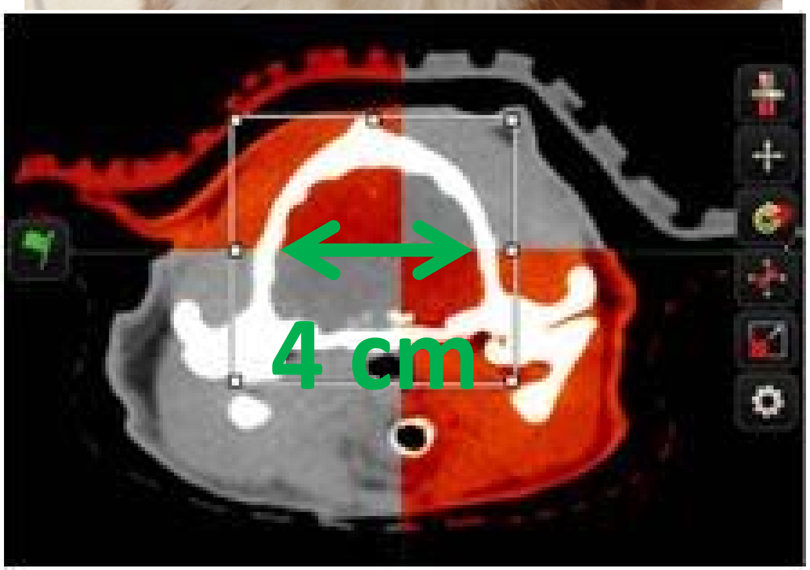
2014 AAPM SUMMER SCHOOL
University of Vermont • Burlington, VT • June 22–26, 2014
SRS/SBRT/SABR:
Safely and Accurately Delivering
High-Precision, Hypofractionated Treatments

Uncertainty in Linac and CK SRS/SBRT

Sonja Dieterich, Ph.D.

UCDAVIS
UNIVERSITY OF CALIFORNIA

When Do We Need Accuracy?


4 cm

Organization of Presentation

1. Introduce the specific Uncertainty
2. Example on Linac
3. Example on CK

Mechanicals

Major Contributors to Uncertainty

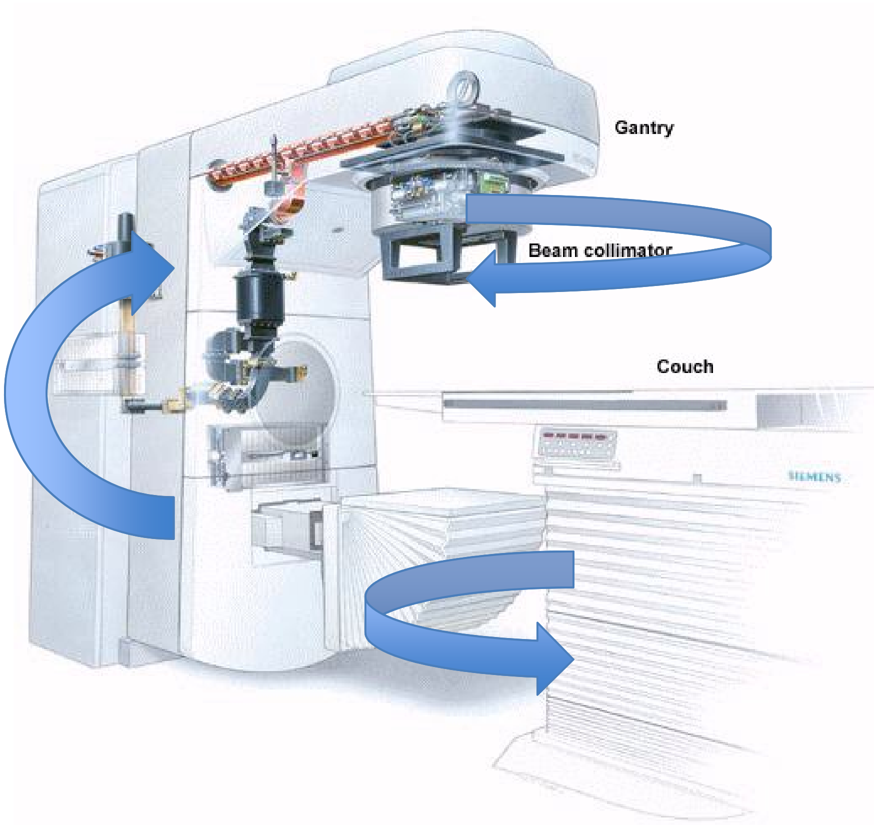
Type	Uncertainty	Linac	CK	Type
Mechanical	Mechanical Isocenter	Star shots	Robot pointing	B
	Collimator	MLC starshot, picket fence, etc	Film/Large chamber	A/B
	Imaging Isocenter	Phantom	Isocrystal on imager	B
	Imaging algorithm	?	Anthropomorphic phantom	B?
Dosimetry	Beam data	Water tank setup, kQ, detector/beam noise, data processing, detetcor correction factors …		A
	Dose calculation algorithm	Algorithm uncertainty	MC uncertainty	A
Treatment	Residual patient motion	Similar for both machines		A/B
	Contouring	Similar for both machines		B

Mechanical Accuracy

TG-142 Mechanical Tolerance Limits for SRS/SBRT

Procedure	SRS/SBRT Tolerance
Radiation/Mechanical Isocenter	±1 mm from baseline
Collimator Rotation Isocenter	±1 mm from baseline
Gantry Rotation Isocenter	±1 mm from baseline
Couch Rotation Isocenter	±1 mm from baseline
Laser Localization	1 mm
Collimator Size Indicator	1mm
Couch Position	1mm/0.5º
Table Top Sag	1 mm

Linac Mechanical/Radiation Isocenters



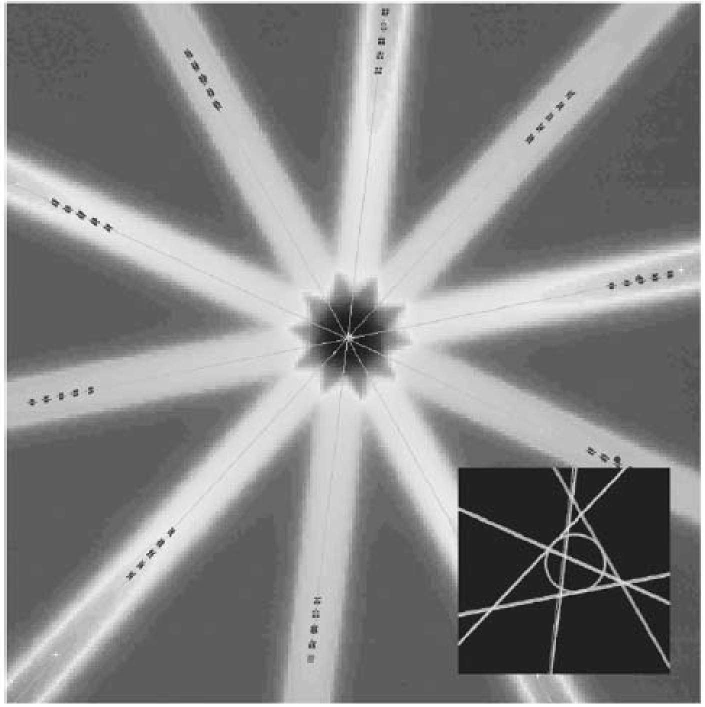


Figure 2. Star shot analysis, showing field axis segmentation. The inset shows the enlarged crossing of all detected beam axes and the calculated smallest intersecting circle, of which the radius is called the radiation isocenter size.

Depuydt, Tom, et al. "Computer-aided analysis of star shot films for high-accuracy radiation therapy treatment units." *Physics in medicine and biology* 57.10 (2012): 2997.

CK Mechanical Isocenter

FIG. 3. The black isopost is mechanically mounted on the base frame of the imager system. The isocrystal at the tip of the post defines the coordinate system reference of the CyberKnife® system. The robot is going through the path calibration process (Sec. III B 1), with the beam laser scanning the isocrystal.

CK Mechanical Isocenter: Robot Pointing

- Linac CAX laser light intensity on isocrystal
- Robot runs automated grid pattern
- Calibration followed by verification
- Acceptance <0.5mm average rms error per path
- Robot pointing stable for up to 2 years (longer data not available)

Point	Node			Calibrated Node			Error			Calculation				
	X	Y	Z	X	Y	Z	X	Y	Z	X*X	Y*Y	Z*Z	E*E	E
1	-161.42	-522.36	584.02	-161.63	-522.49	583.85	-0.012	0.099	0.085	0.0001	0.0098	0.0072	0.0172	0.1310
2	247.21	-400.00	647.21	247.24	-399.86	647.28	-0.017	0.093	0.064	0.0003	0.0086	0.0041	0.0130	0.1142
3	82.48	-412.78	680.30	82.26	-412.52	680.48	-0.036	0.084	0.055	0.0013	0.0071	0.0030	0.0114	0.1067
4	322.84	-261.18	683.78	322.91	-260.75	683.91	-0.021	0.104	0.049	0.0004	0.0108	0.0024	0.0137	0.1169
5	164.96	-279.32	731.28	165.05	-278.97	731.39	-0.021	0.104	0.044	0.0004	0.0108	0.0019	0.0132	0.1149
6	462.95	-215.74	615.74	462.85	-215.17	616.02	-0.023	0.060	0.038	0.0005	0.0036	0.0014	0.0056	0.0747
7	247.21	-133.33	749.07	247.37	-132.95	749.08	-0.017	0.091	0.022	0.0003	0.0083	0.0005	0.0091	0.0952

Linac/Imaging Isocenter Match

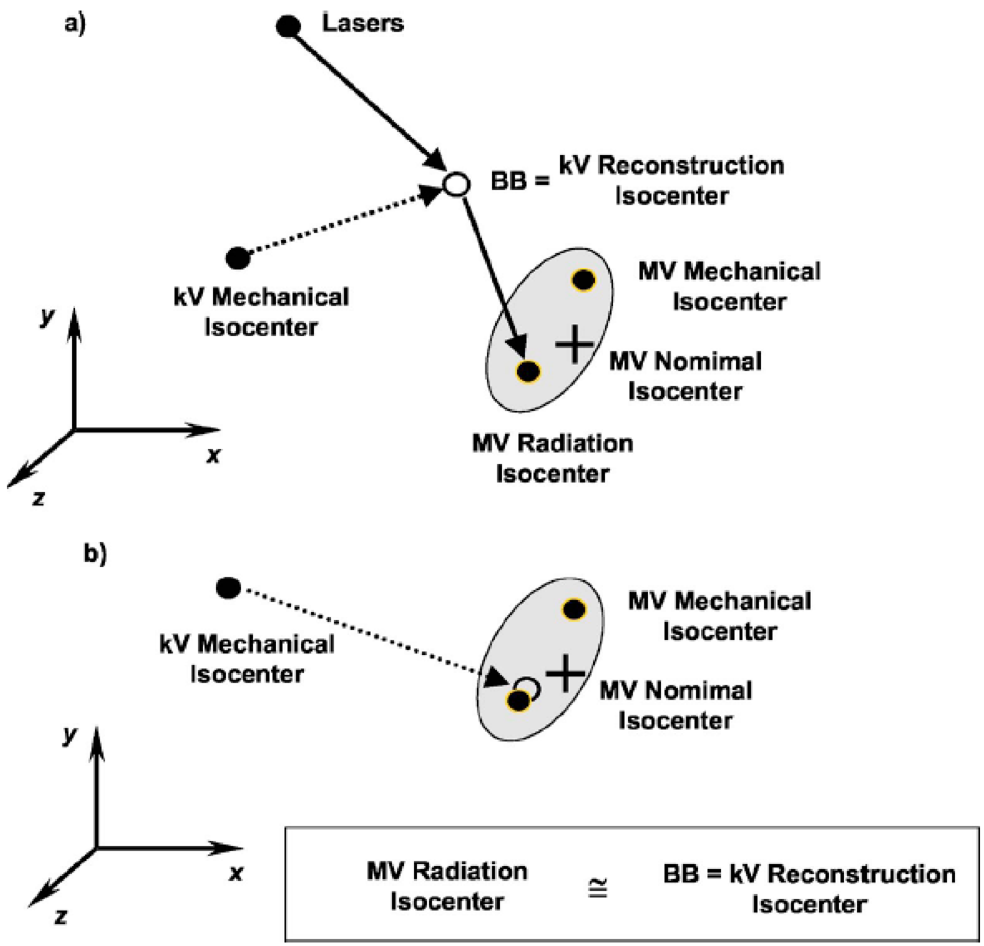
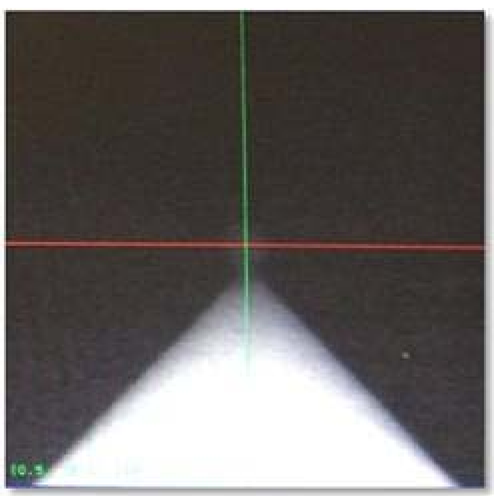


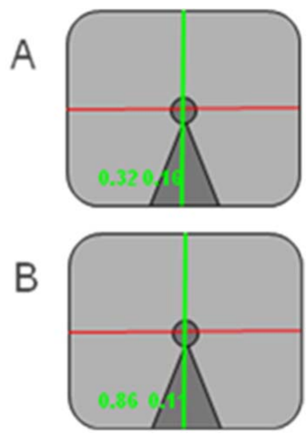
FIG. 2. Schematic of the kV-MV calibration procedure. (a) Relative position of "iso-centers" and ball-bearing (BB) prior to adjustment in BB placement based upon MV portal images. The portal imaging procedure provides an estimate of the BB location with respect to the MV radiation iso-center of the treatment unit. (b) Following adjustment in BB location to the MV radiation iso-center, the BB position is taken as an accurate estimate of the MV radiation iso-center. A calibration table is formed from a series of kV radiographs over 360° which capture the BB location. The kV cone-beam CT reconstruction system is designed to place the reconstruction center at this location in the world coordinate system (i.e. MV radiation iso-center is located at the center of all subsequent reconstructions).

Sharpe, Michael B., et al. "The stability of mechanical calibration for a kV cone beam computed tomography system integrated with linear accelerator)." *Medical physics* 33.1 (2005): 136-144.

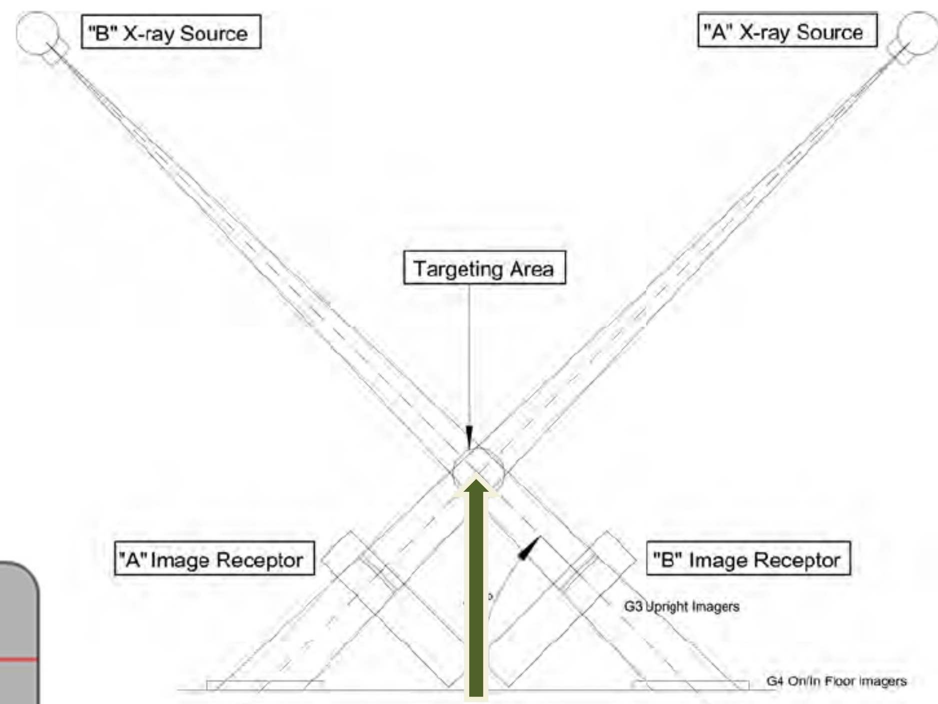
CK Imaging/Robot Isocenter Match

- Isocrystal defines spatial origin of room coordinate system
- Image of isocrystal on imager center tolerance < 1 mm





Dieterich *et al.*: Report of AAPM TG 135



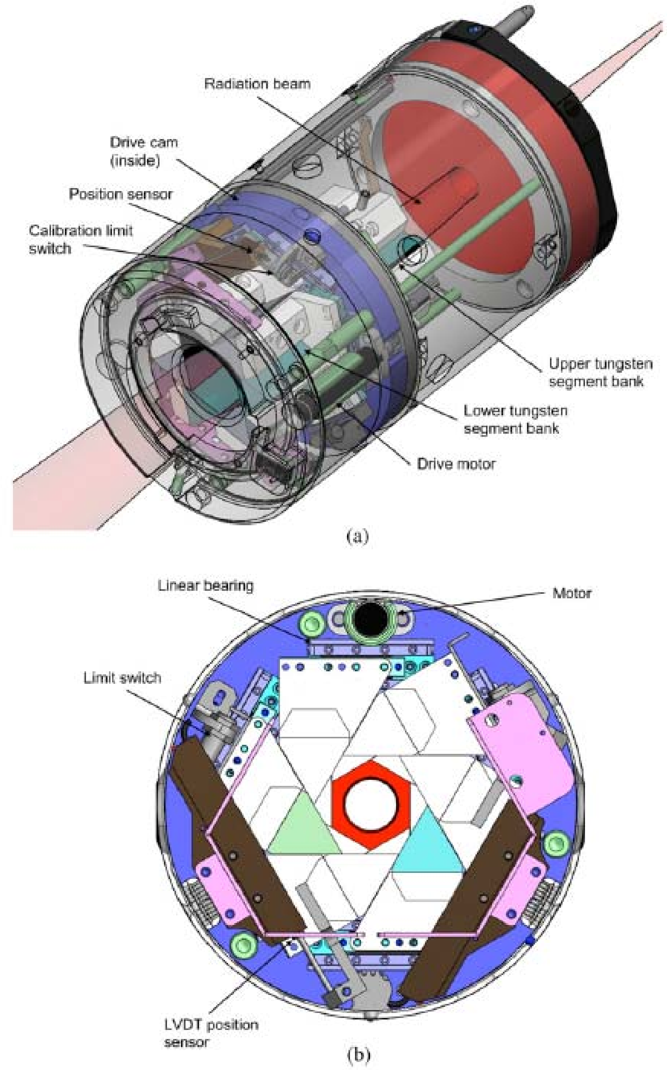
Linac Collimator/MLC (TG-142)

Table V. Multileaf collimation (with differentiation of IMRT vs non-IMRT machines).

Procedure	Tolerance
Weekly (IMRT machines)	
Qualitative test (i.e., matched segments, aka "picket fence")	Visual inspection for discernable deviations such as an increase in interleaf transmission
Monthly	
Setting vs radiation field for two patterns (non-IMRT)	2 mm
Backup diaphragm settings (Elekta only)	2 mm
Travel speed (IMRT)	Loss of leaf speed >0.5 cm/s
Leaf position accuracy (IMRT)	1 mm for leaf positions of an IMRT field for four cardinal gantry angles. (*Picket fence* test may be used, test depends on clinical planning-segment size)
Annually	
MLC transmission (average of leaf and interleaf transmission), all energies	±0.5% from baseline
Leaf position repeatability	±1.0 mm
MLC spoke shot	≤1.0 mm radius
Coincidence of light field and x-ray field (all energies)	±2.0 mm
Segmental IMRT (step and shoot) test	<0.35 cm max. error RMS, 95% of error counts <0.35 cm
Moving window IMRT (four cardinal gantry angles)	<0.35 cm max. error RMS, 95% of error counts <0.35 cm

CK Mechanical Collimator

- Fixed Collimator:
  - Commissioning data reflects actual mechanical collimator
- IRIS:
  - Aperture reproducibility at lower bank ≤ 0.1 mm (40 cm SAD)
  - RMS variation in 50% dose radius <0.8%
  - RMS variation in 20%-80% penumbra 0.1 mm (5 mm) to 0.5 mm (60 mm)
- Mechanical uncertainty with impact on **commissioning data!**



CK Mechanical: Imaging Algorithm

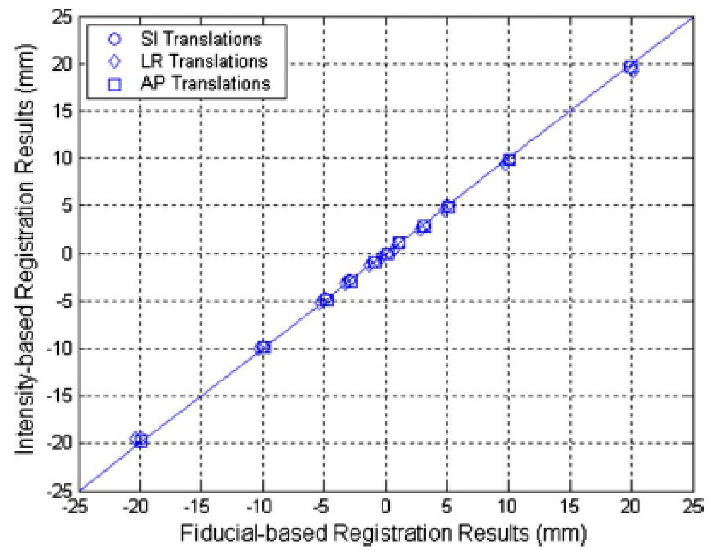


TABLE I. Registration errors of individual translation, overall translation, individual rotation, and overall rotation using fiducial-based registration as the reference. These statistic results were calculated from the measured results of 49 phantom motion positions in Table V in the Appendix.

	Errors of translations (mm)				Errors of rotations (deg)			
	SI	LR	AP	Overall	SI	LR	AP	Overall
Mean	−0.14	0.01	−0.22	0.33	−0.10	−0.18	0.00	0.29
STDEV	0.10	0.19	0.14	0.16	0.09	0.14	0.16	0.11
Max	0.36	0.58	0.63	0.86	0.40	0.46	0.51	0.66

D. Fu and G. Kuduvalli: 2D–3D image registration for image-guided cranial radiosurgery

What is the tolerance of the CyberKnife Isocrystal to Imager Center?

40%	1.	0.5 mm
38%	2.	1 mm
1%	3.	2 mm
20%	4.	1 pixel
1%	5.	2 pixels

What is the tolerance of the CyberKnife Isocrystal to Imager Center?

Feedback:

The image of the isocrystal should be within 1 mm of the isocenter.

Slide Location:

Mechanical: Imaging/Robot Isocenter Match (#11)

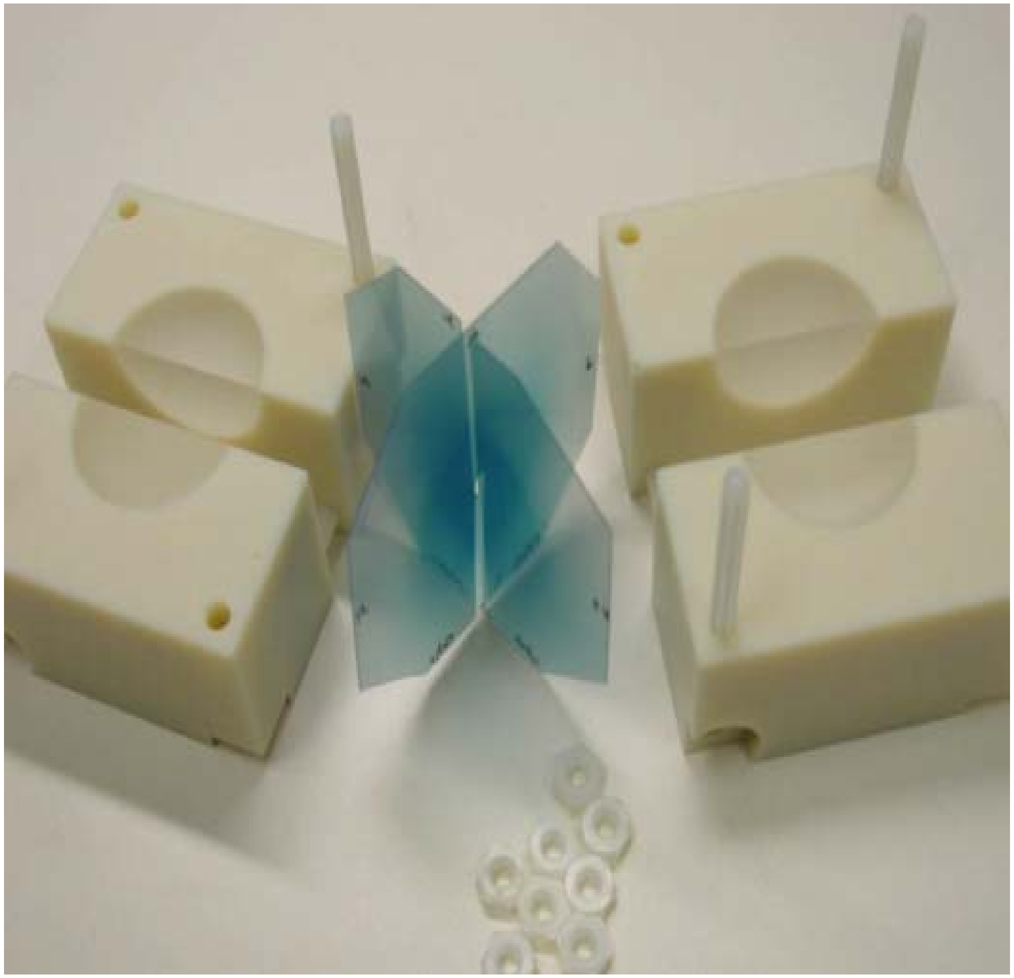
Reference:

1) AAPM TG-135
2) CK Physics User Guide

And now it gets complicated!

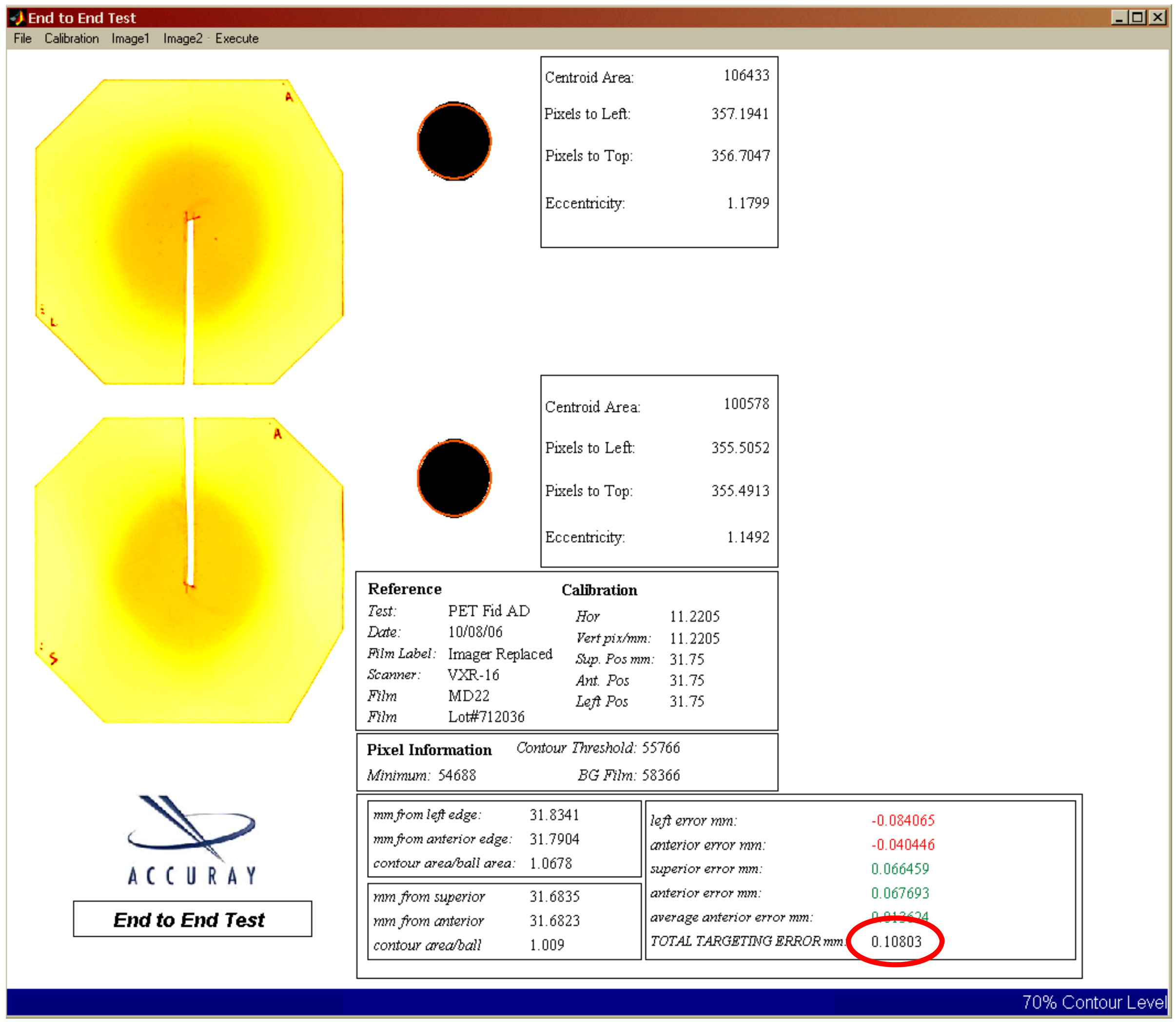
… Enter the E2E/Δ–man test …

Experimental Accuracy:
The E2E (modified Winston-Lutz)



Details of E2E test

- Isocentric plan
- Homogeneous Phantom
- Measure shift of delivered 70% isodose line vs. plan
- Tolerance < 1mm



Linac E2E (on TrueBeam)

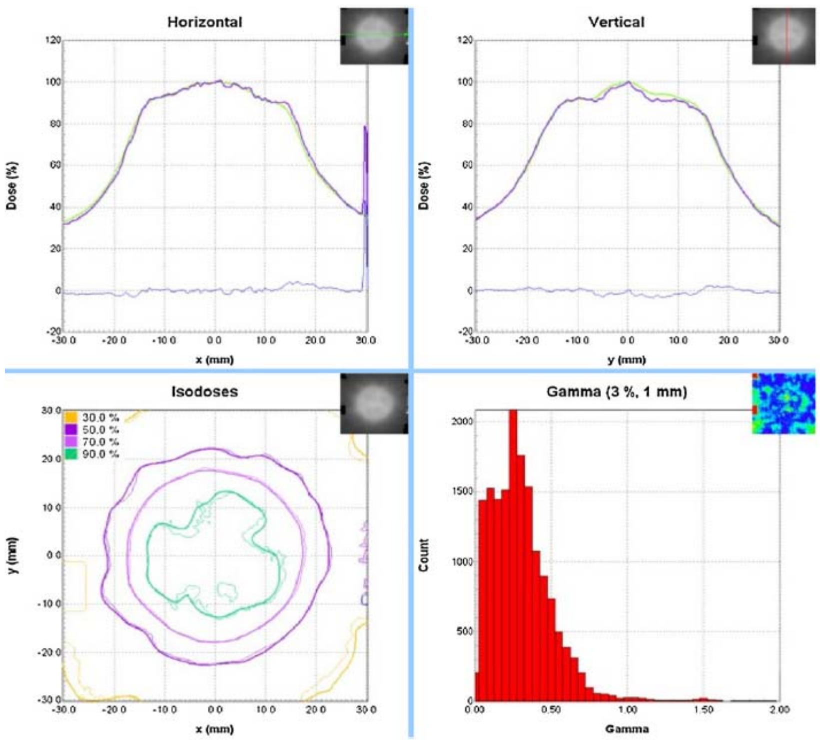


Figure 5. Dose comparison for a 6 MV FFF RapidArc plan with 3 cm diameter target in the axial

Plan	Target diameter (cm)	AL film X(RL) (mm)	AL film Y(AP) (mm)	AS film X(SI) (mm)	AS film Y(AP) (mm)	AP averag (mm)	Magnitude (mm)
6 MV FFF rapid arc	3	0	0	−0.4	0.1	0.05	0.40
10 MV FFF rapid arc	3	0	0	−0.7	−0.1	−0.05	0.70
6 MV FFF IMRT	3	0.5	−0.2	−0.5	−0.1	−0.15	0.72
10 MV FFF IMRT	3	0	0	−0.7	−0.1	−0.05	0.70
6 MV WFF IMRT	3	0.4	−0.2	−0.5	−0.2	−0.2	0.67
10 MV WFF IMRT	3	0.2	−0.3	−0.7	−0.4	−0.35	0.81
15 MV WFF IMRT	3	0.2	−0.2	−0.8	−0.1	−0.15	0.84
6 MV FFF rapid arc	2	−0.2	−0.5	−0.5	−0.2	−0.35	0.64
6 MV FFF rapid arc	1	0.3	−0.3	−0.4	−0.5	−0.4	0.64

Wang, Lei, et al. "An end-to-end examination of geometric accuracy of IGRT using a new digital accelerator equipped with onboard imaging system." *Physics in medicine and biology* 57.3 (2012): 757.

- E2E result 0.4 – 0.85 mm
- Result is FYI
- No mechanical correction/action performed

CK E2E: The Δ-man Parameter

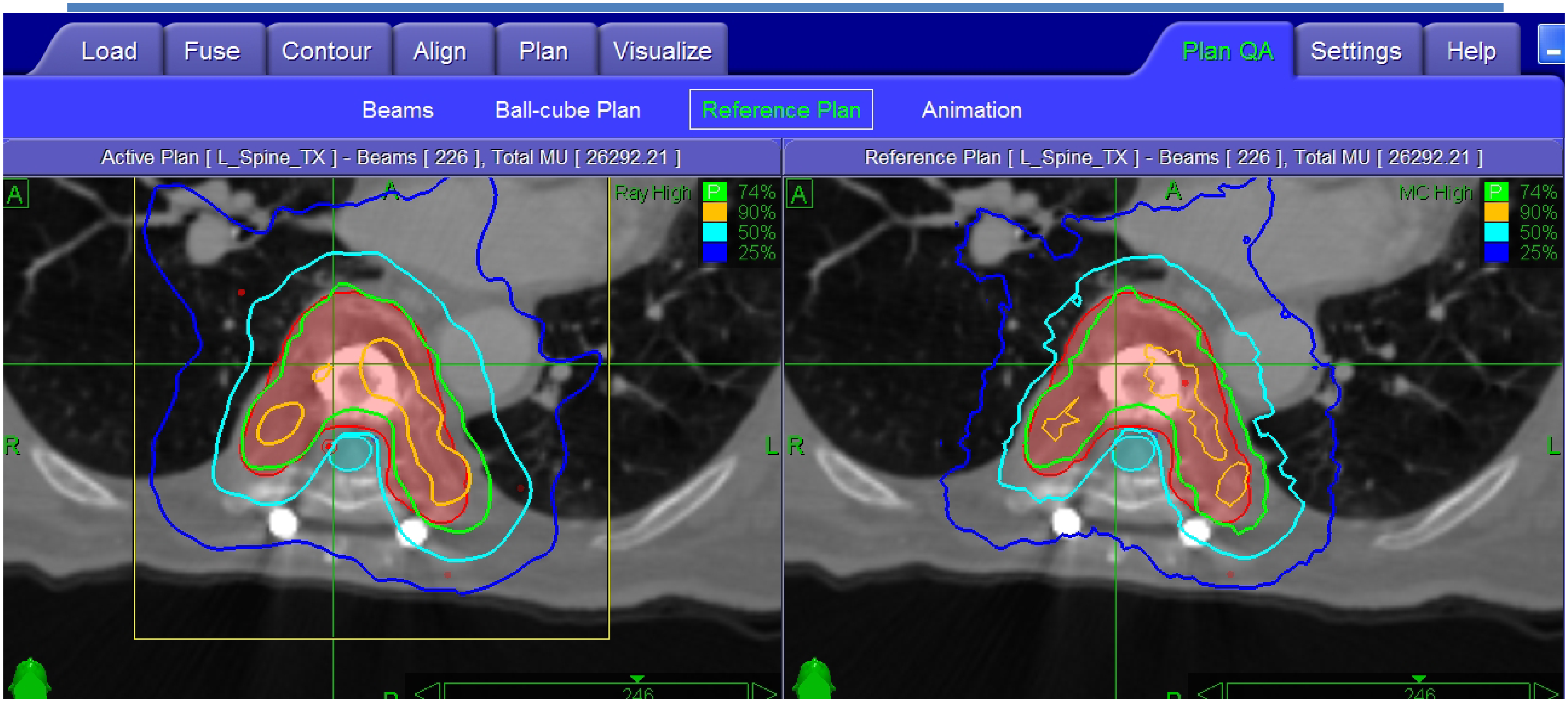
- E2E for all robot paths for each tracking algorithm (cranial, spine, …)
- Determine *systematic shift* of E2E
- Result is applied as *global* correction
- Repeat until (nominally) <0.95 mm
- In clinical practice: **E2E ~0.6 mm**
- Adjusts for global systematic mechanical errors

```
:DELTA_MAN
# DELTA MANIPULATOR VECTOR (X,Y,Z) IN MM
#km 2009-12-16 16:46:37 DELTA_MAN_VECTOR_FIXED_MMSTRING     0.8 0.1 0.9
DELTA_MAN_VECTOR_FIXED_MM                         STRING     1 0.1 1.2
DELTA_MAN_VECTOR_IRIS_MM                          STRING     0.9 0.3 0.7
```

Uncertainties Common to All SRS Delivery Systems

Linac/CK Dosimetric Accuracy (CK example, for time)

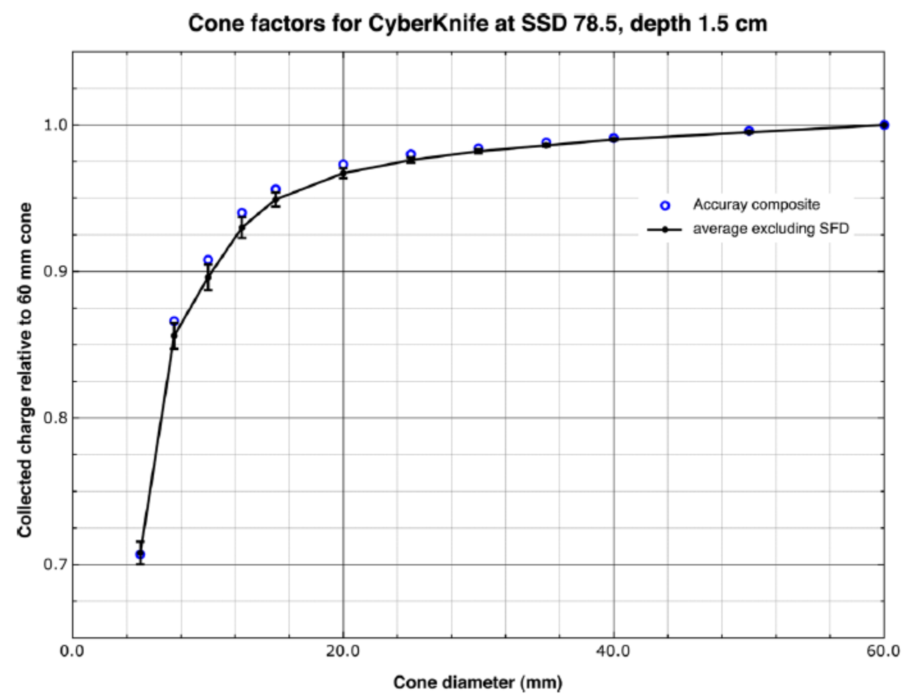
Why Include Dose Calculation?



Dose calculation uncertainty = spatially shifting isodose lines!

Dosimetry: Commissioning Beam Data

- **<u>All</u>** measured data comes with error bars
- TG-106 states inter-user and equipment repeatability should be <1%
- CK needs 3 (4) sets of data: output factor, TPR, and profiles. (In-air OF data for MC)
- Effects of combined beam data error, processing artifacts, etc. challenging to assess
- Assumption: 1% error each for unconnected data sets



S. Dieterich and G. W. Sherouse: Comparison of seven commercial dosimetry diodes for SRS

→ I do not know how to express this as spatial uncertainty

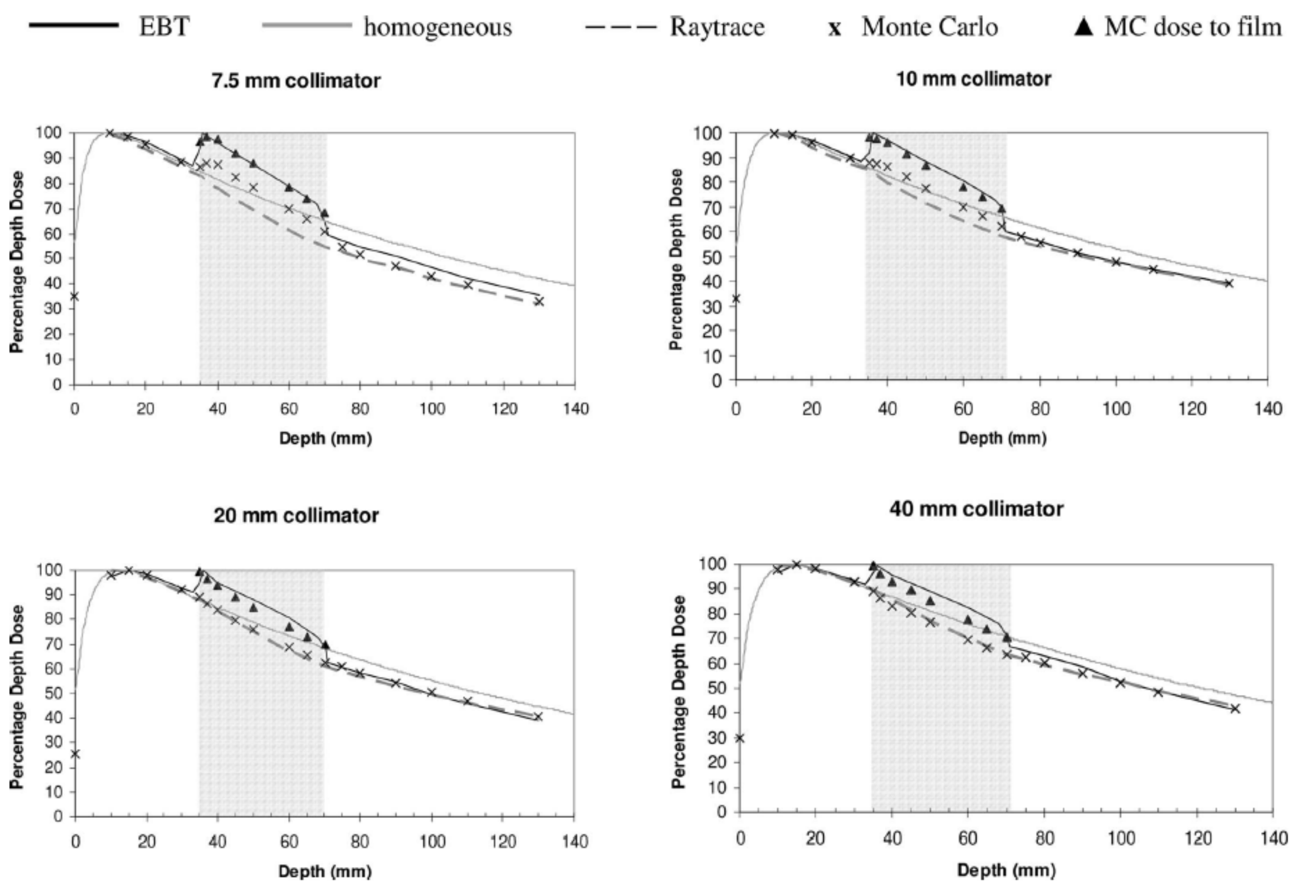
Dosimetry: Dose Calculation Algorithm

Structure	Typical HU	Typical thickness [cm]
Air	-1000	varies
Fat	-100 to -50	1
Cranium	900	1.5
Grey Matter	37-45	14 cm total
White matter	20-30	
CSF	15	varies

- Relatively homogeneous tissues:
  - Major & present: Cranium and air
  - Major & rare: Onyx or glue in AVMs
  - Minor & common: Iodine contrast
  - Minor & rare: Aneurism clips
- No published data for CK dose calculation uncertainty in anthropomorphic phantom

Dosimetry: Dose Calculation Algorithm

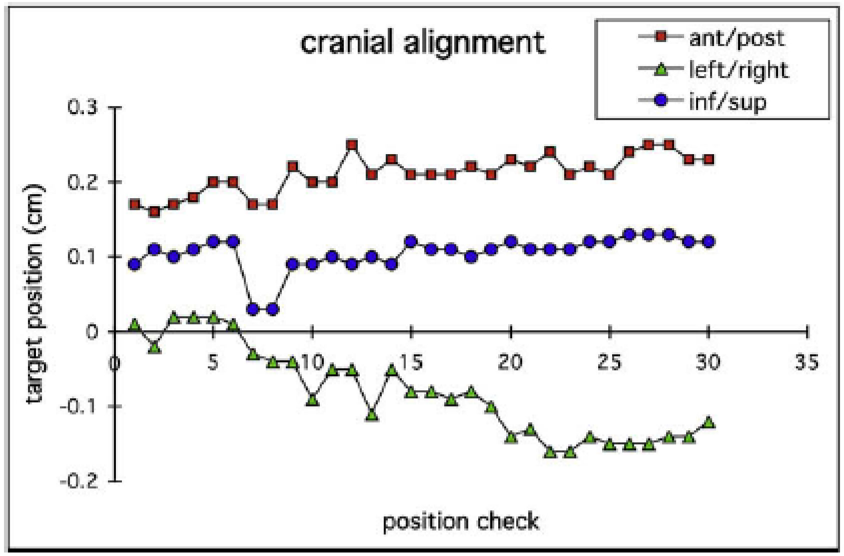
2264 E. E. Wilcox and G. M. Daskalov: Accuracy of dose within and beyond heterogeneities 2264



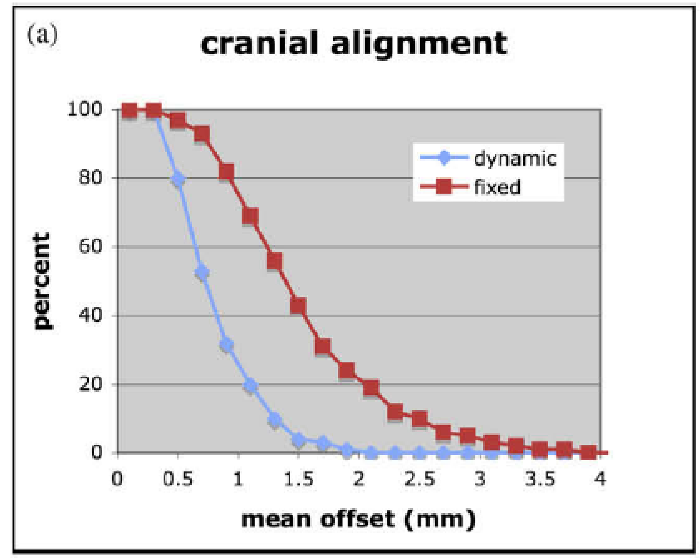
Common MC uncertainty setting: 2% at maximum dose

Linac/CK Residual Patient Motion (CK example, for time)

Dosimetry Uncertainty: Introduction to Residual Patient Motion



Patient movement in frameless image-guided radiosurgery ● M. J. MURPHY *et al*



	Fixed alignment			Dynamic alignment		
	σ	Σ	M	σ	Σ	M
Cranial	1.7	1.3	4.4 mm	1.0	0.2	1.2 mm

- Residual motion ***between*** images
- Results depend on imaging frequency
- Data from 1999-2002; updates in Motion Management Session

Let’s take a step back and summarize what we have learned so far

Qualitative Accuracy Comparison of SRS/SBRT

Linac	GK	CK
Mechanical	Simpler than linac	Similar to linac
Commissioning Data	Simpler than linac	Similar to linac
Patient Positioning	Similar: frame	Similar: IGRT
Target localization	Similar: frame	Similar: IGRT
Dose calculation	Similar	similar
Biological model	Same	
Target Definition	Same	
3D imaging (in-beam imaging)	TBD (CBCT?)	Depends on 2D-3D imaging frequency

Quantitative Accuracy Comparison: It's Complicated ...

- While Linac SRS accuracy contributing factors are generally similar to CK …
- …they combine differently.
- Why?
  - Delta-man concept on CK to determine & adjust systematic mechanical/imaging errors
  - Winston-Lutz vs. E2E concept
  - Intra-fraction imaging & position correction:
    - clinical on CK,
    - under development on linac
- My Dream: measure uncertainty with same test procedure on all three SRS/SBRT modalities

Treatment Uncertainties

Tx: Imaging and Registration

Target Localization Uncertainty

- CT, MRI, PET, SPECT
- Compare measured target position with mechanically known coordinates
- Highest accuracy (as expected) for CT
- MRI more susceptible to distortions

Stereotactic imaging for radiotherapy: accuracy of CT, MRI, PET and SPECT

Christian P Karger[1], Peter Hipp[2], Marcus Henze[2,3], Gernot Echner[1], Angelika Höss[1], Lothar Schad[4] and Günther H Hartmann[1]

Table 3. Deviations between measured and mechanically defined positions.

	Deviation (mean ± standard deviation)			
Modality	Δx (mm)	Δy (mm)	Δz (mm)	Δr^{a} (mm)
CT				
Points ($n = 5$)	-0.1 ± 0.2	-0.1 ± 0.1	0.3 ± 0.2	0.4 ± 0.2
Tubes ($n = 72$)	-0.1 ± 0.2	-0.2 ± 0.2	–	0.3 ± 0.2
Maximum	−0.6	−0.6	0.6	
MRI				
Siemens Magnetom Vision plus				
T1-weighted				
Points ($n = 5$)	-0.5 ± 0.3	0.1 ± 0.2	-0.8 ± 0.4	1.0 ± 0.4
Tubes ($n = 64$)	-0.5 ± 0.3	-0.3 ± 0.3	–	0.7 ± 0.3
Maximum	−1.1	−0.7	−1.4	
T2-weighted				
Points ($n = 5$)	-0.5 ± 0.3	0.1 ± 0.3	-0.2 ± 0.3	0.7 ± 0.2
Tubes ($n = 64$)	-0.5 ± 0.2	-0.4 ± 0.2	–	0.6 ± 0.3
Maximum	−1.00	−0.9	−0.5	
Siemens Magnetom Symphony				
T1-weighted				
Points ($n = 5$)	0.0 ± 0.4	-0.5 ± 0.9	-0.6 ± 0.8	1.4 ± 0.3
Tubes ($n = 68$)	0.1 ± 0.2	-0.7 ± 0.3	–	0.8 ± 0.3
Maximum	0.7	−1.4	−1.4	
T2-weighted				
Points ($n = 5$)	-0.1 ± 0.3	-0.6 ± 0.3	-0.6 ± 1.2	1.4 ± 0.5
Tubes ($n = 68$)	0.1 ± 0.3	-0.4 ± 0.4	–	0.6 ± 0.3
Maximum	0.7	−1.1	−2.1	

Image Fusion

- CT-MR most common
- Fusion performed in dedicated planning system (MultiPlan, GammaPlan) <u>or</u> with 3rd party systems (MIMVista, Velocity, …)
- Mutual Information based algorithm
- Accuracy depends on:
  - Amount of common data
  - Voxel size of images used
- Need to determine clinical accuracy based on institution’s imaging protocol and software combination

Which imaging modality has the highest spatial localization accuracy in a phantom?

92%	1.	CT
0%	2.	PET
0%	3.	SPECT
6%	4.	MRI
2%	5.	US

Which imaging modality has the highest spatial localization accuracy in a phantom?

Feedback:

CT has the highest spatial accuracy. MRI may suffer from spatial distortion. PET and SPECT both have uncertainties due to ToF resolution and scatter.

Slide Location:

Target localization uncertainty (#35)

Reference:

Karger, Christian P., et al. "Stereotactic imaging for radiotherapy: accuracy of CT, MRI, PET and SPECT." *Physics in medicine and biology* 48.2 (2003): 211.

Tx: Contouring

The Famous “Expert Users” Papers

- X expert users are given the same patient to contour
- Example of AVM (similar numbers in many papers)
- Agreement ratio < 60%
- 50% time absolute positional shift > 2mm

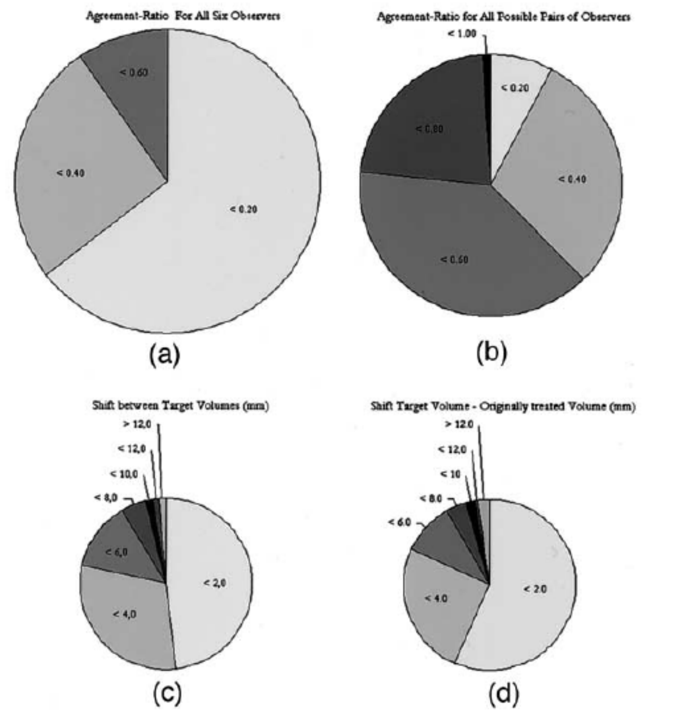


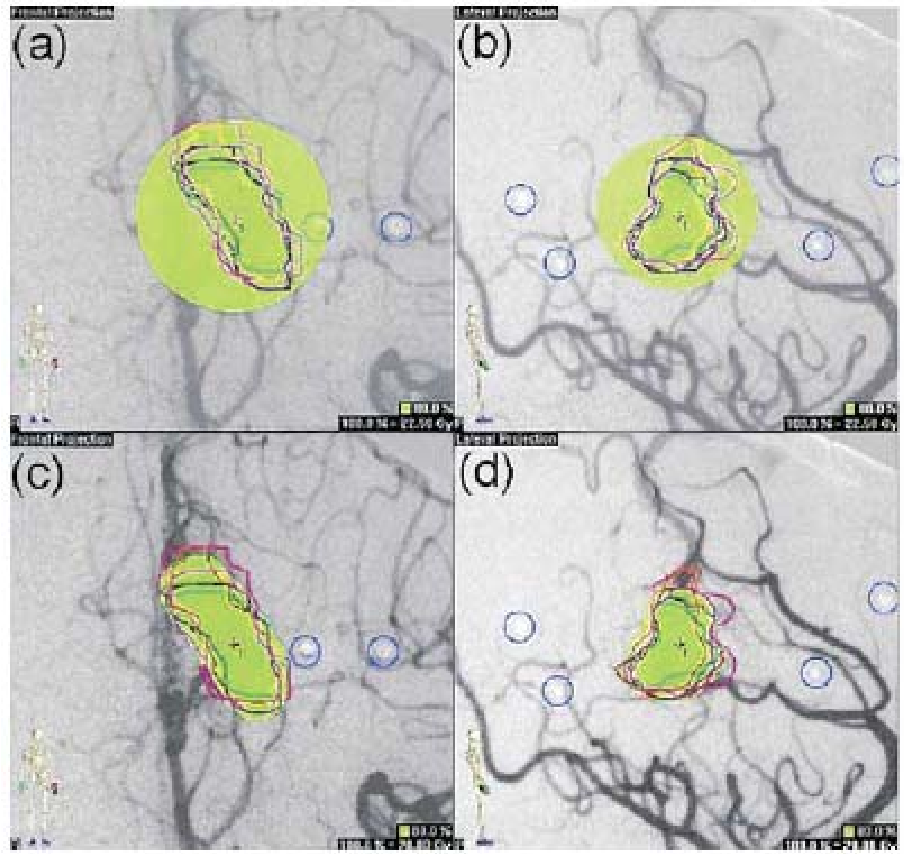
Fig. 3. (a) Agreement ratio, defined as VOA/ECV for all six observers (AR_6) was <60% in all cases. (b) Ratio improved when all possible pairs of observers were compared; however, 76% remained at <60% of agreement. (c) In about 50%, absolute positional shift was <2 mm between mutual individually contoured target volumes (TV) and between target volumes and center of mass of originally treated volume (OTV). (d) However, this shift may increase up to 12 mm.

Interobserver variation of brain AVMs on DSA ● D. R. Buis *et al.*

Higher Accuracy Means Less Room for Uncertainty

a) Isocentric, 1 cone
b) Isocentric, 1 cone coverage 96.8%±4%

c) Dynamic Conf. Arc
d) Dynamic Conf. Arc coverage 78%±4.4%



Interobserver variation of brain AVMs on DSA ● D. R. Buis *et al.*

Selected References on the Topic

The British Journal of Radiology, *77* (2004), 39–42

DOI: 10.1259/bjr/68080920

Delineation of brain metastases on CT images for planning radiosurgery: concerns regarding accuracy

[1]K SIDHU, MD, FRCPC, [2]P COOPER, MD, FRCPC, [1]R RAMANI, PhD, [3]M SCHWARTZ, MD, FRCPC, [1]E FRANSSEN, BSc, MSc and [1]P DAVEY, MD, FRCPC

Interobserver variations in gross tumor volume delineation of brain tumors on computed tomography and impact of magnetic resonance imaging

Caroline Weltens[a,*], Johan Menten[a], Michel Feron[b], Erwin Bellon[b], Philippe Demaerel[c], Frederik Maes[b], Walter Van den Bogaert[a], Emmanuel van der Schueren[a]

Target delineation in post-operative radiotherapy of brain gliomas: Interobserver variability and impact of image registration of MR(pre-operative) images on treatment planning CT scans

Giovanni Mauro Cattaneo[a,*], Michele Reni[b], Giovanna Rizzo[c], Pietro Castellone[d], Giovanni Luca Ceresoli[b], Cesare Cozzarini[b], Andrés José Maria Ferreri[b], Paolo Passoni[b], Riccardo Calandrino[a]

Autosegmentation Can Help

Phys. Med. Biol. 58 (2013) 4071–4097 doi:10.1088/0031-9155/58/12/4071

Segmentation editing improves efficiency while reducing inter-expert variation and maintaining accuracy for normal brain tissues in the presence of space-occupying lesions

M A Deeley[1], A Chen[2], R D Datteri[3], J Noble[3], A Cmelak[2], E Donnelly[4], A Malcolm[2], L Moretti[5], J Jaboin[2,6], K Niermann[2], Eddy S Yang[2,7], David S Yu[2,8] and B M Dawant[3]

- De novo, segmented edit, peer and self-edit
- Segmented edits remained closest to ground truth

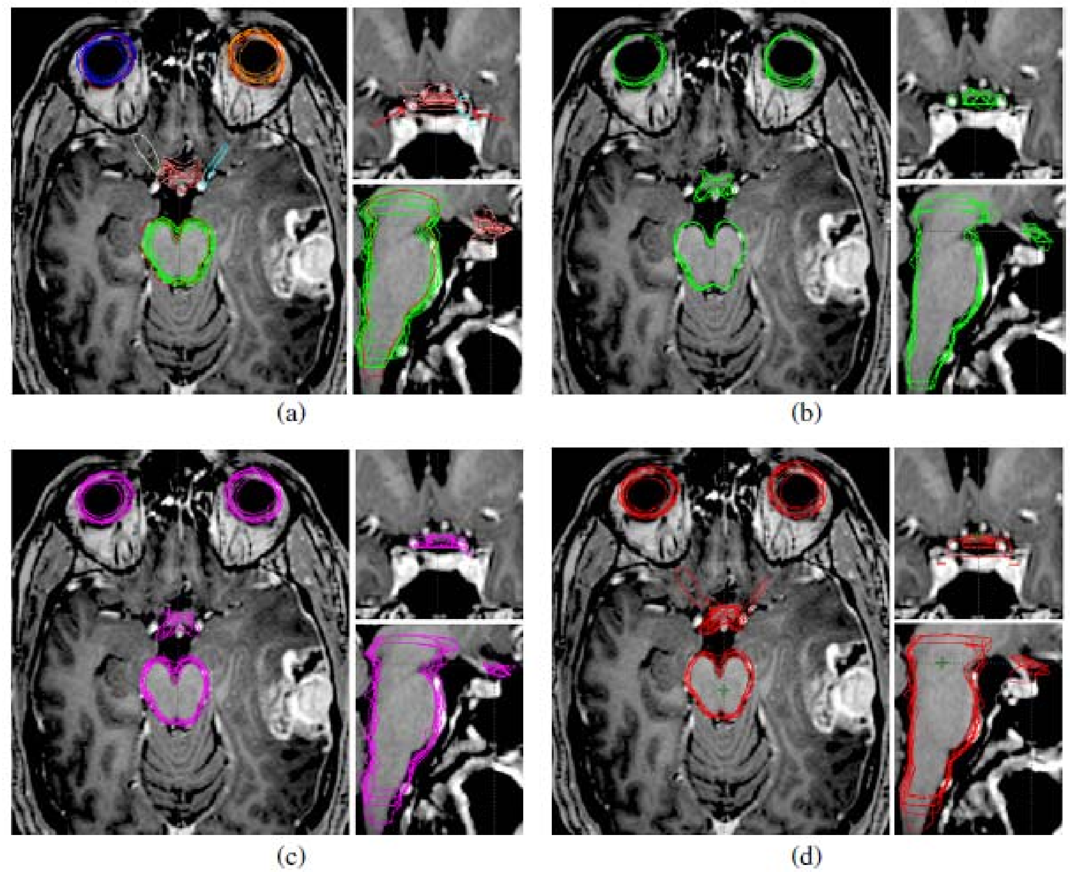


Figure 4. Orthogonal views comparing group results from (a) *de novo*, (b) A_1-edited, (c) self-edited, (d) peer-edited. The red arrows in the upper right (coronal section) of panel (a) point to the internal carotid arteries, which were often erroneously included as part of the optic chiasm in the *de novo* study as well as self- and peer-edited groups. In panel (a) the red contours are those of the A_1 while the other colors represent manual expert segmentations.

What impact has higher technical targeting accuracy on the required target contouring accuracy?

0%	1. The two are not related
4%	2. The CTV margin can be reduced
6%	3. A fused image set should be used
17%	4. A contouring atlas must be used
74%	5. It leaves less room for contouring uncertainty

What impact has higher technical targeting accuracy on the required target contouring accuracy?

Feedback:

The CTV margin depends on the extent of the microscopic disease. A higher technical accuracy means there is more conformality to the tumor contour. Therefore, the tight coverage leaves less room for contouring uncertainties. Using a contouring atlas may help in accurately contouring organs at risk.

Slide Location:

Higher Accuracy means less room for uncertainty (#41)

Reference:

Buis, Dennis R., et al. "Stereotactic radiosurgery for brain AVMs: role of interobserver variation in target definition on digital subtraction angiography." *International Journal of Radiation Oncology* Biology* Physics* 62.1 (2005): 246-252.

Conclusion

1. Dedicated Radiosurgery machines can delivery dose very accurately to homogeneous phantoms

2. Treatment Planning systems are getting much more accurate
   - In-vivo studies of dose calculation accuracy or anthropomorphic phantom DQA sparse in SRS/SBRT
   - DQA methods have technical limits measuring to accuracy better than 3%/1mm

3. Uncertainties in Radiation Biology, imaging disease, image registration & contouring are now large compared to mechanical & dosimetry uncertainty