# Near Misses: Physics Cautionary Tales

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## Conflicts of interest

Research support from Elekta Instruments, AB

## Session Educational objectives

Identify weak points in the SRS/SBRT treatment process

Demonstrate how methodology described in TG-100 can be used to assess and prevent treatment events



# Part I: What could possibly go wrong?

# 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

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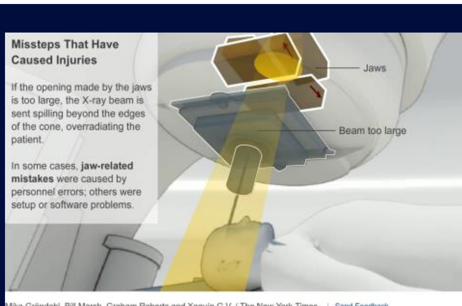
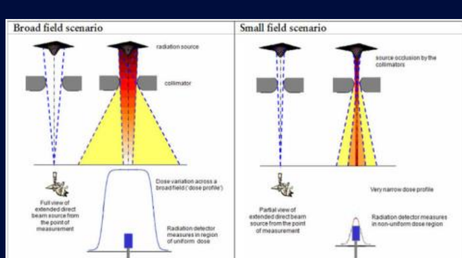



2009: 3 patients (+1 at another center) were overdosed during intracranial SRS treatments on a retrofitted linac. One patient deteriorated to near vegetative state.




http://medicalphysicsweb.org/cws/article/opinion/45334

2006-2007: 145 patients over-treated. Scatter factor measured with a farmer chamber at 20% of value measured with a pinpoint chamber.

2004-2009: 76 patients irradiated incorrectly from by a similar small field calibration error.

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# Medical event

Events, except those which result from patient intervention, in which
Dose differs from Rx (or dose that would result from Rx dose) by:

> 5 rem (0.05 Sv) EDE, or
> 50 rem (0.5 Sv) to organ or tissue, or
> 50 rem shallow dose equivalent to skin

*AND*

Total dose differs from Rx by >= 20%

*OR*

Single Fx dose differs from Rx by >=50%

*OR*

Dose given to wrong individual

*OR*

Dose to tissue other than Tx site >50 rem (0.5 Sv) and >=50% of the dose expected from the administration defined in the Written Directive

**NRC 10 CFR § 35.3045 Report and notification of a medical event.**

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# Misadministrations and other terms

## Reportable events

Patient or operator suffers a mechanical injury

Weekly teletherapy x-ray or electron dose differs from planned by ≥15%

X-ray brachytherapy dose differs from planned by ≥ 10%

Diagnostic x-ray exposure where suspected or actual long-term damage to organs or systems occurs.

## Misadministration

X-ray teletherapy:

Wrong patient / wrong site

Calculated total dose differs from planned by >20% (>10% 3 or fewer fx)

Weekly dose differs > 30%

X-ray brachytherapy:

Wrong patient / wrong site

Total dose differs from planned by > 20%

Definitions from 12VAC5-481

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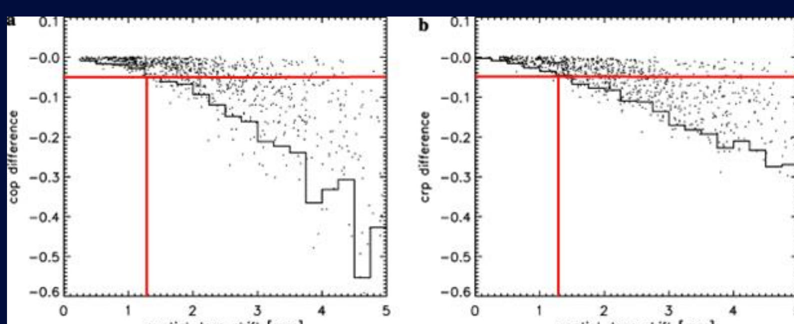
## More likely…this sort of thing can happen:



## You can miss your target…



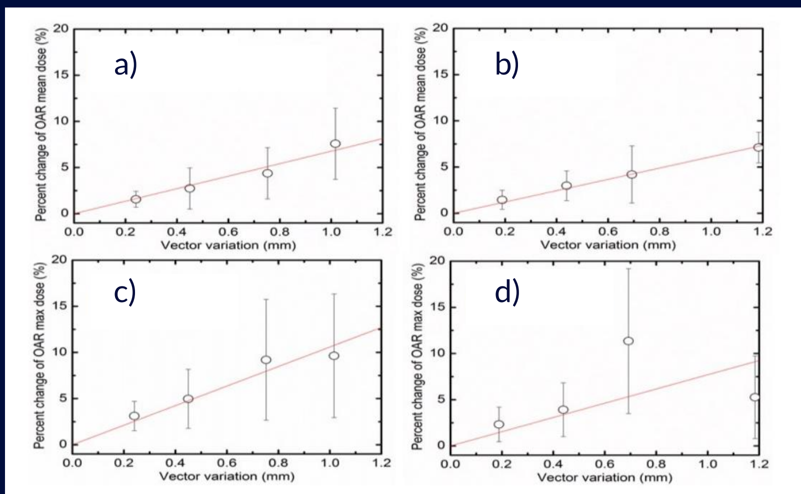

Change in obliteration probability (AVMs)

Change in remission probability (mets)

**Impact of target point deviations on control and complication probabilities in stereotactic radiosurgery of AVMs and metastases.**

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: inter-fractional (a), intra-fractional (b)

Change in max OAR dose vs positioning deviation: inter-fractional (c), intra-fractional (d)

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



If you practice ~~SRS/SBRT~~ anything long enough, you will make a mistake.

This isn't a talk about the gory details. (Sorry).

# Here’s where you can find the gory details….

U.S.NRC
United States Nuclear Regulatory Commission
*Protecting People and the Environment*

Event Notification Reports

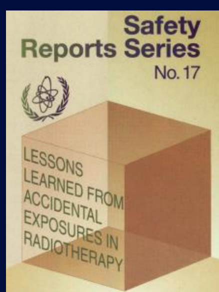
Event Notification Report (Last Month) (raw data text file) | Data Dictionary (Microsoft Excel)

**2010s:** | 2016 | 2015 | 2014 | 2013 | 2012 | 2011 | 2010 |

**2000s:** | 2009 | 2008 | 2008 | 2007 | 2006 | 2005 | 2004 | 2003 | 2002 | 2001 | 2000 |

**1990s:** | 1999 |

http://www.nrc.gov/reading-rm/doc-collections/event-status/event/




http://www-pub.iaea.org/MTCD/publications/PDF/Pub1084_web.pdf



# Part II: Why do things go wrong?

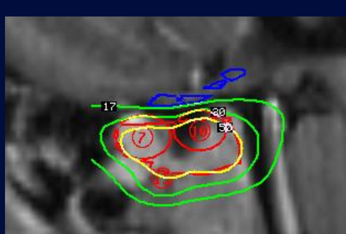
# Radiosurgery is hard.

Uncertainty makes it harder.

People make it harder still.



# 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 (GK)
>10%/mm (linac)

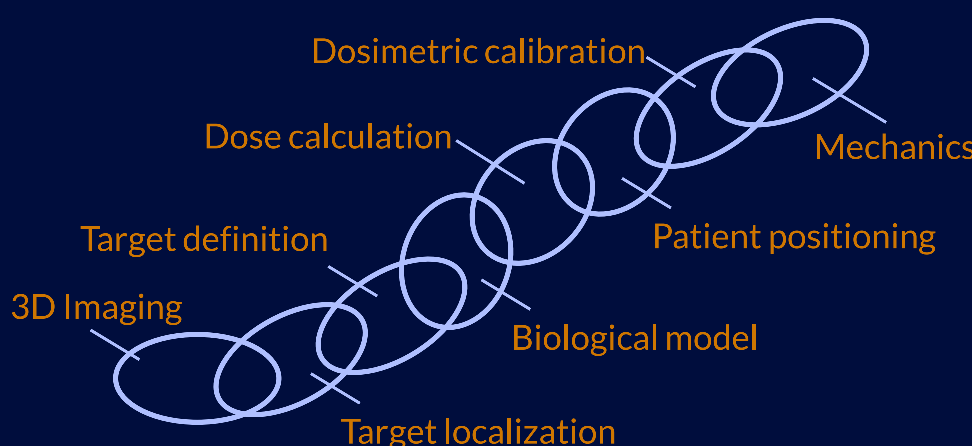
Extremely high requirements for accuracy and precision!

Radiosurgery is hard.

**Uncertainty makes it harder.**

People make it harder still.



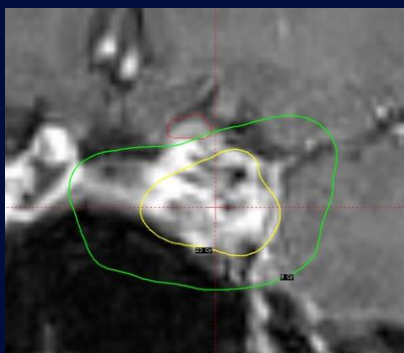



SRS/SBRT has a complex uncertainty chain

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

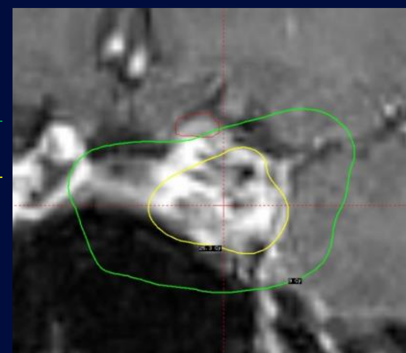
# Procedural uncertainty = isodose uncertainty

What difference does a 10% change in dose make?



9.0 Gy
23.0 Gy

9.0 Gy
25.3 Gy



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 $cm^3$

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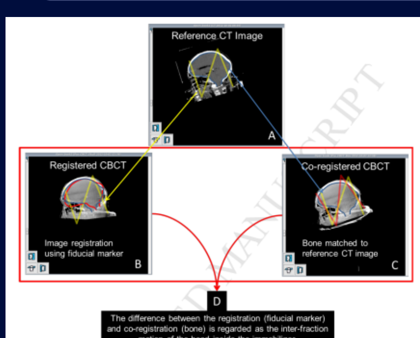
# Frames do not have perfect immobilization.

Or localization!




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.

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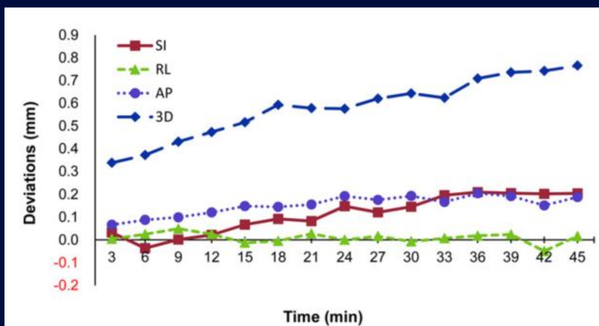
# …and neither do thermoplastic masks.




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.

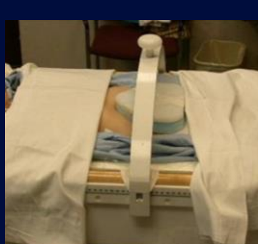
Intrafraction shifts have been reported between 0.1 mm and 2.0 mm.

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

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



# …and neither do body frames!



| Treatment site: technique (# patients/ # fractions) | Mean 3D error (mm) Pretreatment | Intrafraction |
|---|---|---|
| Lung: compressed (55/223)) | 7.29 ± 4.05 | 1.72 ± 1.98 |
| Lung: uncompressed (86/339) | 7.40 ± 3.97 | 1.28 ± 1.53 |
| Liver (29/112) | 6.64 ± 3.46 | 1.21 ± 1.74 |
| Prostate (48/240) | 7.62 ± 3.97 | 1.95 ± 1.76 |
| Spine (45/91) | 8.00 ± 4.43 | 1.29 ± 1.45 |

R. Foster, et al., Localization Accuracy and Immobilization Effectiveness of a Stereotactic Body Frame for a Variety of Treatment Sites, IJROBP 87(5), 2013.

# Machine calibrations are not always perfect

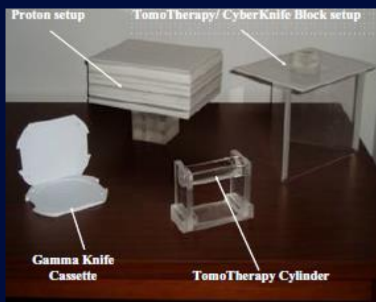
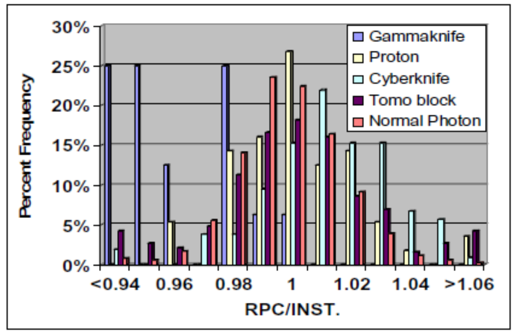



Figure 1. The various TLD miniphantoms used to perform the machine output audits of the CyberKnife, Gamma Knife, Hi-Art TomoTherapy and proton synchrotron/cyclotron machines.




Percent frequency histogram of the RPC/INST ratios for the TG-51 non-compliant beams measured to date compared to the normal TG-51 compliant photon beams (n=6000). With the exception of the Gamma Knife, the distribution of results for the TG-51 non-compliant beams is the same as for the compliant beams. Gamma Knife shows a 4-5% low result of which 1% is due to the muscle to water conversion and the remaining 3% due to differences between TG-21 in polystyrene and TG-51 in water dose calculations.

Quality Audits of the Calibration for TG-51 Non-Compliant Beams by the Radiological Physics Center

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

D. Followill, et al., Medical Physics 35:2774, 2008.

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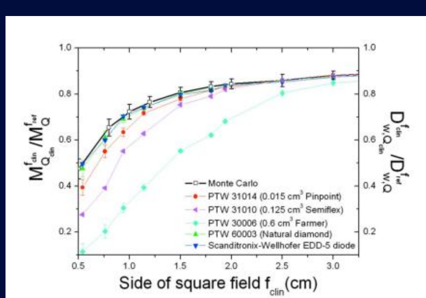
# Small fields are difficult to measure

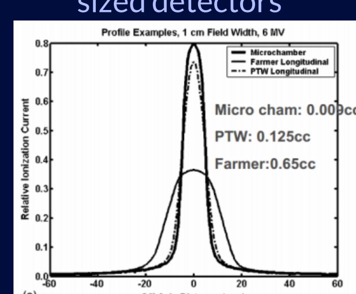



Charged particle equilibrium assumption no longer valid

Detector itself becomes a prominent source of measurement uncertainty

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

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.

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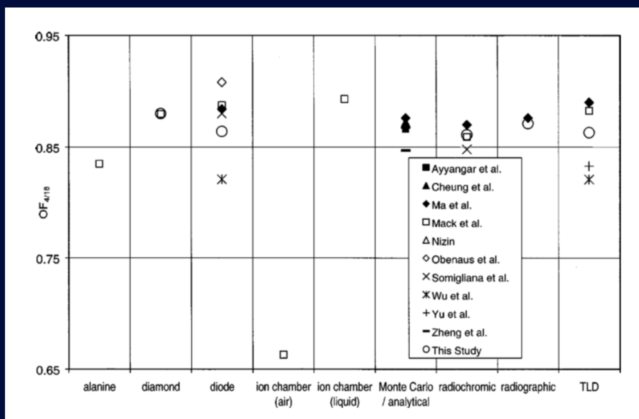


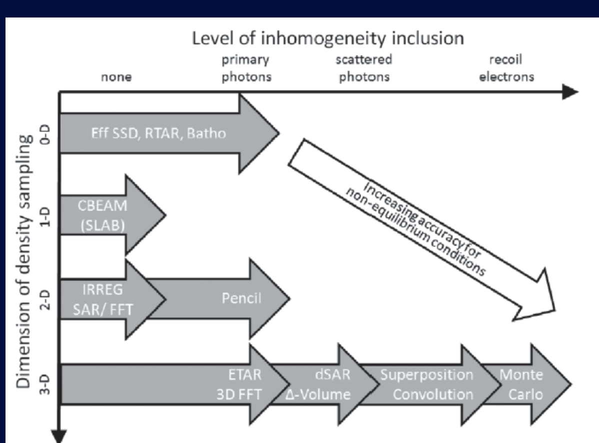

Determination of the 4 mm Gamma Knife helmet relative output factor using a variety of detectors (summary of literature)

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

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



# Not all planning systems work well for SRS/SBRT



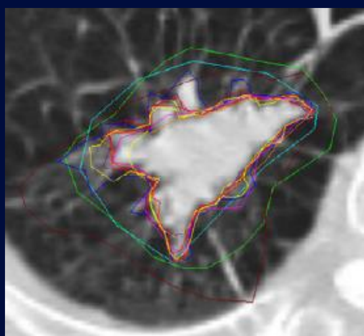

J. Siebers, AAPM Summer School 2011 – Uncertainties in External Beam Radiation Therapy

## TPS uncertainties

- Beam data collection
- Beam data modeling
- MLC modeling
- Dose calc algorithms
- CT to election density
- Dose grid interpolation
- Accelerator output variations vs plan
- Range uncertainty (protons)

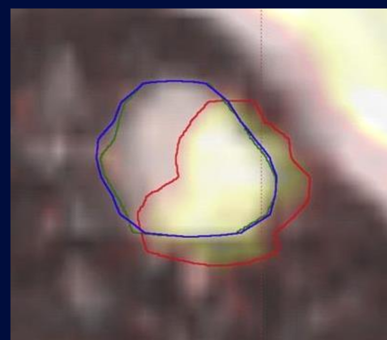
# It can be difficult to decide on a target

Contours from 11 observers, 4 institutions



Delineation variability correlated with irregularity (r=0.77, p=0.005)

Peulen et al., Radiother Oncol, 114, 2015.



$GTV_{3D}$ = free breathing CT

$ITV_{MIP}$ = MIP

$ITV_{10phase}$ = combination of GTVs from each phase of 4DCT

$ITV_{10phase}$ does not completely cover $GTV_{3D}$ and $ITV_{MIP}$.

Ge et al., IJROBP 85, 2013.




Fig. 1. Contouring variations in a patient with a brainstem arterio-venous 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 = 0.19 ± 0.14

**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

# Even subtle timing differences can matter

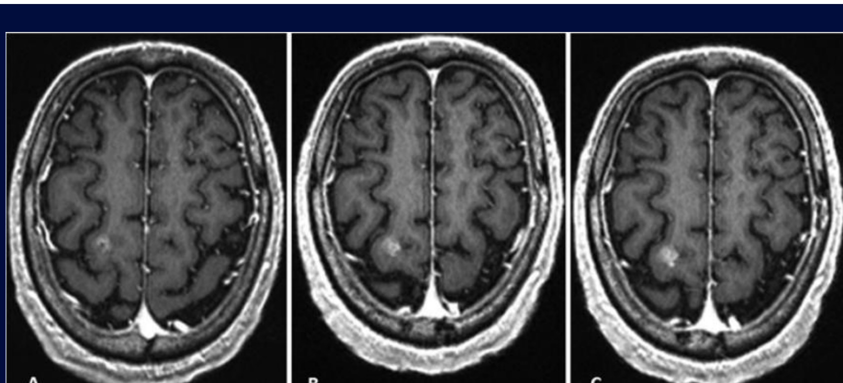
Timing of contrast injection can have significant effects on GTV definition

| Lesion | Immediate scan: Mean volume (SD) (mm³) | | Delayed scan: Mean volume (SD) (mm³) | | % change in volume | 3D shift in isocentre (mm) |
|---|---|---|---|---|---|---|
| A1 | 279 | (79) | 474 | (59) | 70 | 1.4 |
| A2 | not analysed | | | | | |
| B1 | 290 | (87) | 325 | (63) | 12 | 1.0 |
| B2 | 879 | (114) | 1134 | (103) | 28 | 0.7 |
| C | 477 | (15) | 492 | (21) | 3 | 0.9 |
| D1 | 1479 | (32) | 1798 | (22) | 21 | 1.3 |
| D2 | 1780 | (33) | 1767 | (35) | −1 | 0.4 |
| E | 1708 | (33) | 2093 | (101) | 22 | 0.6 |
| F1 | 1807 | (21) | 2731 | (39) | 51 | 0.5 |
| F2 | 2326 | (23) | 3179 | (45) | 36 | 1.5 |
| G1 | 1961 | (161) | 2871 | (559) | 46 | 0.2 |
| G2 | 3764 | (234) | 5952 | (188) | 58 | 1.4 |
| H1 | 5333 | (138) | 6434 | (166) | 20 | 2.4 |
| H2 | not analysed | | | | | |
| I | 11358 | (344) | 13047 | (115) | 14 | 4.6 |
| J | 19787 | (894) | 16688 | (5009) | −16 | not planned |

Delayed scan was after a mean of 65 minutes
Planners would select larger collimator sizes in 92% of delayed CT scans

Delineation of brain metastases on CT images for planning, radiosurgery: concerns regarding accuracy, K. Sidhu, P Cooper, R. Ramani, et. al. BR J Radiol (77), 2004.



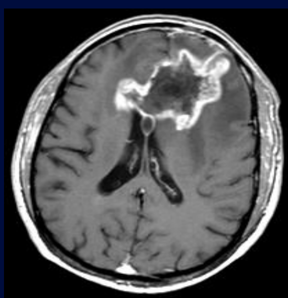



Scan 1: time of injection
Scan 2: ~10 min delay
Scan 3: ~15 min delay

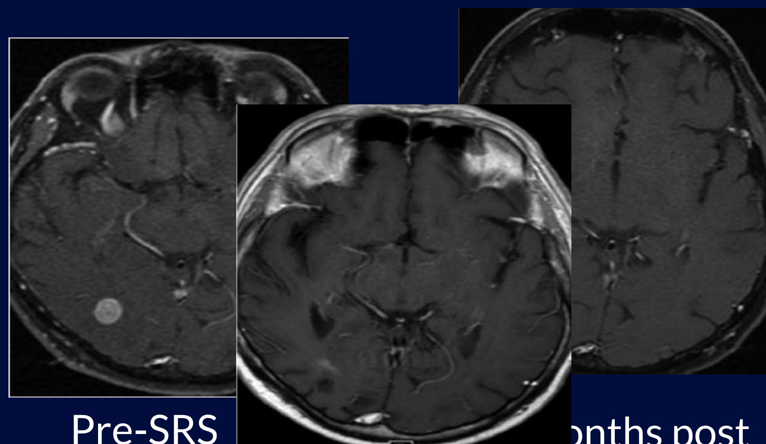
| Scans compared | % studies w ≥ 1 new lesion | 95% CI | Range of # new lesions |
|---|---|---|---|
| Scan 1:2 | 35.3% | 22.4%-49.9% | 1-10 |
| Scan 2:3 | 21.6% | 11.3%-35.3% | 1-9 |
| Scan 1:3 | 43.1% | 29.3%-57.8% | 1-14 |

M. Kushnirsky et al., JNS 124, 2016

# Biology is not always predictable



Radiation necrosis



Pre-SRS

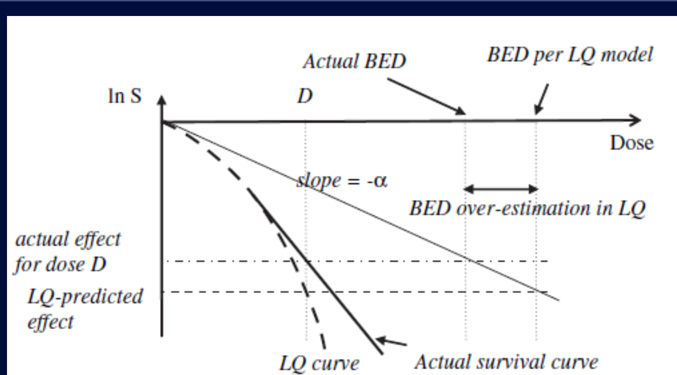
nths post

16 months post

R. Shah, et al, RadioGraphics 32(5), 2012



# SRS/SBRT radiobiology may be different…




In in-vitro cultures, LQ model parameters overestimate BED as compared to empirical survival curves at SBRT doses

C. Park, L. Papiez, S. Zhang, M. Story, R.D. Timmerman, Int. J. Radiation Oncology Biol. Phys., 70(3), 2008

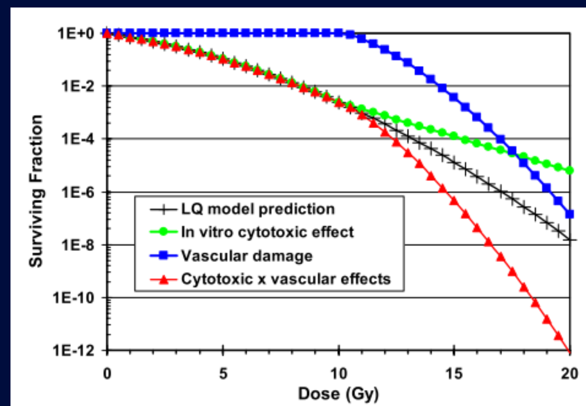
# …so there is uncertainty in the LQ model

Observed in-vitro cell survival not as good as LQ model predicts

But clinically SRS performs better than LQ model predicts

Microvascular damage has been shown to occur at doses > 10Gy.

SRS biological effect may involve DNA damage + vascular damage




J. Kirkpatric, J. Meyer, L.B. Marks, Semin Rad Onc, 18(4), 2008.

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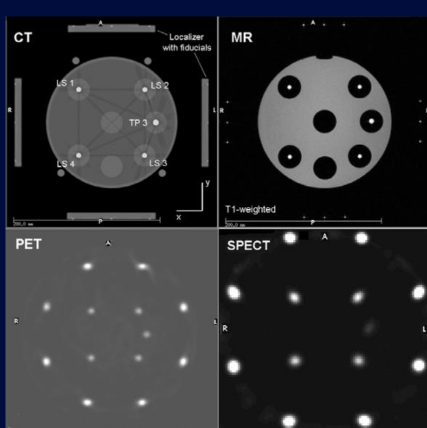
# You can't localize targets perfectly




Localization of known stereotactic targets with various modalities

| Modality | Radial Deviation (mean ± STD) (mm) |
|---|---|
| CT | 0.4±0.2 |
| *MR (T1-weighted) | 1.4±0.3 |
| *MR (T2-weighted) | 1.4±0.5 |
| †PET | 1.1±0.5 |
| ‡SPECT | 1.6±0.5 |

*Siemens Magnetom Symphony, †Siemens CTI ECAT EXACT HR, ‡Siemens MULTISPECT 3

C.P. Karger, P. Hipp, M. Henze, G. Echner, et al., Phys Med Biol 48, 2003.

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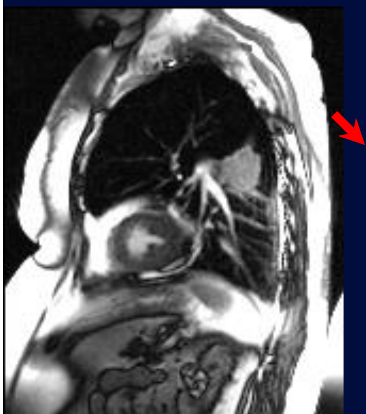
## Internal anatomy moves!

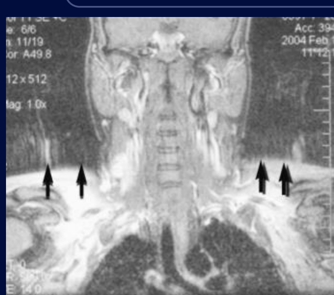


Be careful of dose interplay effects!

Images courtesy of S. Benedict, UC-Davis

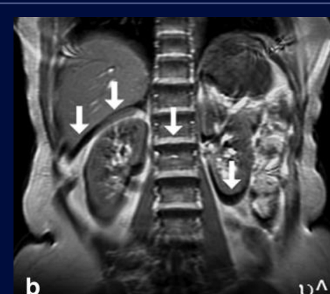


## …and images are not necessarily reality!



Motion artifact

Metal artifact



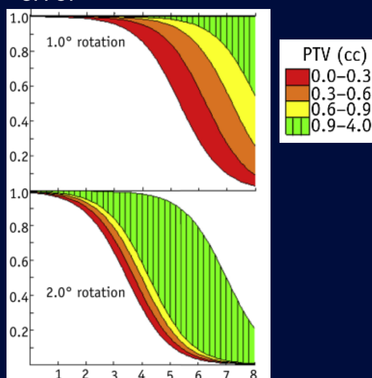

Chemical shift artifact

L. J. Erasmus, et al.,SA Journal of Radiology 8/2004
M.J. Graves, et al., J. of Magnetic Resonance Imaging 38, 2013.

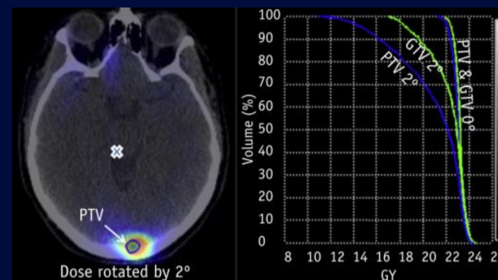
# Small errors can lead to large effects

Rotations and targeting error

Prob of PTV coverage (95% dose to 95% volume)




Distance to isocenter (cm)




Example of rotational "lever effect"

Single-isocenter treatments place isocenter near centroid of all targets.

Rotational errors grow with distance from isocenter to target.

Good co-registration is critical!

Roper, et. al., IJROBP 93(3), 2015

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Radiosurgery is hard.

Uncertainty makes it harder.

People make it harder still.

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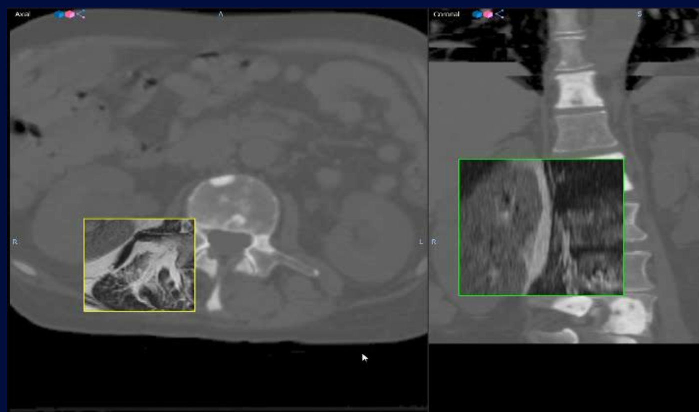
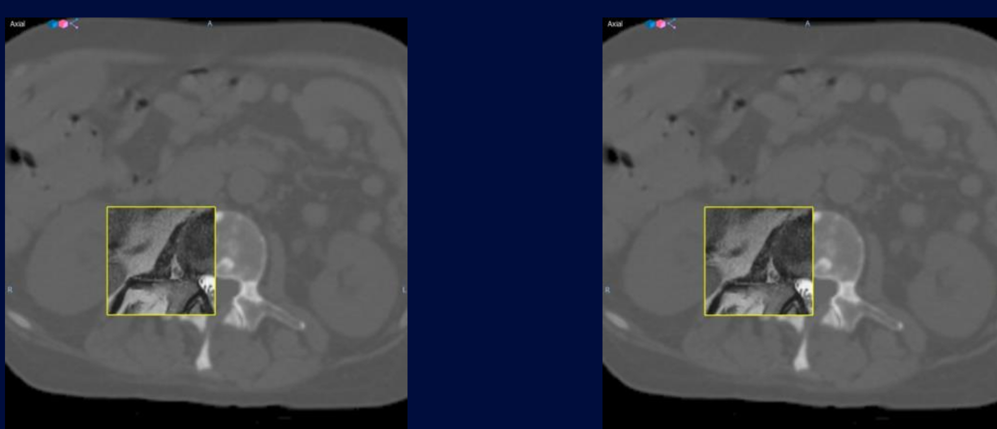
# Humans are (maybe) not so good at 3D registration



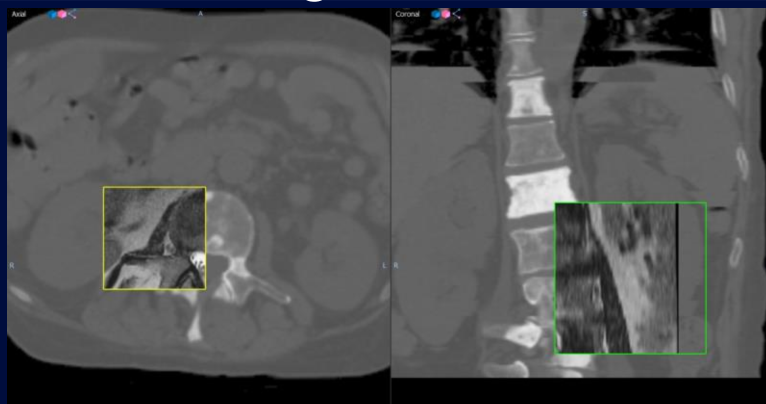


# Humans are (maybe) not so good at 3D registration



Can you spot the differences between these two registrations?

# Humans are (maybe) not so good at 3D registration



Δ translation x: -1.00 mm
Δ translation y: -0.64 mm
Δ translation z: 1.52 mm

Δ rotation x: 0.05°
Δ rotation y: -2.00°
Δ rotation z: 0.00°

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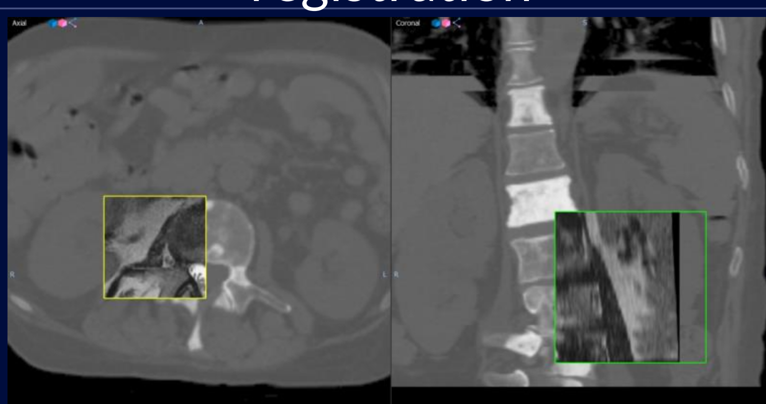
Humans are (maybe) not so good at 3D registration



Δ translation x: -1.00 mm
Δ translation y: -0.64 mm
Δ translation z: 1.52 mm

Δ rotation x: 0.05°
Δ rotation y: -2.00°
Δ rotation z: 0.00°

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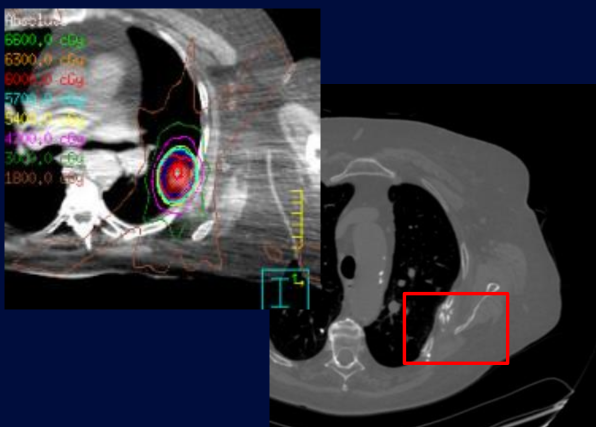
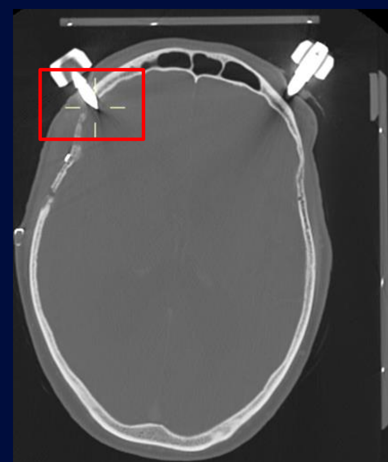
# Even "simple" procedures can go wrong



Chronic rib fracture/fragmentation post SBRT

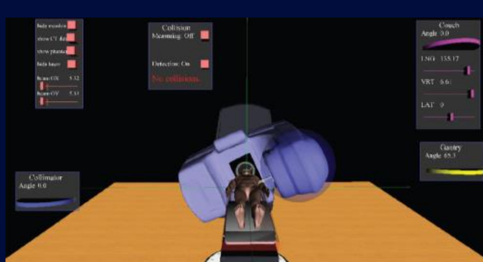


Frame pin pushed through skull defect

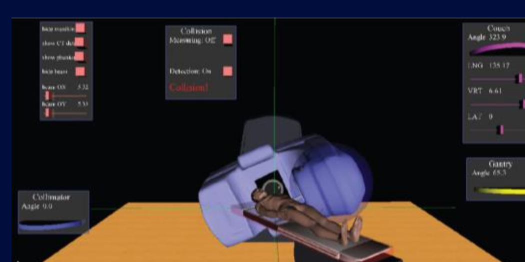
Images courtesy of University of Virginia



# SRS/SBRT can have unusual machine settings



Couch 0.0° / Gantry 65.3°
No collision

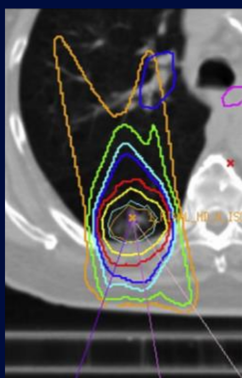


Couch 323.9° / Gantry 65.3°
Collision!

Beams are often non-coplanar, requiring unusual couch angles. Not difficult to have a collision with patient!

Image from D. Schlesinger, et al., Treatment Planning for Spine Radiosurgery, in Spine Radiosurgery 2nd ed., 2015.

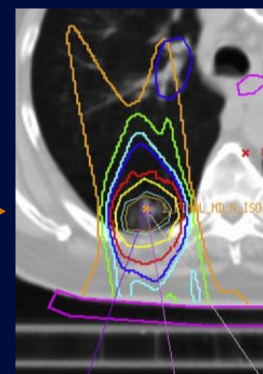
# SRS/SBRT treatment plans require extreme care



Clinical plan with narrow beam arrangement and no accounting for couch or immobilization devices

Actual grade 4 skin necrosis

Replan including 1 cm bolus to simulate couch and immobilization



Hoppe et a., IJROBP 72, 2008

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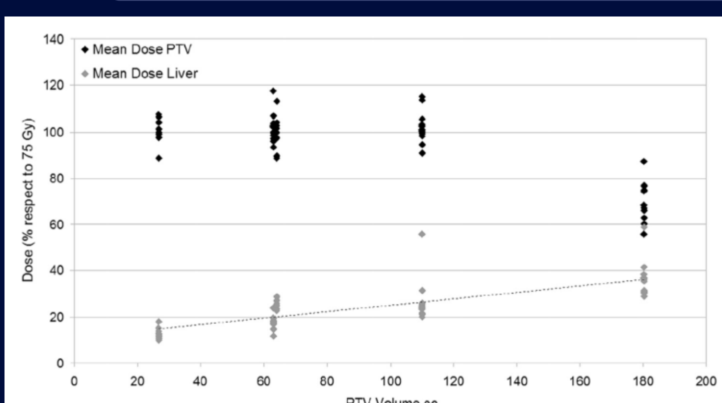
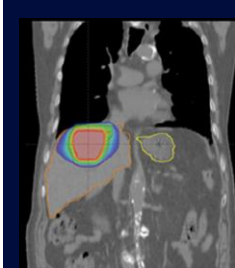
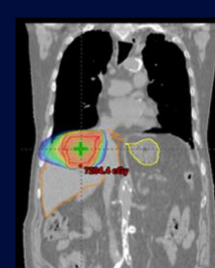
# Variations in technique can be large




mean dose to PTV: 99.7 ± 3.5%
mean dose to V98%: 93.6 ± 4.4%, respectively





14 centers, 5 patient image sets w single liver metastasis

Common set of dose constraints

Local equipment, planning technique

Esposito et al., Physica Medica 32 (2016)

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One theme so far is that humans are fallible!



# Part III: How not to be a victim

# Perform QA specific for SRS/SBRT

Follow accepted best practices

Value training, credentialing, and peer-review

Apply systems engineering

Keep innovating

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# Prescriptive QA for SRS/SBRT

Confusing?

| AAPM Task Group | Title | Year Published |
|---|---|---|
| TG-42 | Stereotactic Radiosurgery | 1995 |
| TG-53 | QA for clinical radiotherapy treatment planning | 1998 |
| TG-51 | Clinical reference dosimetry of high-energy photon and electron beams | 1999 |
| TG-142 | QA of medical accelerators | 2009 |
| TG-101 | Stereotactic body radiation therapy | 2010 |
| TG-148 | QA for helical tomotherapy | 2010 |
| TG-135 | QA for robotic radiosurgery | 2011 |
| TG-179 | QA for image-guided radiation therapy using CT-based technologies | 2012 |
| TG-147 | QA for nonradiographic radiotherapy localization and positioning systems | 2012 |

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# Example: TG-142 (Accelerator QA)

TABLE III. Annual.

| Procedure | Machine-type tolerance: Non-IMRT | IMRT | SRS/SBRT |
|---|---|---|---|
| **Dosimetry** | | | |
| X-ray flatness change from baseline | | 1% | |
| X-ray symmetry change from baseline | | ±1% | |
| Electron flatness change from baseline | | 1% | |
| Electron symmetry change from baseline | | ±1% | |
| SRS arc rotation mode (range: 0.5–10 MU/deg) | NA | NA | Monitor units set vs delivered: .0 MU or 2% (whichever is greater) Gantry arc set vs delivered: 1.0° or 2% (whichever is greater) |
| X-ray/electron output calibration (TG-51) | | ±1% (absolute) | |
| Spot check of field size dependent output factors for x ray (two or more FSs) | | 2% for field size <4×4 cm², 1% ≥4×4 cm² | |
| Output factors for electron applicators (spot check of one applicator/energy) | | ±2% from baseline | |
| X-ray beam quality ($PDD_{10}$ or $TMR_{10}^{20}$) | | ±1% from baseline | |
| Electron beam quality ($R_{50}$) | | ±1 mm | |
| Physical wedge transmission factor constancy | | ±2% | |
| X-ray monitor unit linearity (output constancy) | ±2% ≥5 MU | ±5% (2–4 MU), ±2% ≥5 MU | ±5% (2–4 MU), ±2% ≥5 MU |
| Electron monitor unit linearity (output constancy) | | ±2% ≥5 MU | |

TABLE I. Daily.

| Procedure | Machine-type tolerance: Non-IMRT | IMRT | SRS/SBRT |
|---|---|---|---|
| **Dosimetry** | | | |
| X-ray output constancy (all energies) / Electron output constancy (weekly, except for machines with unique e-monitoring requiring daily) | | 3% | |
| **Mechanical** | | | |
| Laser localization | 2 mm | 1.5 mm | 1 mm |
| Distance indicator (ODI) @ iso | 2 mm | 2 mm | 2 mm |
| Collimator size indicator | 2 mm | 2 mm | 1 mm |
| **Safety** | | | |
| Door interlock (beam off) | | Functional | |

TABLE VI. Imaging.

| Procedure | Application-type tolerance: non-SRS/SBRT | SRS/SBRT |
|---|---|---|
| **Daily[a]** | | |
| **Planar kV and MV (EPID) imaging** | | |
| Collision interlocks | Functional | Functional |
| Positioning/repositioning | ≤2 mm | ≤1 mm |

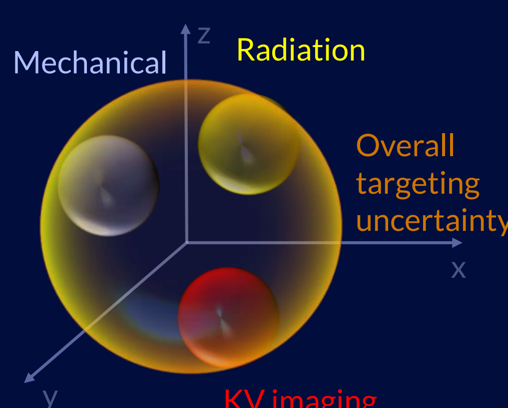
TABLE II. Monthly.

| Procedure | Machine-type tolerance: Non-IMRT | IMRT | SRS/SBRT |
|---|---|---|---|
| **Dosimetry** | | | |
| X-ray output constancy | | | |
| Electron output constancy | | 2% | |
| Backup monitor chamber constancy | | | |
| Typical dose rate[a] output constancy | NA | 2% (@ IMRT dose rate) | 2% (@ stereo dose rate, MU) |
| Photon beam profile constancy | | 1% | |
| Electron beam profile constancy | | 1% | |
| Electron beam energy constancy | | 2%/2 mm | |
| **Mechanical** | | | |
| Light/radiation field coincidence[b] | | 2 mm or 1% on a side | |
| Light/radiation field coincidence[b] (asymmetric) | | 1 mm or 1% on a side | |
| Distance check device for lasers compared with front pointer | | 1mm | |
| Gantry/collimator angle indicators (@ cardinal angles) (digital only) | | 1.0° | |
| Accessory trays (i.e., port film graticle tray) | | 2 mm | |
| Jaw position indicators (symmetric)[c] | | 2 mm | |
| Jaw position indicators (asymmetric)[d] | | 1 mm | |
| Cross-hair centering (walkout) | | 1 mm | |
| Treatment couch position indicators[e] | 2 mm/1° | 2 mm/1° | 1 mm/0.5° |
| Wedge placement accuracy | | 2 mm | |
| Compensator placement accuracy[f] | | 1 mm | |
| Latching of wedges, blocking tray[g] | | Functional | |
| Localizing lasers | ±2 mm | ±1 mm | <±1 mm |
| **Safety** | | | |
| Laser guard-interlock test | | Functional | |
| **Respiratory gating** | | | |

E. Klein, et al., Med Phys 36(9), 2009.



# Linear accelerator isocenters



# Winston-Lutz test

WL pointer with embedded BB at end

WL pointer mounted to treatment couch

Determines alignment of mechanical, radiation, and imaging isocenters of a linac

- Mount WL-pointer with embedded BB to the end of the treatment couch (usually special mounting hardware)
- Align BB end of pointer to the isocenter as suggested by the room lasers
- MV and KV detectors used to ensure isocenter alignment

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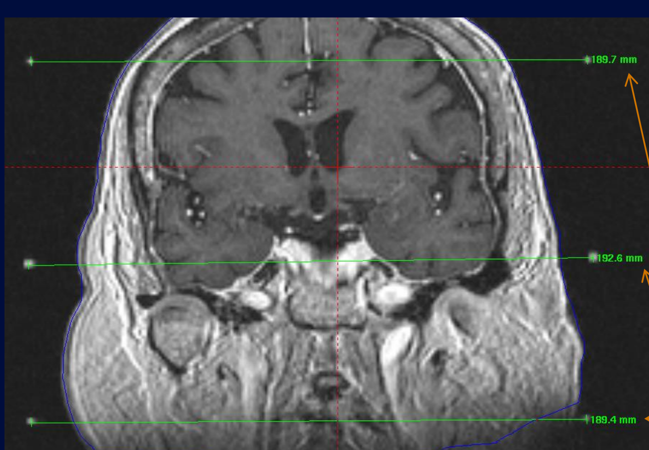
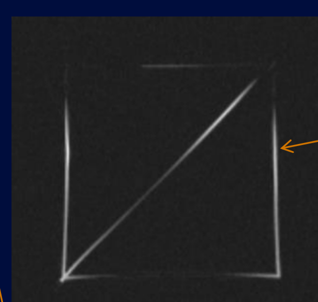
# Don't forget imaging QA!



These should be straight lines!

These distances should be the same!

Regular QA of imaging systems is critical for SRS/SBRT!
This includes after hardware/software upgrades.

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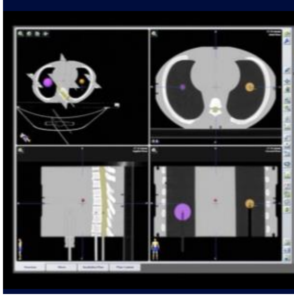
## SRS/SBRT end to end tests

Usually includes an imaging target and a detector

Tests the entire treatment procedure

Remember that phantoms provide a best case measure of uncertainty



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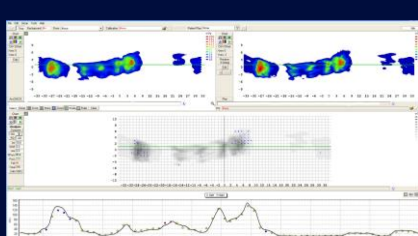
## Patient-specific QA

Performed using phantoms that have arrays of ion chambers or diodes

Assures that machine can technically deliver a given treatment plan



1. Recalculate plan onto image of phantom
2. Deliver treatment to phantom
3. Analyze results

Be careful! Not patient geometry!

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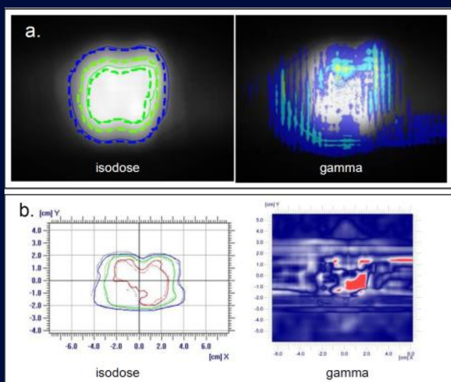
# Evaluating patient-specific QA

Popular metric: Gamma Index




Dose difference: Percentage difference on a pixel by pixel basis.

Distance to agreement (DTA): Distance to closest point with same dose

Gamma index looks for pixels where dose difference and DTA are simultaneously greater than a pre-selected threshold (example:
1 mm/1% or 3mm/3%).

Results usually expressed as a passing rate (example: >95% passing)

Be careful: How to choose criteria?

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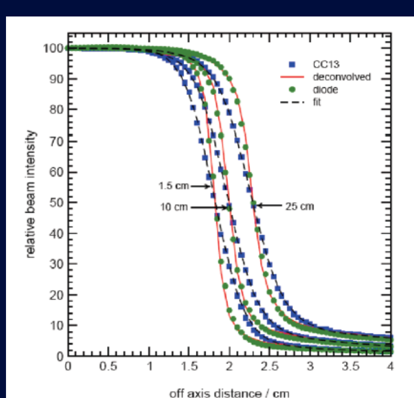
# SRS detectors are critical!




4x4 cm2 field, cross-beam profile

CC13 ion chamber vs diode vs deconvolved ion chamber signal

Ion chamber: 0.13 cm2 active volume

Diode: 0.8x0.8 mm2 cross sectional area

Use dedicated stereotactic ion chambers or diodes for making high-resolution measurements!

The extraction of true profiles for TPS commissioning and its impact on IMRT patient-specific QA, Yan, et al., Med Phys 35(8), 2008

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Perform QA specific for SRS/SBRT

**Follow accepted best practices**

Value training, credentialing, and peer-review

Apply systems engineering

Keep innovating



# Apply consensus experience

TABLE III. Summary of suggested dose constraints for various critical organs. Note that for serial tissues, the volume-dose constraints are given in terms of the critical maximum tissue volume that should receive a dose equal or greater than the indicated threshold dose for the given number of fractions used. For parallel tissue, the volume-dose constraints are based on a critical minimum volume of tissue that should receive a dose equal to or less than the indicated threshold dose for the given number of fractions used.

| | | One fraction | | Three fractions | | Five fractions | | |
|---|---|---|---|---|---|---|---|---|
| Serial tissue | Max critical volume above threshold | Threshold dose (Gy) | Max point dose (Gy)[a] | Threshold dose (Gy) | Max point dose (Gy)[a] | Threshold dose (Gy) | Max point dose (Gy)[a] | End point (≥Grade3) |
| Optic pathway | <0.2 cc | 8 | 10 | 15.3 (5.1 Gy/fx) | 17.4 (5.8 Gy/fx) | 23 (4.6 Gy/fx) | 25 (5 Gy/fx) | Neuritis |
| Cochlea | | | 9 | | 17.1 (5.7 Gy/fx) | | 25 (5 Gy/fx) | Hearing loss |
| Brainstem (not medulla) | <0.5 cc | 10 | 15 | 18 (6 Gy/fx) | 23.1 (7.7 Gy/fx) | 23 (4.6 Gy/fx) | 31 (6.2 Gy/fx) | Cranial neuropathy |
| Spinal cord and medulla | <0.35 cc | 10 | 14 | 18 (6 Gy/fx) | 21.9 (7.3 Gy/fx) | 23 (4.6 Gy/fx) | 30 (6 Gy/fx) | Myelitis |
| | <1.2 cc | 7 | | 12.3 (4.1 Gy/fx) | | 14.5 (2.9 Gy/fx) | | |
| Spinal cord subvolume (5–6 mm above and below level treated per Ryu) | <10% of subvolume | 10 | 14 | 18 (6 Gy/fx) | 21.9 (7.3 Gy/fx) | 23 (4.6 Gy/fx) | 30 (6 Gy/fx) | Myelitis |
| Cauda equina | <5 cc | 14 | 16 | 21.9 (7.3 Gy/fx) | 24 (8 Gy/fx) | 30 (6 Gy/fx) | 32 (6.4 Gy/fx) | Neuritis |
| Sacral plexus | <5 cc | 14.4 | 16 | 22.5 (7.5 Gy/fx) | 24 (8 Gy/fx) | 30 (6 Gy/fx) | 32 (6.4 Gy/fx) | Neuropathy |
| Esophagus[b] | <5 cc | 11.9 | 15.4 | 17.7 (5.9 Gy/fx) | 25.2 (8.4 Gy/fx) | 19.5 (3.9 Gy/fx) | 35 (7 Gy/fx) | Stenosis/fistula |
| Brachial plexus | <3 cc | 14 | 17.5 | 20.4 (6.8 Gy/fx) | 24 (8 Gy/fx) | 27 (5.4 Gy/fx) | 30.5 (6.1 Gy/fx) | Neuropathy |
| Heart/pericardium | <15 cc | 16 | 22 | 24 (8 Gy/fx) | 30 (10 Gy/fx) | 32 (6.4 Gy/fx) | 38 (7.6 Gy/fx) | Pericarditis |

Organ at risk tolerance data is sparse

Good references: AAPM TG-101, RTOG-0915, RTOG-0236, RTOG-0618, RTOG-1112, RTOG-0813, QUANTEC

If you experiment, formalize as an approved clinical trial!

Benedict, et al., AAPM Task Group 101, Medical Physics, 37(8), 2010.

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Clinical Trials & Standards

Technical Standards

Potters, et al., ASTRO and ACR Practice Guidelines for the Performance of Stereotactic Body Radiation Therapy, IJROBP 76(2), 2010.

Solberg, et al., Quality and Safety Considerations in Stereotactic Radiosurgery and Stereotactic Body Radiation Therapy, PRO, Aug 2011.

Benedict, et al., Stereotactic Body Radiation Therapy: The report of AAPM Task Group 101, Medical Physics, 37(8), 2010.



Perform QA specific for SRS/SBRT

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Apply systems engineering

Keep innovating

# Credentialing and training

**Quality and Safety Considerations in Stereotactic Radiosurgery and Stereotactic Body Radiation Therapy**

Timothy D. Solberg, Ph.D.[1], James M. Balter, Ph.D.[2], Stanley H. Benedict, Ph.D.[3], Benedick A. Fraass, Ph.D.2, Brian Kavanagh, M.D.[4], Curtis Miyamoto, M.D.[5], Todd Pawlicki, Ph.D.[6], Louis Potters, M.D.[7], Yoshiya Yamada, M.D.[8]

"If the radiation oncologist's formal training did not include SRS/SBRT, then specific training in SRS/SBRT, including a minimum of 5 CME credit hours and direct observation of treatment of at least 3 different patients, should be obtained prior to performing any SRS or SBRT procedures"

Same idea for medical physicist and neurosurgeon!

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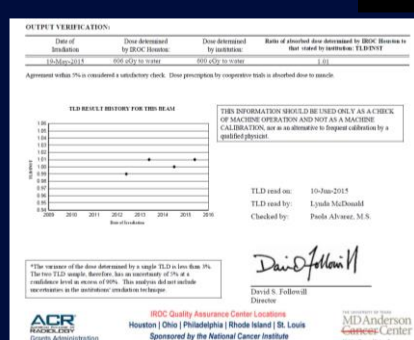
# Peer-review and independent audits

IROC Lung/Spine Phantom



OUTPUT VERIFICATION:

| Date of Irradiation | Dose determined by IROC Houston: | Dose determined by institution: | Ratio of absorbed dose determined by IROC Houston to that stated by institution: TLD/INST |
|---|---|---|---|
| 19-May-2015 | 606 cGy to water | 600 cGy to water | 1.01 |

Agreement within 5% is considered a satisfactory check. Dose prescription by cooperative trials is absorbed dose to muscle.

TLD RESULT HISTORY FOR THIS BEAM

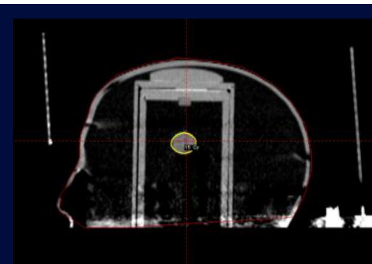
THIS INFORMATION SHOULD BE USED ONLY AS A CHECK OF MACHINE OPERATION AND NOT AS A MACHINE CALIBRATION, nor as an alternative to frequent calibration by a qualified physicist.

TLD read on: 10-Jun-2015
TLD read by: Lynda McDonald
Checked by: Paola Alvarez, M.S.

*The variance of the dose determined by a single TLD is less than 3%. The two TLD sample, therefore, has an uncertainty of 5% at a confidence level in excess of 90%. This analysis did not include uncertainties in the institutions' irradiation technique.

David S. Followill
Director

ACR Radiology Grants Administration
IROC Quality Assurance Center Locations
Houston | Ohio | Philadelphia | Rhode Island | St. Louis
Sponsored by the National Cancer Institute
MD Anderson Cancer Center



IROC Brain SRS Phantom

Include charts, QA, clinical procedures – anything and everything!

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**Apply systems engineering**

Keep innovating

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## Treatment machines are just like manufacturing machines

Kuka 240-2 Robot
(Kuka Roboter, GMBH, Augsberg)

CyberKnife G4
(Accuray, Sunnyvale)

So it is logical to look to systems engineering for guidance!

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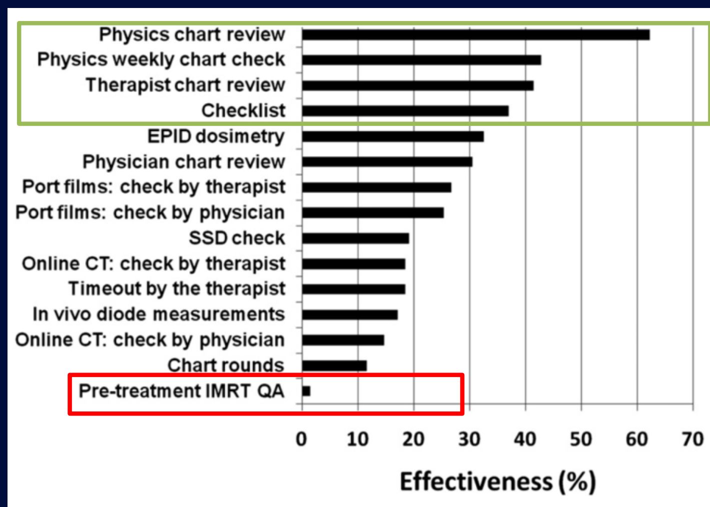
# QA alone is not always effective




Ford *et al* Int. J. Radiat. Oncol. Biol. Phys., 84(3), 263-269, (2012).

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# Can we even do sub-mm QA for SRS/SBRT?

| Device | Detector spacing |
|---|---|
| Mapcheck 2 | 7.0 mm |
| ArcCheck | 10.0 mm (effective 7.0 mm w helical geometry) |
| Octavius 1000 SRS | 2.5 – 5.0 mm |
| MatriXX | 7.6 mm |
| SRS MapCheck (2017 release) | 2.5 mm |
| Radiochromic film | Limited by scanner resolution / uncertainty! |

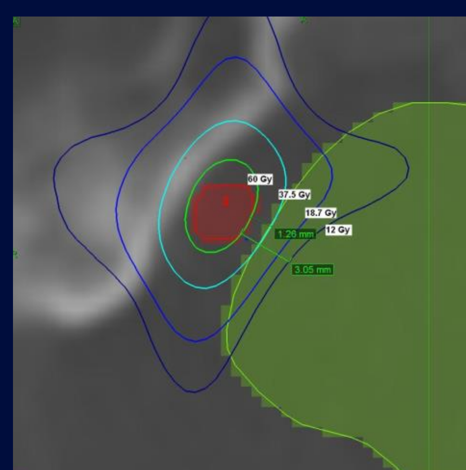


Image courtesy of Sonja Dieterich, Ph.D.

Dose gradient of 16 Gy/ mm -> challenging even for film!

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More effective

Effectiveness

Eliminate – make error impossible

Replace – more reliable process

Facilitate– make work simpler/easier

Detect– make problems more apparent — QA

Mitigate– minimize effect / control damage

Less effective

We can do better than only QA

Hierarchy of mistake-proofing principles (poka-yoke), various sources (usually attributed to Shigeo Shingo and the Toyota Production Method)



## Systems engineering tools

Incident Learning: Lessons from your (almost) mistakes

Statistical Process Control: Detect changes in your process

Process Mapping: Think through and diagram clinical process

Failure Mode and Effects Analysis (FMEA): start with process, identify and prioritize failure modes

Fault Tree Analysis: Start with failure mode, identify causes and find opportunities to improve

# Report and learn from almost mistakes

AGGREGATE REPORT CARD –
Q3 2016
*July 1, 2016 – September 30, 2016*

| METRIC | AGGREGATE CURRENT QUARTER | AGGREGATE HISTORICAL SUM |
|---|---|---|
| **Reported Events** | **274** | **2345** |
| Therapeutic Radiation Incidents | 58 | 645 |
| Other Safety Incidents | 21 | 171 |
| Near Miss | 79 | 773 |
| Unsafe Conditions | 89 | 695 |
| Operational/Process Improvement | 27 | 61 |
| **Most Commonly Identified Workflow Step Where Event *Occurred*** | **Treatment Planning:** 30% (83/274) | **Treatment Planning:** 28% (662/2345) |
| **Most Commonly Identified Workflow Step Where Event was *Discovered*** | **Treatment Delivery Including Imaging (e.g. at the machine):** 28% (77/274) | **Pre-treatment QA Review (e.g. Physics Plan Check):** 25% (580/2345) |
| **Most Commonly Identified Treatment Technique** | **3-D:** 27% (101/274) | **3-D:** 21% (514/2345) |
| **Most Commonly Identified Dose Deviation for Therapeutic Radiation Incidents** | **≤5% Maximum Dose Deviation to Target:** 61% (30/49) | **≤5% Maximum Dose Deviation to Target:** 78% (307/394) |

https://www.astro.org/RO-ILS-Education.aspx

Incident learning systems

Report mistakes and almost mistakes

Focus on process improvement, not assigning blame

Foster a sense that group learning is of critical importance

RO-ILS
RADIATION ONCOLOGY INCIDENT LEARNING SYSTEM
*Sponsored by ASTRO and AAPM*

CLARITY PSO
A Patient Safety Organization

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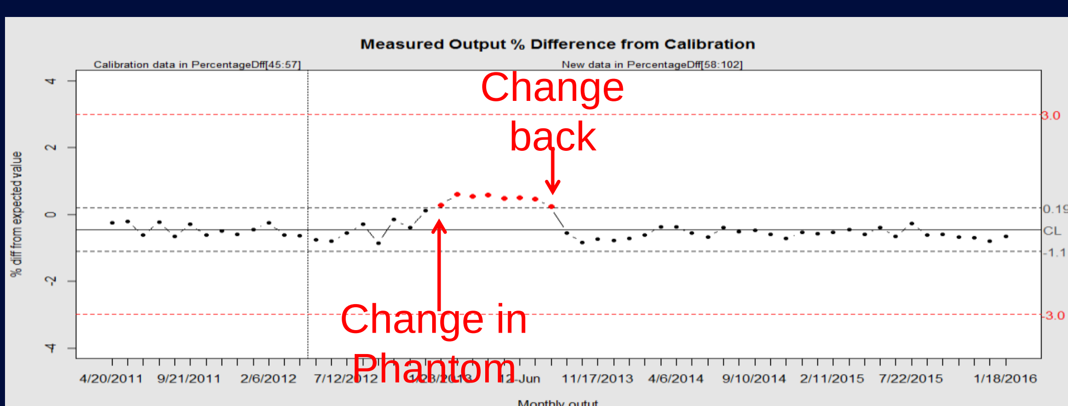
# Use statistical process control

Tools to make it possible to set rational action levels




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

Regulatory annual limit: ±3.0%

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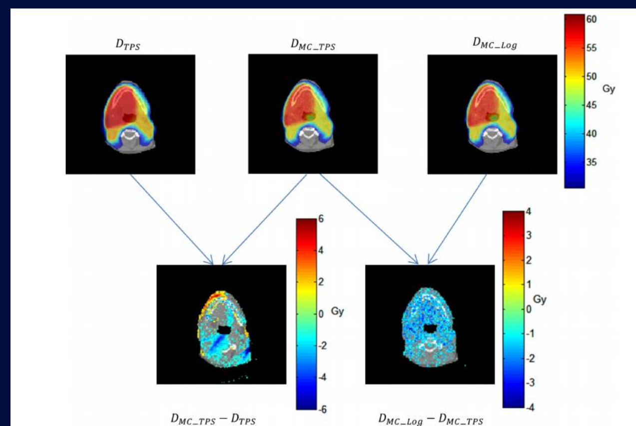
Machine logs are analyzed for planned vs actual machine parameters (such as MLC positions and beam on/off status).

Fluence maps are reconstructed based on actual machine parameters during delivery.

Comparisons made against planned fluence maps.

Method can overcome limitations of phantom-based patient-specific QA.

## ..and logfile-based QA




Handsfield, et. al., Med Phys 41(10), 2014

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Apply systems engineering

**Keep innovating**

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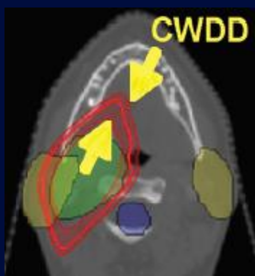
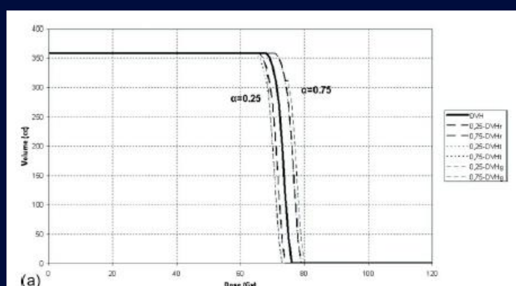
# The future: Make uncertainty explicit



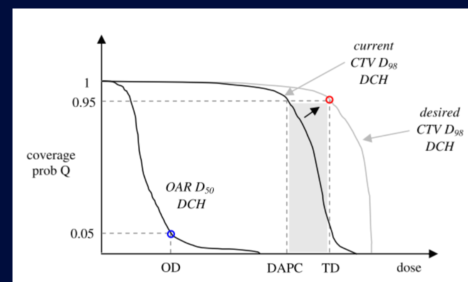

Confidence-weighted dose distributions

H. Jin, Med Phys 32, 2005




F. Henríquez, et al., Med Phys 37, 2010

DVH Confidence Intervals




Dose coverage histograms

J. J. Gordon, et al., Med Phys 37, 2010



# The future: Autosegmentation

De novo, segmented edit, peer and self-edit

Segmented edits remained closest to ground truth

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, et al., Phys Med Bio 58 (2013)

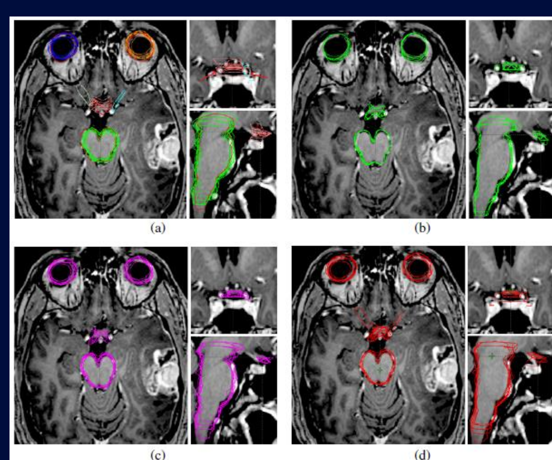



**Figure 4.** Orthogonal views comparing group results from (a) *de novo*, (b) $A_1$-edited, (c) self-edited, (d) peer-edited. The red arrows in the upper right (coronal section) of panel (a) point to the internal carotid arteries, which were often erroneously included as part of the optic chiasm in 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.

# The future: Updated RadBio modeling

| Author/Year | Model Name | Strategy |
|---|---|---|
| Guerrero and Allen (2004) | Modified LQ model (MLQ) | Linear-Quadratic-Linear |
| Park, et al. (2008) | Universal Survival Curve | Hybrid LQ and multi-target model |
| Kavanagh and Newman (2008) | Kavanagh-Newman | Dose-dependent increase in exponential rate of cell kill |
| Astrahan (2008) | L-QL model | Linear-quadratic linear |
| Hanin and Zaider (2010) | | Microdosimetry model |
| Wang, et. al. (2010) | Generalized Linear Quadratic Model (gLQ) | Adds a parallel $\beta_2$ term to account for less sub-lethal repair at high doses |

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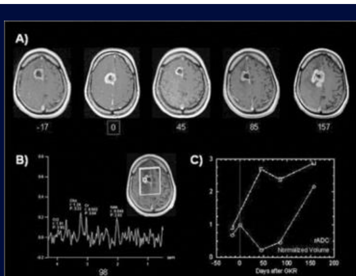
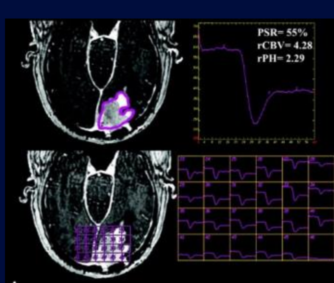
# The future: Image the biology



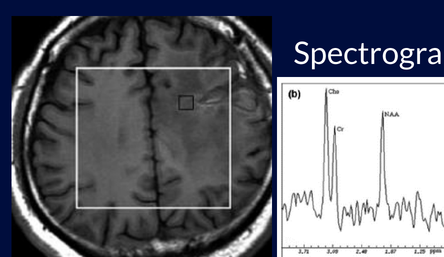

Diffusion Imaging

M. Goldman et al., JNS 105(7), 2006.



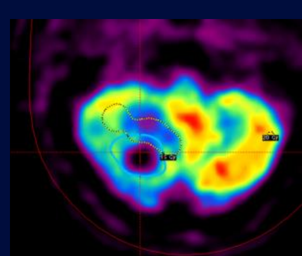

Perfusion Imaging

Barajas R et al. AJNR Am J Neuroradiol 2009;30:367-372




Spectrography

Q. Zeng, et al., IJROBP 68(1), 2007



Metabolic Imaging (PET/SPECT)

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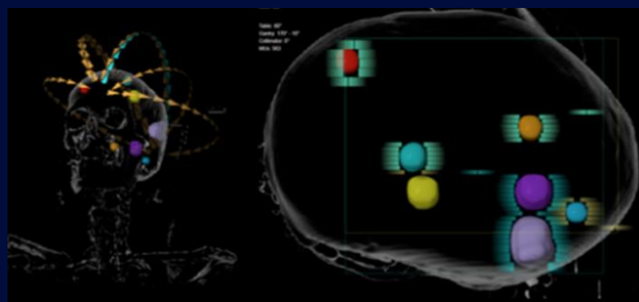
## The future: Treatment planning automation?



Software automatically segments brain metastases and creates radiosurgery-ready plans using multiple conformal arcs.
Treatment planning takes minutes. Removes the human component (and error?).

T. Gevaert, et al., Radiation Oncology (11) 2016



## In the next presentation:

## Systems engineering tools

Incident Learning: Lessons from your (almost) mistakes

Statistical Process Control: Detect changes in your process

Process Mapping: Think through and diagram clinical process

Failure Mode and Effects Analysis (FMEA): start with process, identify and prioritize failure modes

Fault Tree Analysis: Start with failure mode, identify causes and find opportunities to improve



## Conclusions

SRS/SBRT are complicated procedures with many sources of uncertainty.

There are many ways to have a misadventure.

There are proven ways to reduce risk:

- Training and credentialing
- Formal analysis of procedural risk
- Constant learning – including close calls
- Formalizing new techniques as clinical trials


Universal Pictures, 2014.

# Thank You!

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