SRS Uncertainty:
Linac and CyberKnife Uncertainties

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Linac/CyberKnife Technological Uncertainties

Linac Mechanical/Radiation Isocenters

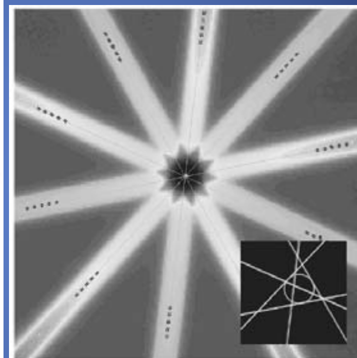


Figure 2. Star shot analysis, showing field axis segmentation. The inset shows the enlarged crossing of all detected beam axes and the calculated smallest intersecting circle, of which the radius is called the radiation isocenter size.

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.

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

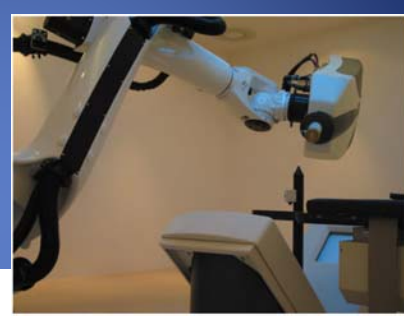
Independent errors are added in quadrature: **2 mm !**

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 for highest light intensity on crystal
- Calibration followed by verification
- Acceptance <0.5mm average rms error per path



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

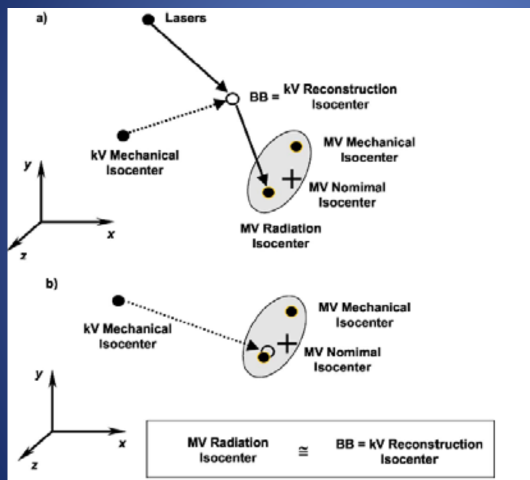
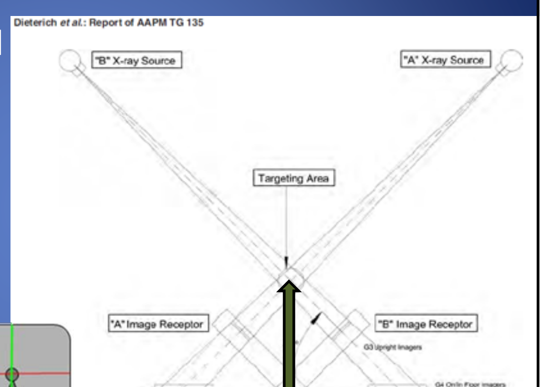


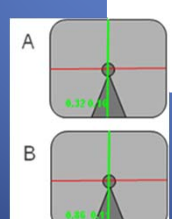
FIG. 2. Schematic of the kV-MV calibration procedure. (a) Relative position of "iso-centers" and ball-bearing (BB) prior to adjustment in BB placement based upon MV portal images. The portal imaging procedure provides an estimate of the BB location with respect to the MV radiation iso-center of the treatment 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





Linac Mechanical/Radiation: Winston-Lutz

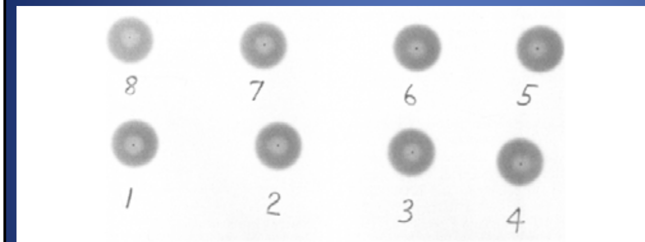


Fig. 9. Test film from target simulator. The eight exposures correspond to the eight combinations of gantry and turntable angles shown in Table 1. The small dots, which indicate the center of the "steel ball" target, were added to help in measuring beam-target displacement errors.

Lutz, Wendell, Ken R. Winston, and Nasser Maleki. "A system for stereotactic radiosurgery with a linear accelerator." *International Journal of Radiation Oncology* Biology* Physics* 14.2 (1988): 373-381.

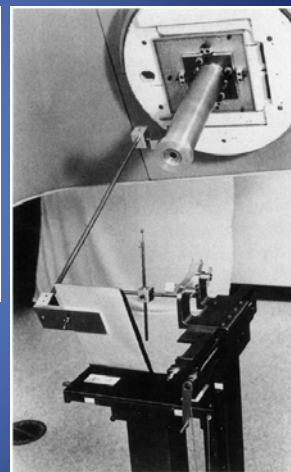
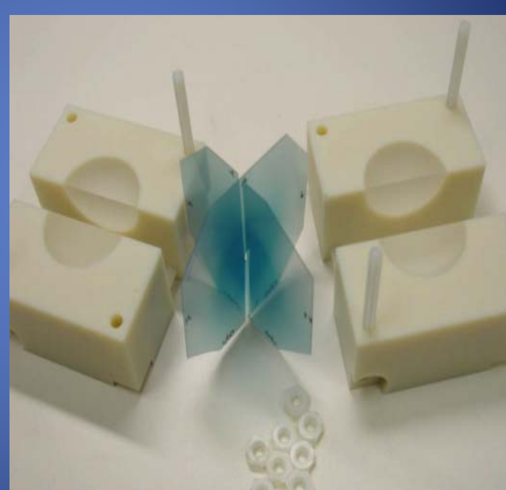


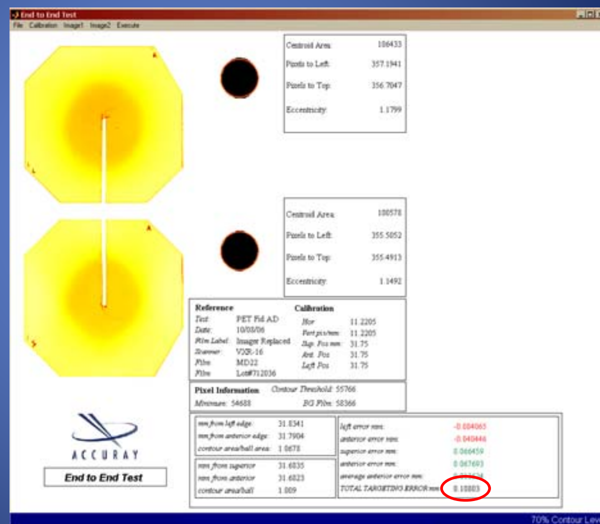
Fig. 8. Target simulator in use. The target simulator and the floor stand are independently set to the patient's target coordinates. If everything is aligned and set correctly, the ball bearing will remain the center of the radiation beam regardless of the angle of the turntable or the gantry.

Frameless SRS: 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)

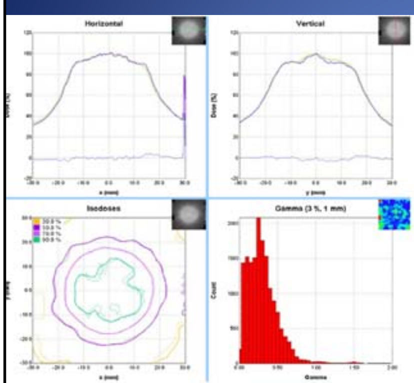


Figure 5. Dose comparison for a 6 MV FFF RapidArc plan with 3 cm diameter target in the axial

		AL film		AS film			
Plan	Target diameter (cm)	X(RL) (mm)	Y(AP) (mm)	X(SI) (mm)	Y(AP) (mm)	AP average (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
```

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

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

10

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

Uncertainties Common to All SRS Delivery Systems

Imaging Algorithm Uncertainty

1. Target Localization Error: error extracting target position
2. Target registration error: mean distance between image data and real patient after registration
3. Target Positioning error: Mismatch between intended position and actual position

➢ Methodology of Measuring is the same for all algorithms

Target Localization Error

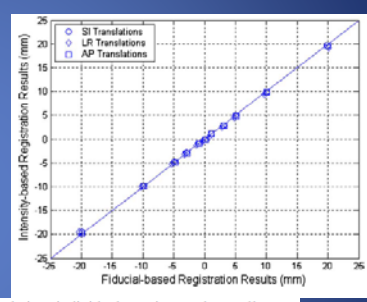


TABLE I. Registration errors of individual translation, overall translation, individual rotation, and overall rotation using fiducial-based registration as the reference. These statistic results were calculated from the measured results of 49 phantom motion positions in Table V in the Appendix.

	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

Target Registration Error

- Testing against a "gold standard"
  - E.g. track with fiducials, then edit them out and track on skeletal features
  - Fu, D., et al. "3D target localization using 2D local displacements of skeletal structures in orthogonal X-ray images for image-guided spinal radiosurgery." *Int J CARS* 1.Suppl 1 (2006): 198-200.

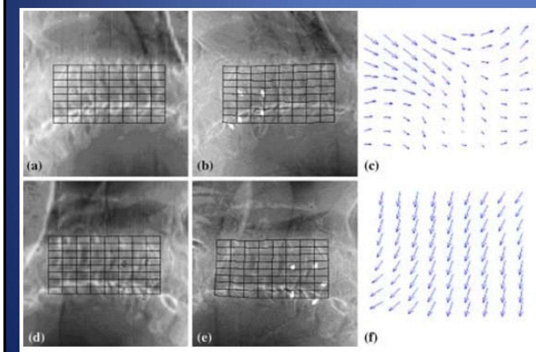


Table 1 Validation results using clinical patient data

Patient no	Spine level	Target 1	Target 2	Target 3	Target 4	Mean
1	Cervical	0.55	0.96	0.36	0.50	0.59
2	Cervical	0.61	0.34	0.77	0.21	0.48
3	Thoracic	0.49	0.32	0.42	0.39	0.41
4	Thoracic	0.68	0.60	0.92	0.70	0.73
5	Lumbar	0.24	0.24	0.60	0.63	0.43
6	Lumbar	0.46	0.24	0.37	0.48	0.39

Target Positioning Error

- Depends on how you adjust for patient position
- With couch:
  - couch motion accuracy
  - Measure using realistic patient weight!
- With delivery system (CK, VERO, Linac):
  - Robot pointing accuracy
  - Gimbal rotation accuracy
  - MLC shift accuracy

What is the Target Registration Error?

20%	
20%	
20%	
20%	
20%	

1. Error extracting target position
2. Mean distance between image data and re patient after registration
3. Mismatch between intended and actual position
4. Error caused by choosing incorrect fusion algorithm
5. Uncertainty in couch movement

10

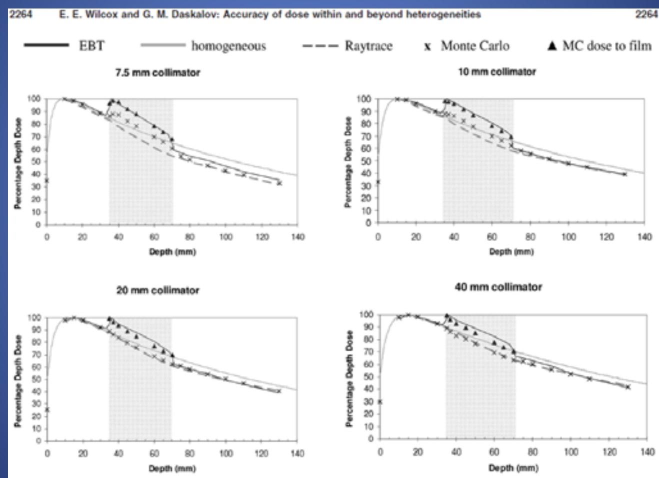
What is the Target Registration Error?

Feedback:
Mean distance between image data and real patient after registration

Slide Location:
Imaging Algorithm Uncertainty

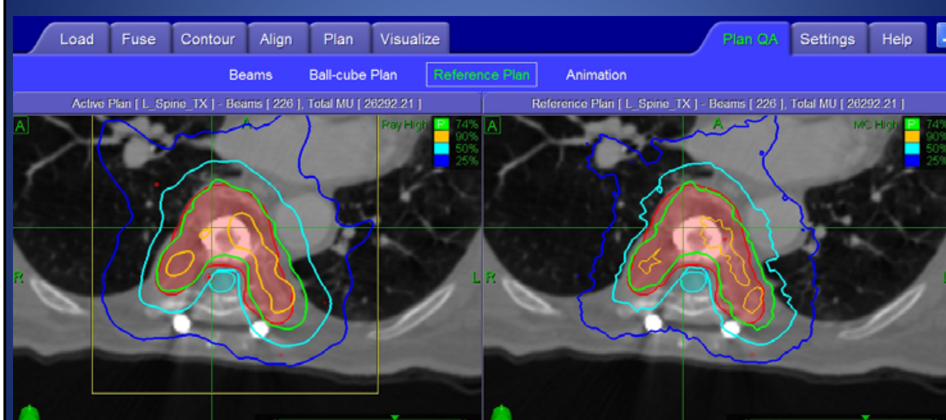
Reference:
Uncertainties in External Beam Radiotherapy, Chapter 14 Image Guidance to Reduce Setup error

Dosimetry: Dose Calculation Algorithm



Common MC uncertainty setting: 2% at maximum dose

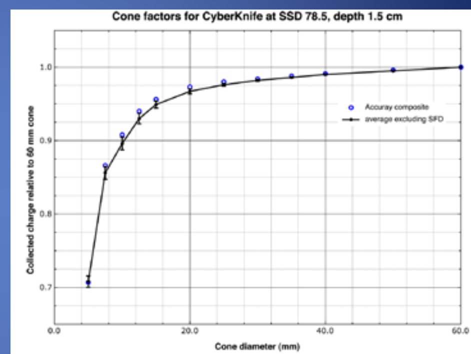
Why Include Dose Calculation?



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



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

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

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
Planning(Geneser lecture)	Contouring	Similar for both machines		B
Treatment	Residual patient motion	Similar for both machines		A/B

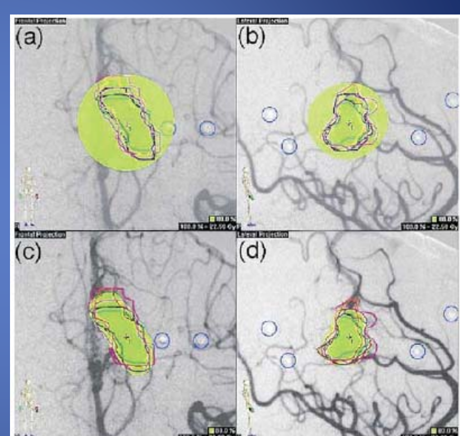
Quantitative Accuracy Comparison: It's Complicated …

- 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

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.*

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

20% 1. The two are not related
20% 2. The CTV margin can be reduced
20% 3. A fused image set should be used
20% 4. A contouring atlas must be used
20% 5. It leaves less room for contouring uncertainty

10

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