Therapy SAM Symposium: WE-A-BRCD-1

Stereotactic Radiosurgery: State of the Art Technology and Implementation
Linear Accelerator Radiosurgery

Kamil M. Yenice, PhD
Associate Professor
Chief of Clinical Physics
The University of Chicago

Radiosurgery

Å The use of radiation as a “surgical” tool

- *Small* volumes of tissues *within the brain* are treated with *large* doses delivered in a *single* fraction
- Normal tissues are protected by the rapid dose falloff and by delivering the treatment with *high precision*

Most Important!

Å Do you know where to aim?

ï Target (anatomy) localization

Å Common problem for all SRS modalities

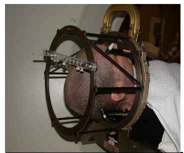
Å Can you hit what you are aiming at?

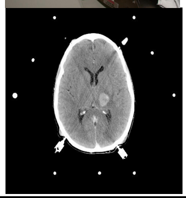
ï Dose Localization

Å Procedure, process, equipment, technique specific

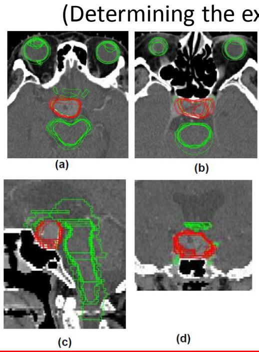
Do you know where to aim?
(Determining exact coordinates of the tumor)

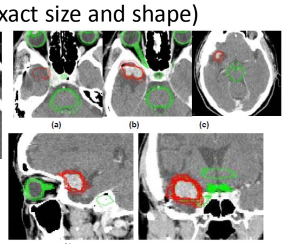
Stereotactic Frames Provide
- patient immobilization
  - rigid fixation of cranial anatomy
- target localization
  - precise identification of target coordinates in a stereotactic coordinate frame
- treatment setup
  - patient setup must guarantee accurate placement of target coordinates to the nominal isocenter of the linac

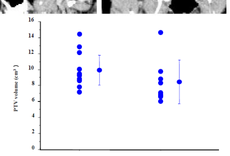




Do you know where to aim?
(Determining the exact size and shape)

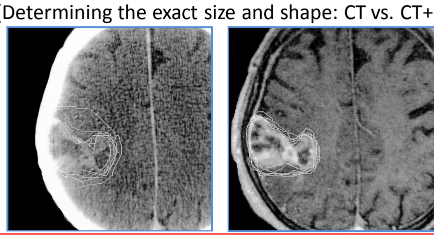






21 plans by 11 clinicians in seven CK centers
(Yamazaki et al. Radiation Oncology 2011)

Do you know where to aim?
(Determining the exact size and shape: CT vs. CT+MRI)



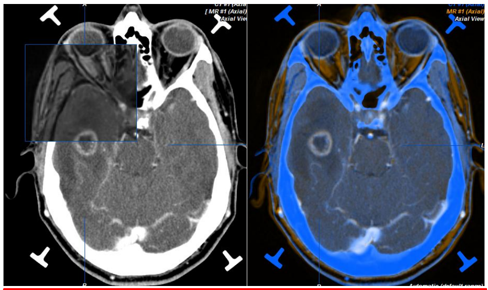
GTV delineations on CT alone and MRI + CT: Coefficients of variance (COV) given as the mean per specialism

	COV	Patient 1 (%)	patient 2 (%)	Patient 3 (%)	patient 4 (%)	patient 5 (%)	All (%)
CT alone	Radiat. Oncol.	58.4	28.7	25.2	21.4	24.2	31.6
	Radiologist	11.9	4.5	8.5	19.3	3.1	9.5
	Neurosurgeon	16.9	7.9	28.5	8	9.7	14.2
MRI + CT	Radiat. Oncol.	29.3	14.6	9.1	36.9	16.0	21.2
	Radiologist	29.5	7.1	9.3	47.8	4.8	19.7
	Neurosurgeon	46.7	11.7	30.2	19.3	12.9	24.2
	All on CT	32.8	21	19.4	20.1	20.7	22.8
	All on MRI	32.7	18.1	17.1	31.9	14	22.7

C. Weltens et al. / Radiotherapy and Oncology (2001)

Do you know where to aim?

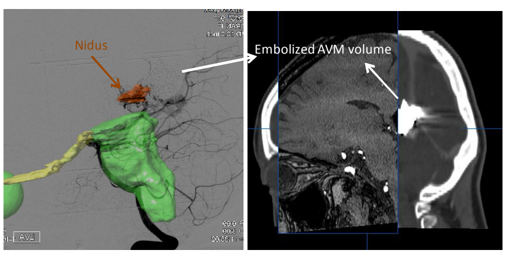
(Determining the exact size and shape: CT and MR Registration)



CT: high spatial fidelity
MR: enhanced soft tissue contrast but reduced spatial fidelity

Do you know where to aim?

(Determining the exact size and shape: AVM Nidus)



DSA images are registered to CT/MR through stereotactic localization

Angiography helps identification of the nidus position and differentiation from feeding arteries and draining veins, not easily identifiable on CT or MR images

Most Important!

Å Do you know where to aim?
 ï Target (anatomy) localization
  Å Common problem for all SRS modalities
Å Can you hit what you are aiming at?
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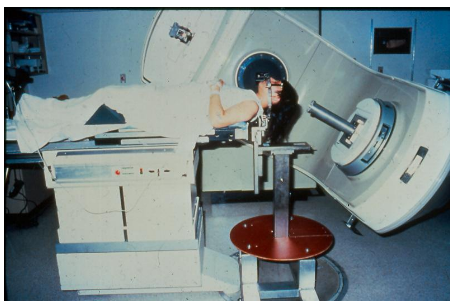
  Å Procedure, process, equipment, technique specific

Linac Radiosurgery: Early Conceptualization

"If radiation surgery will reach a position as a standard procedure, improved electron accelerators for roentgen production, adapted for the purpose, would seem a most attractive alternative."

B. Larsson, K. Liden, and B. Sarby: "Irradiation of small structures through the intact skull," Acta Radiol. Ther. Phys. Biol. **13**, 512–534 (1974)

Original Linac Radiosurgery System at the Joint Center (~1986)



Radiation is delivered via small cones in multiple arc geometry with gantry motion
Patient immobilization and setup is achieved with a floor stand

Photo courtesy of Wendell Lutz, PhD

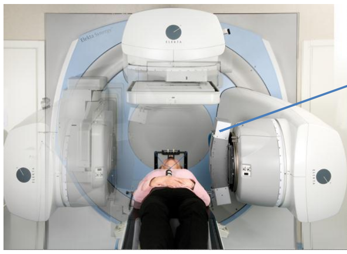
Linac Radiosurgery Technology Evolution (Varian/BrainLab)

Novalis (1998)
M3-microMLC: 3mm leaves
Shaped beam radiosurgery
Single energy

Novalis TX (2007)
HDMLC: 2.5 mm leaves
SRS Mode: 6MV/1000MU/min
Onboard/in-room kV Imaging
Robotic 6D positioning

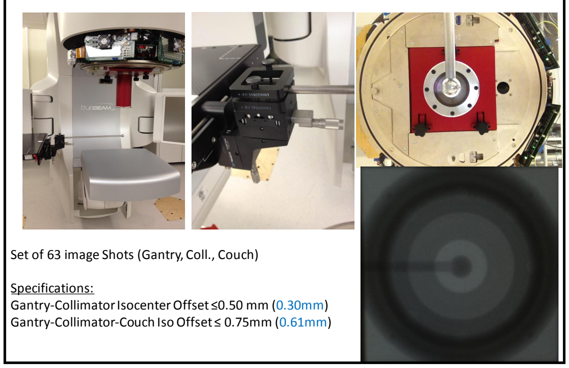
TrueBeam STx (2010)
HDMLC: 2.5 mm leaves
FFF Beams: 6MV/10 MV
(1200-2400 MU/min)
Onboard/in-room kV Imaging
Robotic 6D positioning

Elekta Technology: Linac Based SRS



- Elekta Synergy with Dynamic micro-MLC system :7x7 cm max. field size, 1.9mm leaves
- Also available, Elekta Axesse system with mini-MLC (Beam Modulator with 4mm leaves)

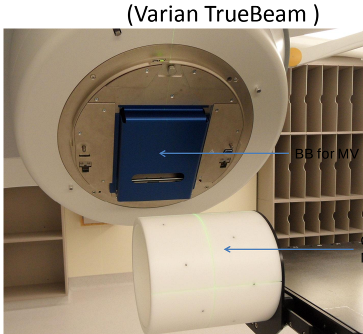
Radiation Isocenter Accuracy at Acceptance



Set of 63 image Shots (Gantry, Coll., Couch)

Specifications:
Gantry-Collimator Isocenter Offset ≤0.50 mm (0.30mm)
Gantry-Collimator-Couch Iso Offset ≤ 0.75mm (0.61mm)

MV-kV Coincidence Test (Varian TrueBeam)



kV-MV isocenter coincidence Ò0.5 mm
Typical results < 0.2 mm

Achievable Uncertainties in SRS (Prior to IGRT) (AAPM TG 42: 1995)

	1mm-CT Slice Thickness	3mm-CT Slice Thickness
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	2.4 mm	3.7 mm

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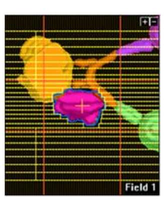
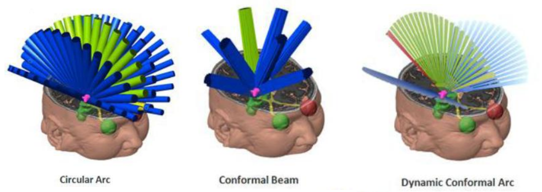
IGRT cannot remove intrinsic (registration) uncertainties!
MR-CT image registration accuracy: ~1mm (Wang et al JACMP 2009)

Linac Radiosurgery: Beam Shaping

- Small fields shaped by tertiary collimating system: Circular cone inserts: 5 mm- 40 mm in diameter
  - precisely machined
  - closer to patient - smaller geometric penumbra
  - diverging beam shaping further minimizes penumbra
- Conformal Beam Shaping by MLC
  - Field shape conforms to the outline of target, uniform intensity across the field
  - Non-target tissue irradiation is minimized by conformal shaping



Linac SRS Treatment Options



Use it for small symmetrical targets, e.g. trigeminal neuralgia, metastases, etc.	Use it to specifically avoid normal structures and for targets too large for dynamic conformal arc	Use it for most cases except larger lesions

Also available is IMRT capability for irregular targets or fractionated SRS

Linac SRS Treatment Process

Å Frame placement: rigid immobilization or frameless approach
Å Imaging/Simulation
Å Treatment Planning
Å Treatment Plan Evaluation
Å Treatment Plan QA
Å Treatment Machine and Patient QA
Å Setup and treatment

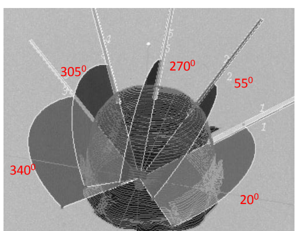
SRS Treatment Planning

Å Isocenter placement
  ï usually at the geometrical center of the PTV
  ï Cone size is chosen to encompass most of the target volume
Å Choice of arcs or beams
  ï based on knowledge of 3D anatomical information, size and location
  ï radiological depth to lesion minimized
  ï no beam passes through a critical structure-could be relaxed
  ï arc plane separation, i.e., the couch rotation depends on collimator size

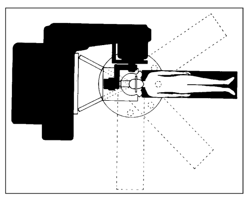
SRS Treatment Planning

- Manual Plan Optimization
  - Arc-length and position
  - Beam number and position
    - Limit no of beams/arcs in ANT/POST directions
    - Multiple non-coplanar beams (8-12) or 4-5 arcs used
  - Spherical lesion
    - Equally spaced arcs (4-7) or beams (11-15)
  - Ellipsoidal lesion
    - Arc weighting or differential collimator size: Coronal plane
    - Adjust arc start and stop positions (arc length): Sagittal plane
    - Use multiple isocenters: axial plane
  - Irregular shape
    - Use multiple isocenters (for circular cones), or
    - Micro-MLC conformal beam shaping (static beams/arcs or dynamic conformal arc)

Circular Cones Example: Standard University of Florida five-arc set

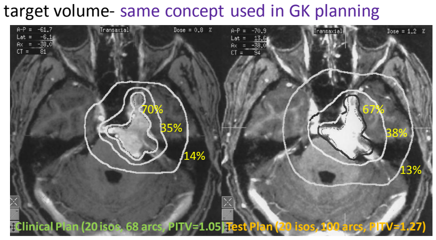


Arc	Couch angle	Gantry start angle	Gantry stop angle	Arc weight (relative units)
1	55	130	30	100
2	20	130	30	100
3	340	230	330	100
4	305	230	330	100
5	270	230	330	100



Arcs are achieved through both couch and gantry rotations

- **Multiple isocenter planning optimization: based on optimal sphere packing arrangement with circular cones.**
- Planning = determining positions and sizes of the multiple spherical high-dose regions that will be used to fill up the target volume- same concept used in GK planning

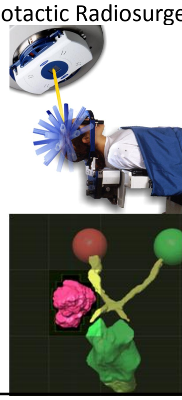


(Wagner et al, "A geometrically based automated radiosurgery planning" IJROBP 2000)

Highly inefficient treatment delivery process with the Linac!
Mostly replaced by MLC based treatment planning and delivery!

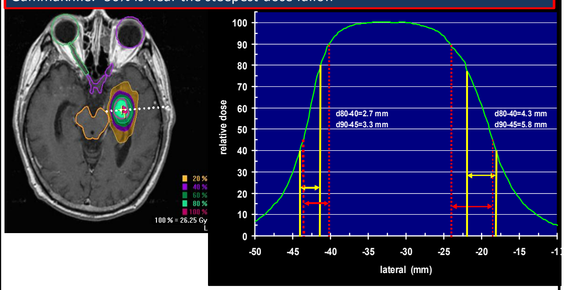
Static Conformal Beam Stereotactic Radiosurgery

- Beam Geometry
  - Maximize the solid angle irradiated: 2π
  - Use a reasonable number of beams
    - How many beams are reasonable?
    - The higher the number of fields the lower the peripheral dose
  - Use unopposed fields
  - Diminishing gains beyond 11 static beams compared to a single-iso 4 arc plan (Bourland & McCollough 1993)

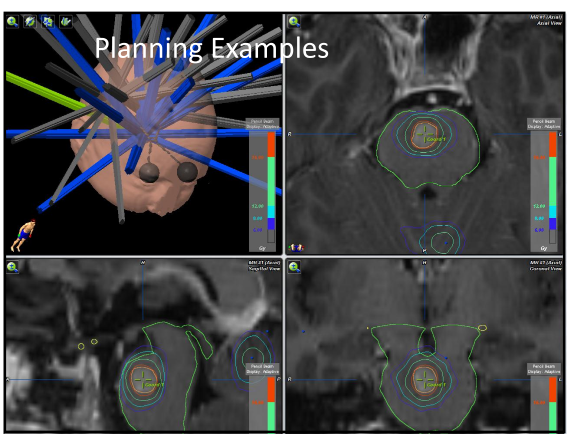


Prescription Isodose Line : 80 % or 90%?

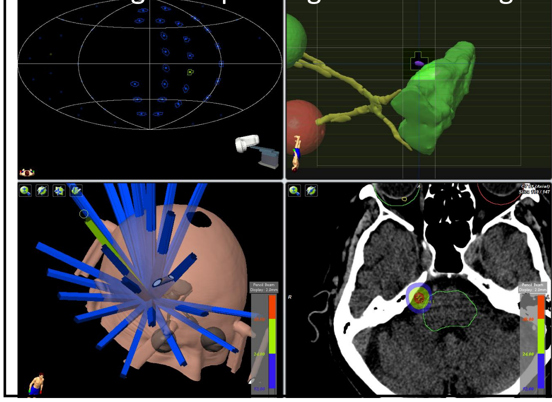
Single isocenter (arcs or static fields): 80% is near the steepest point of dose falloff .
Multi-isocenter : steepest dose falloff region moves near 70% IDL
GammaKnife: 50% is near the steepest dose falloff



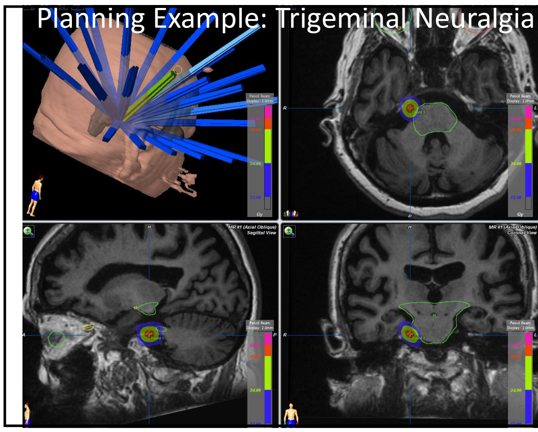
Planning Examples



Planning Example: Trigeminal Neuralgia



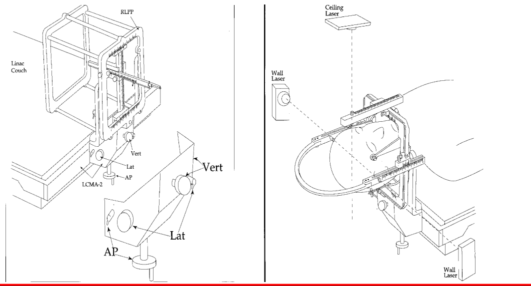
Planning Example: Trigeminal Neuralgia



SRS Treatment QA

Å Known target test (stereotactic localization)
Å Head movement test (frame based SRS)
Å Rigorous verification of treatment setup
Å Daily output verification of SRS beams (FFF or SRS mode)
Å Daily IGRT QA (MV and kV coincidence) if IGRT is used for setup
Å IMRT QA if IMRT is used in treatment delivery

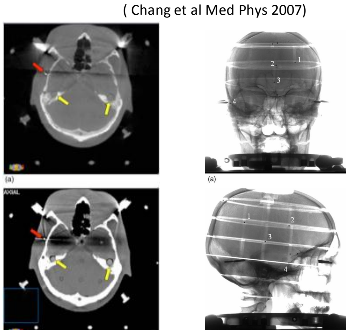
Treatment set-up and QA: Framed Based System



Redundancy check of SRS coordinates with phantom pointer and laser-target localizer (LTLF). Patient is set-up with LTLF to room lasers

SRS Setup Verification with CBCT and OBI Imaging

(Chang et al Med Phys 2007)



Mean CBCT/CT registration accuracy = 0.28 mm SD=0.10 mm.
CBCT setup accuracy mean ~ 1.34 mm, SD=0.33 mm

Fractionated Stereotactic Radiotherapy (SRT)

- Larger Tumors (> 4cm)
- Tumors involved with a critical structure (within <4mm), or benign tumors (acoustic neuromas, meningiomas, pituitary adenomas)

- Conventional or hypo-fractionation
- Radiobiological differences between tumor and normal tissue response
- Immobilization – GTC frame, mask or frameless approach with IGRT
- More labor intensive!

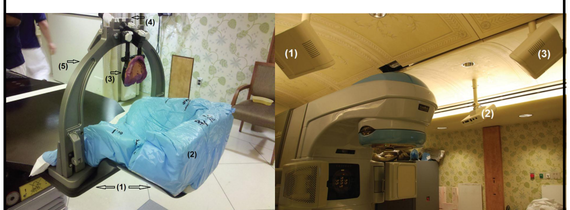
Non-invasive SRT Localization Systems

GTC Frame
Stereotactic Positioning
Relies on repositioning accuracy based on skull-depth measurements
Good immobilization ~1mm
Achievable localization accuracy ~ 3mm
Labor intensive
No-longer marketed (Radionics)

BrainLab Face Mask
Stereotactic Positioning
Relies on repositioning accuracy based on two layer thermoplastic material
Immobilization: non-rigid (>1mm)
Achievable localization accuracy ~ 2-3mm
Available with dental stabilization feature

IMAGE GUIDANCE IMPROVES SETUP ACCURACY

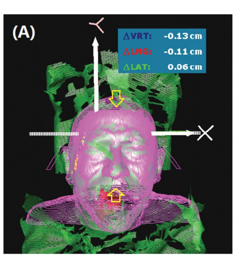
Optical Imaging and CBCT-guided frameless radiosurgery

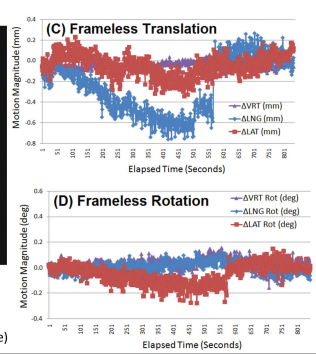


G. Li et al, "Motion monitoring for cranial frameless stereotactic radiosurgery using video-based three-dimensional optical surface imaging" Med. Phys. 38 (7), July 2011

Surface Imaging for Motion Monitoring

(G. Li et al Med Phys, Vol 38, 2011)





With maxillary suction system and surface imaging, head motion was monitored to be <1.1mm (98% of time)

Fractionation Offers Favorable Outcome!

CLINICAL INVESTIGATION Bra

SINGLE-DOSE VERSUS FRACTIONATED STEREOTACTIC RADIOTHERAPY FOR BRAIN METASTASES

Yeon-Joo Kim, M.D.,* Kwan Ho Cho, M.D.,† Joo-Young Kim, M.D.,† Young Kyung Lim, Ph.D.,† Hye Sook Min, M.D.,‡ Sang Hyun Lee, M.D.,† Ho Jin Kim, M.D.,† Ho Shin Gwak, M.D.,† Heon Yoo, M.D.,† and Seung Hoon Lee, M.D.†

Departments of *Radiation Oncology and ‡Pathology, Seoul National University College of Medicine, Seoul, Republic of Korea; and †Research Institute and Hospital, National Cancer Center, Goyang, Republic of Korea

Purpose: To evaluate the efficacy of stereotactic radiotherapy in patients with brain metastases by comparing two different treatment regimens, single-dose radiosurgery (SRS) and fractionated stereotactic radiotherapy (FSRT).
Methods and Materials: Between November 2003 and December 2008, 98 patients with brain metastases were included. Fifty-eight patients were treated with SRS, and forty were treated with FSRT. Fractionated stereotactic radiotherapy was used for large lesions or lesions located near critical structures. The median doses were 20 Gy for the SRS group and 36 Gy in 6 fractions for the FSRT group.
Results: With a median follow-up period of 7 months, the median survival was 7 months for all patients, with a median of 6 months for the SRS group and 8 months for the FSRT group ($p = 0.89$). Local progression–free survival (LPFS) rates at 6 months and 1 year were 81% and 71%, respectively, for the SRS group and 97% and 69%, respectively, for the FSRT group ($p = 0.31$). Despite the fact that FSRT was used for large lesions and lesions in adverse locations, LPFS was not inferior to SRS. Toxicity was more frequently observed in the SRS group than in the FSRT group (17% vs. 5%, $p = 0.05$).

SUMMARY

- Å Current Linac technology presents significant capabilities for radiosurgery applications including
  - ï Improved mechanical accuracy
  - ï Higher dose rates with FFF beams
  - ï Improved conformality and beam delivery efficiency with high-definition MLC
  - ï Image guidance with 2D/3D imaging modalities
  - ï Real time patient monitoring and beam gating
  - ï Flexibility for fractionated radiosurgery techniques
- Å Integration of all IGRT tools into SRS requires significant physics expertise and effort for clinical implementation, continuous QA, and training
- Å Assessment of system accuracy from A to Z (end to end test) is essential
- Å Understanding of failure modes and limitations are important for safe and effective patient treatments

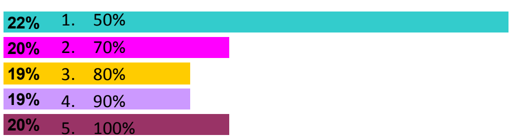
In CT-frame-based radiosurgery, what is the largest source of uncertainty?

18% 1. Stereotactic frame setup.
23% 2. Linac radiation isocenter accuracy
20% 3. CT-image resolution.
19% 4. Tissue motion.
20% 5. Dose calculation algorithm.

Answer: 3

- CT-image resolution.
- Largest uncertainty in the radiosurgery treatment process is due to limitations in CT-image resolution, which is over 1mm in 3d-space. All other factors are in the order of 1mm or less.
- **Reference**:
- M. Schell et al., “**Stereotactic Radiosurgery: The Report of AAPM Task Group 42”**
- Lutz et.al., “**A system for stereotactic radiosurgery with a linear accelerator**” IJROBP (1988)

In a single-isocenter radiosurgery treatment of a symmetrical target the dose gradient outside the target is sharpest for the prescription isodose line of



Answer: 3

- 80%
- Prescribing to the 80% line results in a fall-off from prescription to half of prescription (i.e., 80% to 40%) in shorter distance compared to other isodose prescription levels.
- **Reference**:
- S. Meeks et al., “**TREATMENT PLANNING OPTIMIZATION FOR LINEAR ACCELERATOR RADIOSURGERY”,** Int. J. Radiation Oncology Biol. Phys., Vol. 41, pp. 183–197 (1998)

Which of the following is an appropriate setup verification technique for a single fraction linac radiosurgery treatment?

- 20% 1. Skin marks and tattoos
- 20% 2. 3D-optical imaging
- 22% 3. Orthogonal MV images
- 21% 4. CBCT setup with 3-dimensional image registration to the planning CT
- 18% 5. Depth helmet measurements

Answer: 4

CBCT setup with 3-dimensional image registration to the planning CT

Reference:

Å J. Chang *et al.*, **"Accuracy and feasibility of CBCT for SRS setup"** Med Phys Vol 34, pp. 2077-2084 (2007)

You only get one chance with radiosurgery!

and never forget

FOOLS WITH TOOLS ARE STILL FOOLS