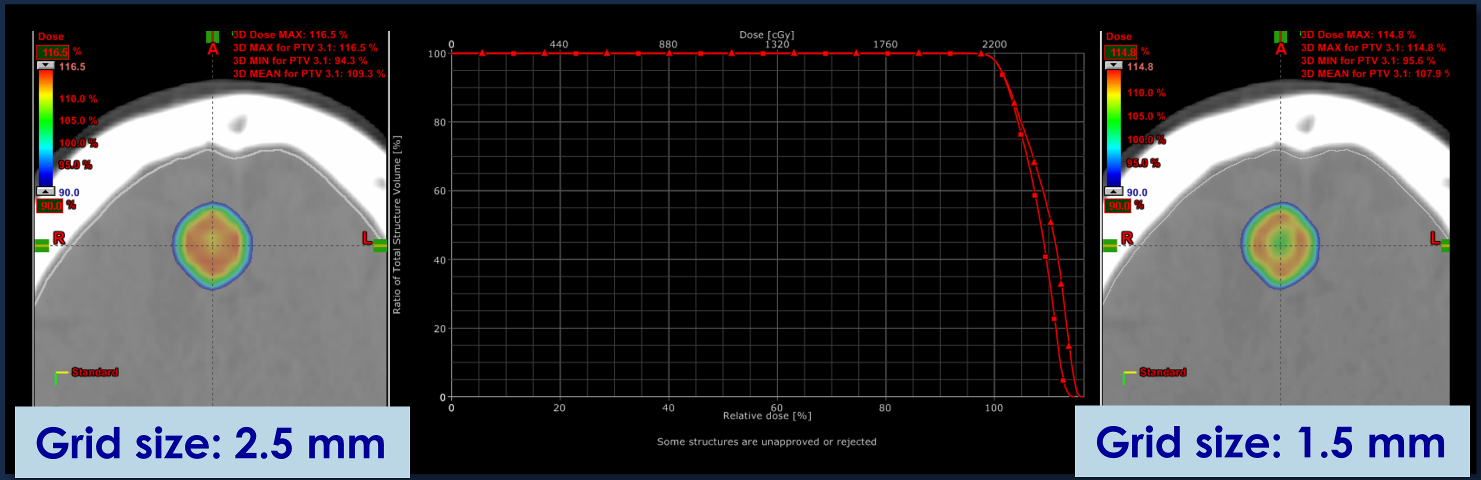




Chung et al., Phys. Med. Biol, 15, 4841-4856 (2006)

Calculation Grid Size

- Expected effects for SRS case



  - Calculation accuracy
  - Max dose
  - Conformity Index
  - Gradient
  - DVH

Plan Evaluation

- Target coverage
  - DVH evaluation
  - Location of hot and cold spots
- Dose to Organ at Risk (OAR)
  - DVH evaluation
- Conformity, Gradient, Homogeneity
- Normal tissue irradiated
- Delivery efficiency
- Number of MU

Gradient

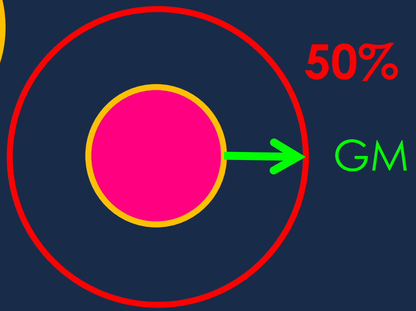
Paddick GI = $PV_{50\%}$ / PV

$PV_{50\%}$ is the volume that received 50% of the effective prescribed dose, and PV the prescribed dose.

- G. Clark et al. GI =3.34 ± 0.42 (15 multi-met patients)

Gradient Measurement (GM)

Difference between the equivalent sphere radius of the prescription and half-prescription



→ Normal Brain Dose, V12 or V10

Conformity

$$\text{RTOG CI} = PV / TV$$

PV = The prescription volume

TV = The target volume

$$\text{Paddick CI} = (TV_{PV})^2 / TV \times PV$$

TV = Target volume

PV = prescription volume

TV_{PV} = Target volume within the prescribed isodose cloud

- G. Clark et al : CI =1.12 ± 0.13 (15 multi-met patients)
- G. Kim et al : CI = 1.14 ± 0.18 (55 multi-met patients)

SAM Question 3.

What should not be used when treatment planning for small size multi-metastases?

1%	1.	High resolution MRI
65%	2.	Co-planar beams
31%	3.	Individual PTV optimization
2%	4.	Smaller calculation grid size
1%	5.	Thin slice planning CT

What should not be used when treatment planning for small size multi-metastases?

Answer: 2. Use co-planar beams

Ref: Audet et al., Evaluation of volumetric modulated arc therapy for cranial radiosurgery using multiple noncoplanar arcs , Medical Physics, Vol. 38, No. 11, November 2011

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