Tolerance Limits and Action Levels for IMRT QA

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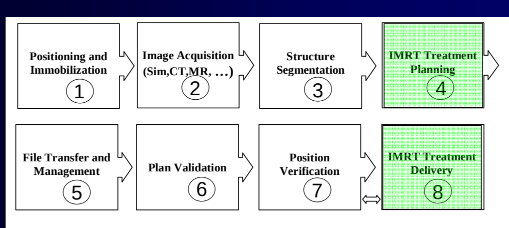
Objectives

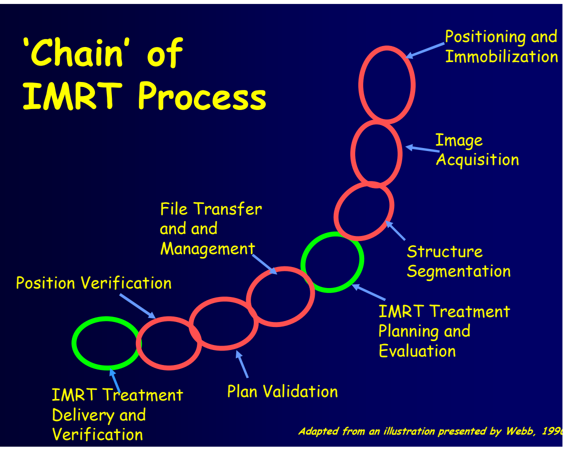
- Describe the uncertainties in IMRT Planning and Delivery
- Describe the impact of spatial and dosimetric uncertainties on IMRT dose distributions
- Describe the limitations of current methodologies of establishing tolerance limits and action levels for IMRT QA
- Describe a new method for evaluating quality if IMRT planning and delivery

The Overall Process of IMRT Planning and Delivery



ASTRO/AAPM Scope of IMRT Practice Report

'Chain' of IMRT Process

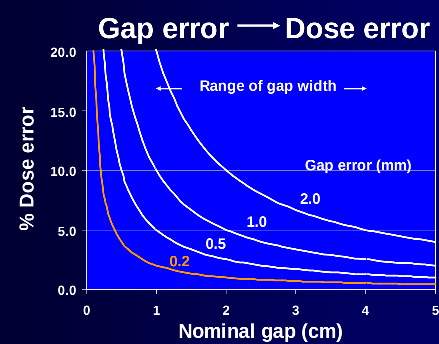


Adapted from an illustration presented by Webb, 199

Uncertainties in IMRT Delivery Systems

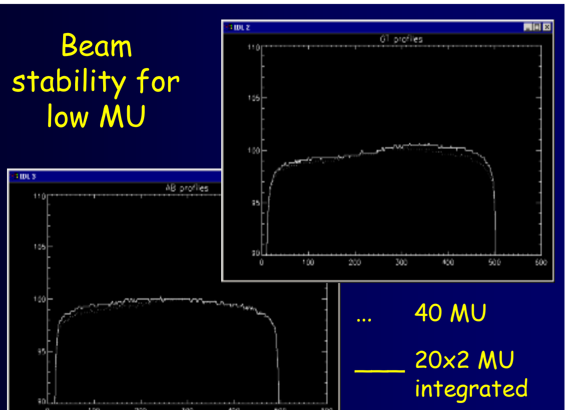
- MLC leaf position
- Gantry, MLC, and Table isocenter
- Beam stability (output, flatness, and symmetry)
- MLC controller

MLC Leaf Position



Data from MSKCC; LoSasso et. al.

Beam stability for low MU

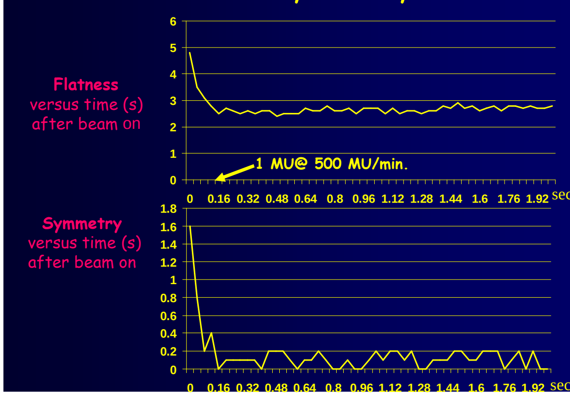


... 40 MU

____ 20x2 MU integrated

Data from Christie Hospital: Geoff Budgell

Beam Flatness and Symmetry for low MU

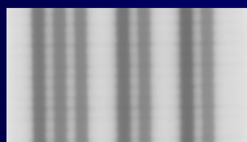


MLC Controller Issue

1 MU per strip

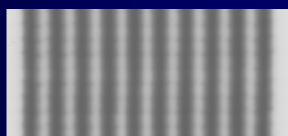
Dose Rate: 600 MU/min

Varian 2100 C/D



Dose Rate: 600 MU/min

Elekta Synergy



Film measurements of a 10-strip test pattern. The linacs were instructed to deliver 1 MU per strip with the step-and-shoot IMRT delivery mode for a total of 10 MU. The delivery sequence is from left to right.

Uncertainties in IMRT Planning

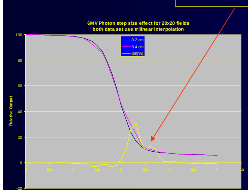
Can be attributed to:

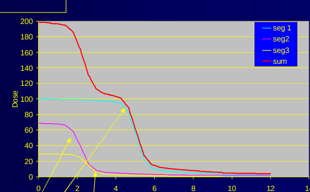
- Dose calculation grid size
- MLC round leaf end –none divergent
- MLC leaf-side/leaf end modeling
- Collimator/leaf transmission
- Penumbra modeling; collimator jaws/MLC
- Output factor for small field size
- PDD at off-axis points

The effect of dose calculation grid size at field edge

- Grid size becomes critical when interpolating high dose gradient.

Can result in large errors



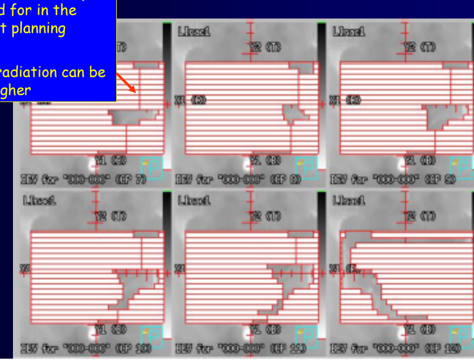


Fine grid size is needed for interpolation

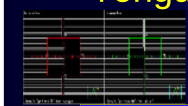
Closed Leaf Position

May not be accurately accounted for in the treatment planning system

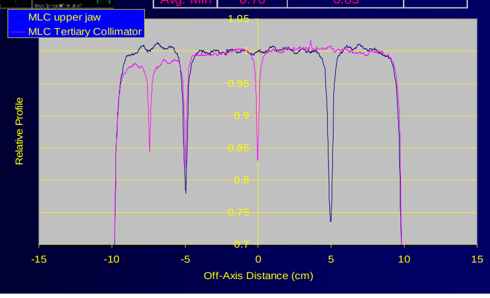
Leakage radiation can be 15% or higher



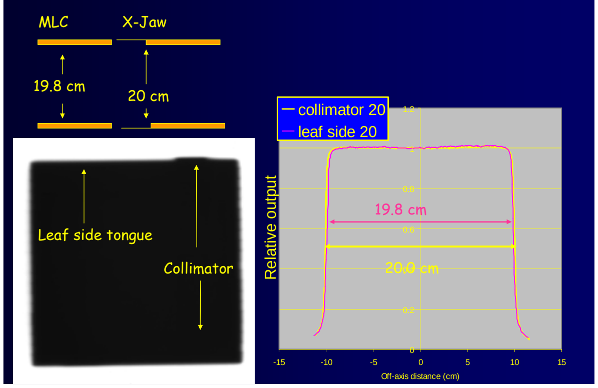
Tongue-and-groove effect



MLC	Upper Jaw	Tertiary Collimator	
FWHM	3.3	2.0	
Avg. Min	0.76	0.83	

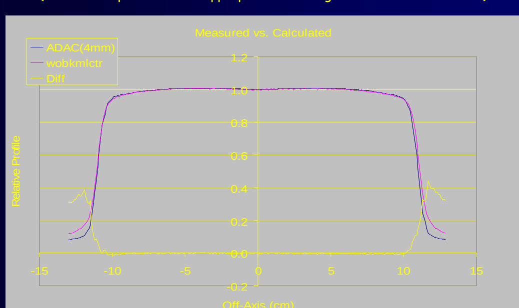


Leaf-side effect



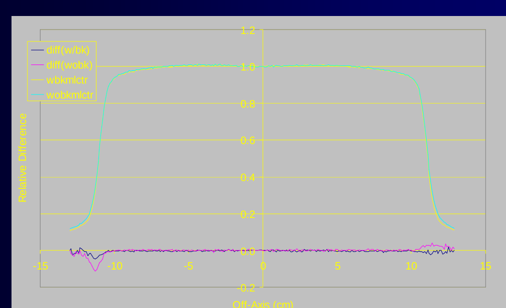
Beam Modeling

(Cross beam profile with inappropriate modeling of extra-focal radiation)



Beam Modeling

(Cross beam profile with appropriate modeling of extra focal radiation)



What should be the tolerance limits and action levels for delivery systems for IMRT?

Segmental Multileaf Collimator (SMLC) Delivery System

	Tolerance Limit	Action Level
MLC*		
Leaf position accuracy	1 mm	2 mm
Leaf position reproducibility	0.2 mm	0.5 mm
Gap width reproducibility	0.2 mm	0.5 mm
Gantry, MLC, and Table Isocenter	0.75 mm radius	1.00 mm radius
Beam Stability		
Low MU Output (<2MU)	2%	3%
Low MU Symmetry (<2MU)	2%	3%

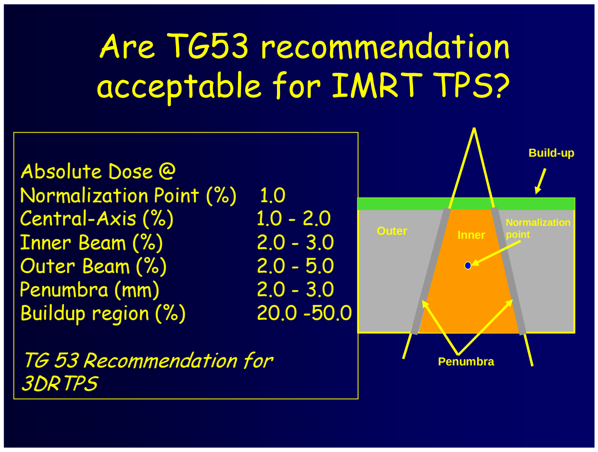
** Measured at all four cardinal gantry angles*

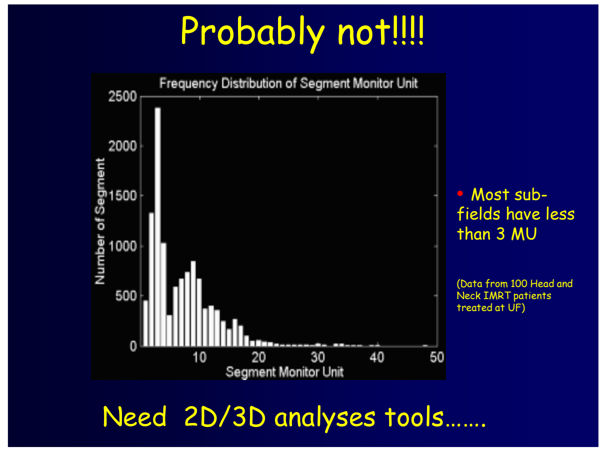
Palta et.al, AAPM Summer School, 2003

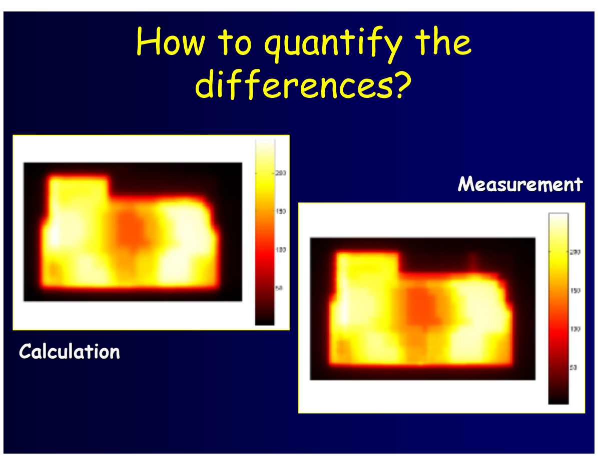
Dynamic Multileaf Collimator (DMLC) Delivery System

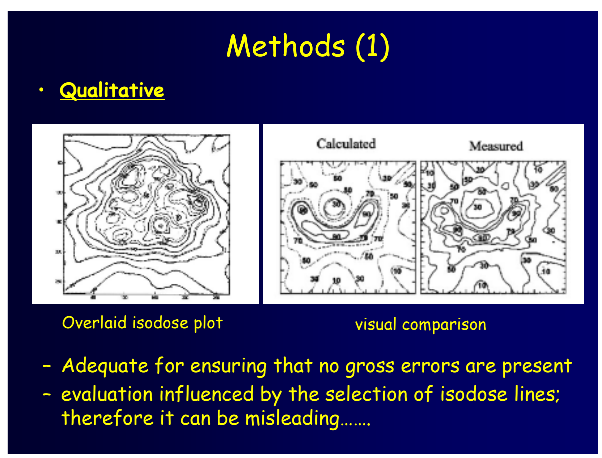
	Tolerance Limit	Action Level
MLC*		
Leaf position accuracy	0.5 mm	1 mm
Leaf position reproducibility	0.2 mm	0.5 mm
Gap width reproducibility	0.2 mm	0.5 mm
Leaf speed	±0.1 mm/s	±0.2 mm/s
Gantry, MLC, and Table Isocenter	0.75 mm radius	1.00 mm radius
Beam Stability		
Low MU Output (<2MU)	3%	5%
Low MU Symmetry (<2MU)	2%	3%

What should be the tolerance limits and action levels for IMRT Planning?


Are TG53 recommendation acceptable for IMRT TPS?
Absolute Dose @
Normalization Point (%) 1.0
Central-Axis (%) 1.0 - 2.0
Inner Beam (%) 2.0 - 3.0
Outer Beam (%) 2.0 - 5.0
Penumbra (mm) 2.0 - 3.0
Buildup region (%) 20.0 -50.0
TG 53 Recommendation for 3DRTPS
Build-up
Outer
Inner
Normalization point
Penumbra

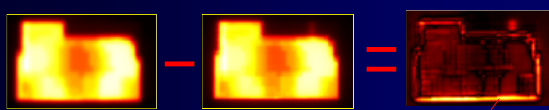

Probably not!!!!
Frequency Distribution of Segment Monitor Unit
Number of Segment
Segment Monitor Unit
2500
2000
1500
1000
500
0
10
20
30
40
50
Most sub-fields have less than 3 MU
(Data from 100 Head and Neck IMRT patients treated at UF)
Need 2D/3D analyses tools.......

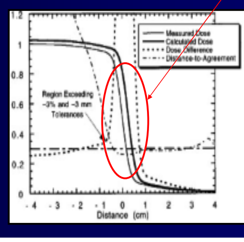

How to quantify the differences?
Measurement
Calculation


Methods (1)
Qualitative
Calculated
Measured
Overlaid isodose plot
visual comparison
– Adequate for ensuring that no gross errors are present
– evaluation influenced by the selection of isodose lines; therefore it can be misleading.......

Methods (2)

- **Quantitative methods: Dose Difference**

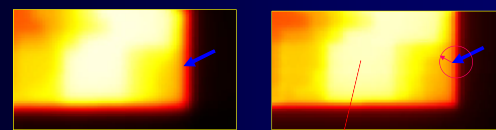




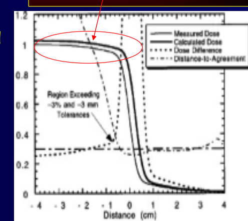
- Possible to quickly see what areas are significantly hot and cold; however, large errors can exist in high gradient regions

Methods (3)

- **Quantitative methods: Distance-to-agreement (DTA)**



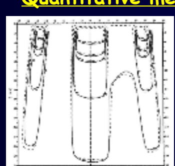
- Distance between a measured dose point and the nearest point in the calculated distribution containing the same dose value
- More useful in high gradient regions; however, overly sensitive in low gradient regions



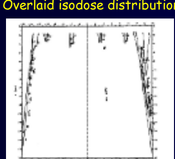
Hogstrom et .al. IJROBP., 10, 561-69, 1984

Methods (4)

- **Quantitative methods: Composite distribution**



Overlaid isodose distribution



Composite distribution

- A binary distribution formed by the points that fail both the dose-difference and DTA criteria

$\Delta D > \Delta D_{tol}$ $\quad B_{DD} = 1$

$\Delta d > \Delta d_{tol}$ $\quad B_{DTA} = 1$

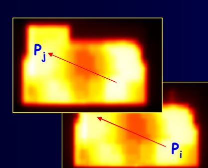
$B = B_{DD} \times B_{DTA}$

- **Useful in both low- and high- gradient areas** to see what areas are off
- **However, No unique numerical index**-that enables the analysis of the goodness of agreement

Harms et .al. Med. Phys., 25, 1830-36,1998

Methods (5)

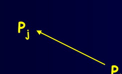
- **Quantitative methods: Gamma index distribution**



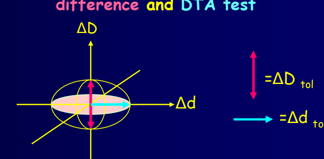
$$\gamma_i = \min\left[\sqrt{\left(\frac{\Delta d}{\Delta d_{tol}}\right)^2 + \left(\frac{\Delta D}{\Delta D_{tol}}\right)^2}\right]_{\forall j}$$

$\gamma \leq 1$, calculation passes, and
$\gamma > 1$, calculation fails

- **Combined ellipsoidal dose-difference and DTA test**



distance, Δd
dose-difference, ΔD



Low et .al. Med. Phys., 25, 656-61,1998

Methods (6)

- Quantitative methods: Normalized Agreement Test (NAT)

$\Delta D < \Delta D_{tol}$, NAT = 0
$\Delta d < \Delta d_{tol}$, NAT = 0
$\%D < 75\%$ & $D_{meas} < D_{cal}$, NAT = 0

Otherwise, $NAT = D_{scale} \times (\delta - 1)$

Try to quantify how much off overall

Where,

$D_{scale}^{i} = \text{larger}[D_{cal}, D_{meas}]^{i} / \max[D_{cal}]$

$\delta^{i} = \text{smaller}[(\Delta D/\Delta D_{tol}), (\Delta d/\Delta d_{tol})]^{i}$

$$\text{NAT index} = \frac{\text{Average NAT value}}{\text{Average of the } D_{scale} \text{ matrix}} \times 100$$

Childress et.al. IJROBP 56, 1464-79 2003

Current Dose Verification Methods

- **Dose difference**
  - Possible to quickly see what areas are significantly hot and cold; however, large errors at high gradient regions
- **Distance-to-agreement (DTA)**
  - Distance between a measured dose point and the nearest point in the calculated distribution containing the same dose value
  - More useful in high gradient regions; however, overly sensitive in low gradient regions
- **Composite distribution**[1]
  - A binary distribution formed by the points that fail both the dose-difference and DTA criteria
- **Gamma index distribution**[2]
  - Gamma function criteria using the combined ellipsoidal dose-difference and DTA tests

[1]**Harms *et al*,** Med. Phys., 26(10), 1998, pp. 1830-1836
[2]**Low *et al*,** Med. Phys., 26(5), 1998, pp. 651-661

Tolerance limits based on statistical and topological analyses

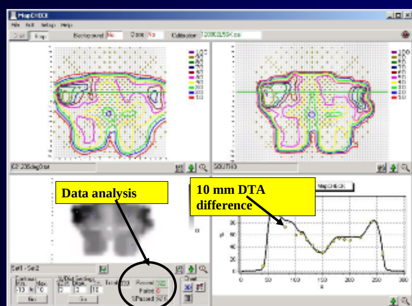
Region	Confidence Limit* (P=0.05)	Action Level
δ_1 (high dose, small dose gradient)	3%	5%
δ_1 (high dose, large dose gradient)	10% or 2 mm DTA	15% or 3 mm DTA
δ_1 (low dose, small dose gradient)	4%	7%
$\delta_{90-50\%}$ (dose fall off)	2 mm DTA	3 mm DTA

* Mean deviation used in the calculation of confidence limit for all regions is expressed As a percentage of the prescribed dose according to the formula,
$\delta_i = 100\% \times (D_{calc} - D_{meas.}/D_{prescribed})$

Palta et.al. AAPM Summer School, 2003

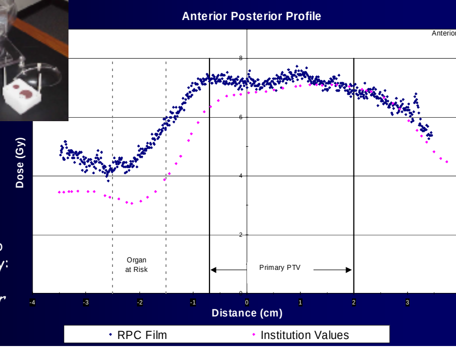
Are there any limitations of current methodologies of establishing tolerance limits for IMRT QA????

Comparison of Measured and Calculated Cross Plot



Measured with a diode-array (Map Check; Sun Nuclear Corp.)

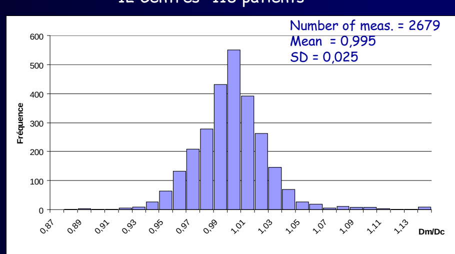
RPC IMRT Phantom Results



RPC criteria of acceptability:
7% for PTV
4 mm DTA for OAR

Radiotherapy Oncology Group for Head &Neck

12 Centres- 118 patients



Recommandations for a Head and Neck IMRT Quality Assurance Protocol: 8 (2004), Cancer/Radiothérapie 364-379, M. Tomsej et al.

IMRT QA Outliers

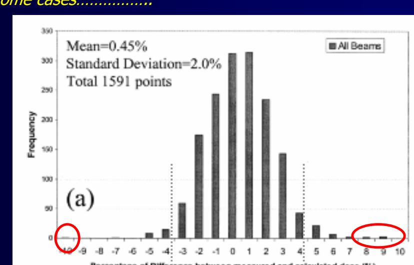
Surely there is something systematic at work in some cases.................

7 Points outside 4σ

In 1600 observations

99.994% C.L.

~Same odds as wining Power ball Multi-state Lotto 4 times



Dong *et al.* IJROBP, Vol. 56, No. 3, pp. 867-877, 2003

Evidence That Something Could Be Amiss…

What could be the reason???

- It could be delivery error
  - Mechanical Errors?
    - MLC Leaf Positioning
  - Fluence and Timing?
    - Orchestration of MLC and Fluence
- It could be dosimetry artifacts
  - Some measurement Problem?
- It could be algorithmic errors
  - Source Model, Penumbra, MLC Modeling

More than likely a conspiracy of effects, each with it own uncertainty…….

A new method for evaluating the quality of IMRT

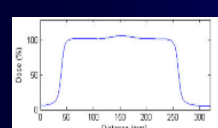
Based on space and dose-specific uncertainty information

Hosang Jin MS; Pre Doctoral Candidate
University of Florida

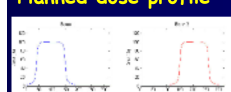
An uncertainty model

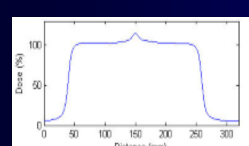
- Space-oriented uncertainty (SOU)

Dose uncertainty is proportional to the gradient of dose

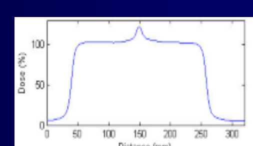


Planned dose profile





with 1 mm



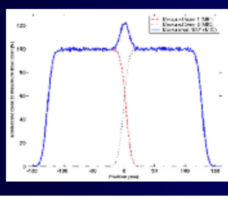
with 2 mm

An uncertainty model

- Non-space-oriented uncertainty (NOU)

Dose uncertainty is inversely proportional to the dose level

  - It follows from the fact that the signal-to-noise ratio (SNR) is proportional to the magnitude of the measured dose



An uncertainty model

$$U(r) = \sqrt{w_1 SOU^2 + w_2 NOU^2 + w_3 SOU \times NOU + \varepsilon}$$

Assuming that the *SOU* and *NOU* are uncorrelated and that there is no offset, meaning that $w_1=w_2=1$, $w_3=0$ and $\varepsilon=0$,

Dose Uncertainty

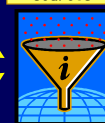
Space-oriented

$$SOU(\sigma_{sou}) \propto \vec{G}(\vec{r}) \cdot \sigma_{\Delta\vec{r}}$$

Non-space-oriented

$$NOU(\sigma_{nou}) \propto \frac{1}{\sqrt{D}}$$

Uncertainty sources



$$\sigma \propto \sqrt{\sigma_{sou}{}^2 + \sigma_{nou}{}^2}$$

Jin *et al*, Medical Physic, 32(6), pp.1747-1756, 2005

An uncertainty model

Space-oriented

$$\sigma_{sou}(r) = \nabla D(r) \cdot \sigma_{\Delta r} \qquad \sigma_{\Delta r} = \sqrt{\sum_i^I \sigma_{\Delta r\_i}{}^2}$$

for SOU sources *i* through *I*,
I is the total number of sources of SOU,
σ_{Dr_i} is a SD of the spatial uncertainty of the source *i*

Non-space-oriented

$$\sigma_{nou}(r) = \sigma_{ro}\sqrt{D(r)D_o} \qquad \sigma_{ro} = \sqrt{\sum_j^J \sigma_{ro\_j}{}^2}$$

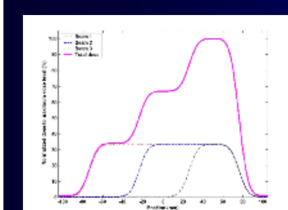
for NOU sources *j* through *J*,
J is the total number of sources of NOU,
σ_{ro_j} is a SD of the spatial uncertainty of the source *j*

$$\sigma(r)_{total} = \sqrt{\sigma_{sou}(r)^2 + \sigma_{nou}(r)^2} \qquad \sigma(r)_{overall} = \sqrt{\sum_k^K \sigma_{total\_k}(r)^2}$$

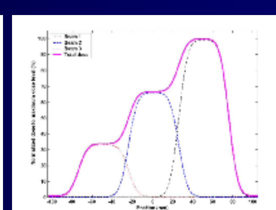
For a combination of multiple fields

1-D Simulation

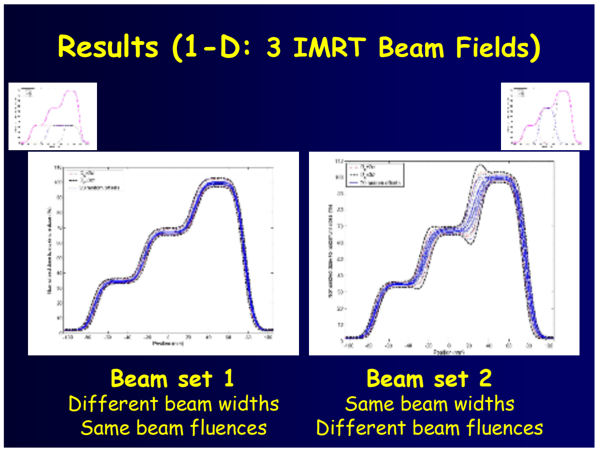
3-Segmented IMRT Field

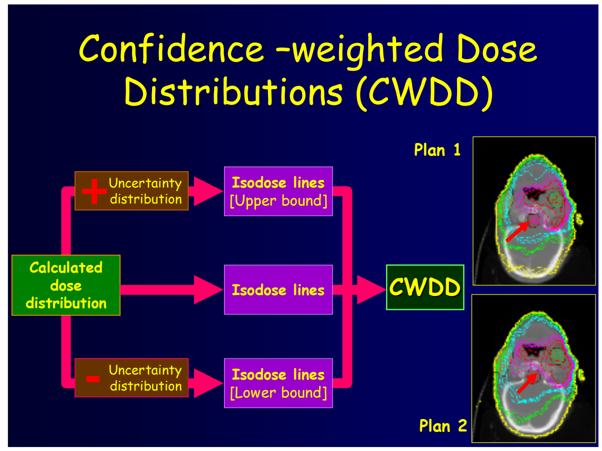


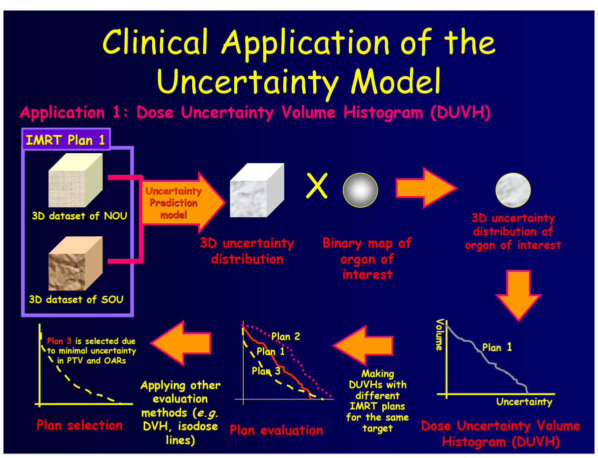
Beam set 1
Different beam width
Same beam fluence

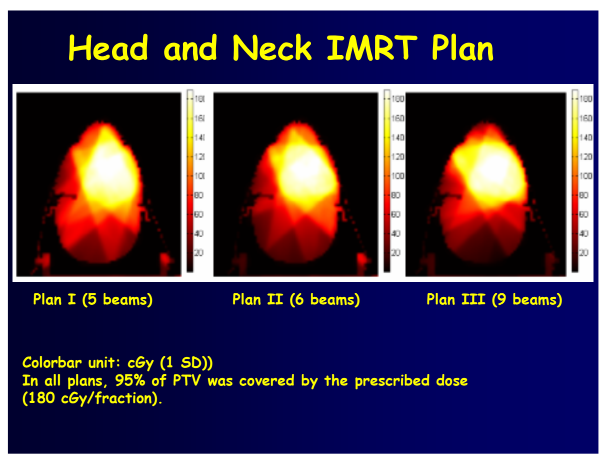


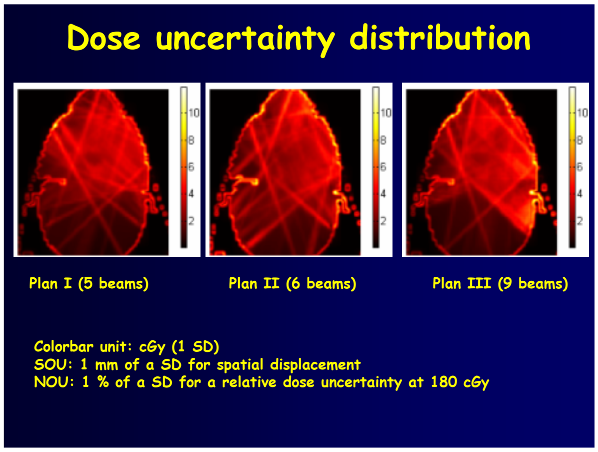
Beam set 2
Same beam width
Different beam fluence

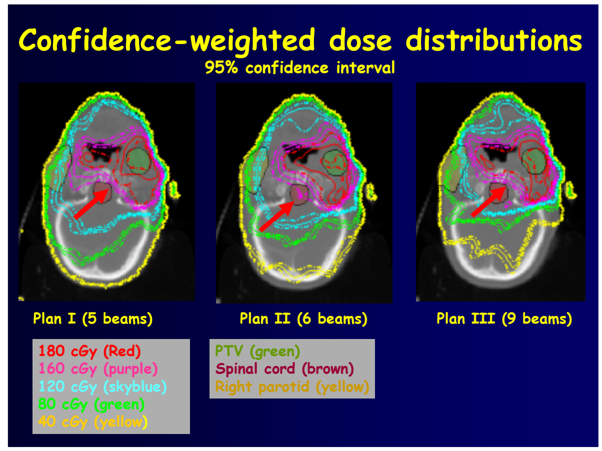

Results (1-D: 3 IMRT Beam Fields)
Beam set 1
Different beam widths
Same beam fluences
Beam set 2
Same beam widths
Different beam fluences

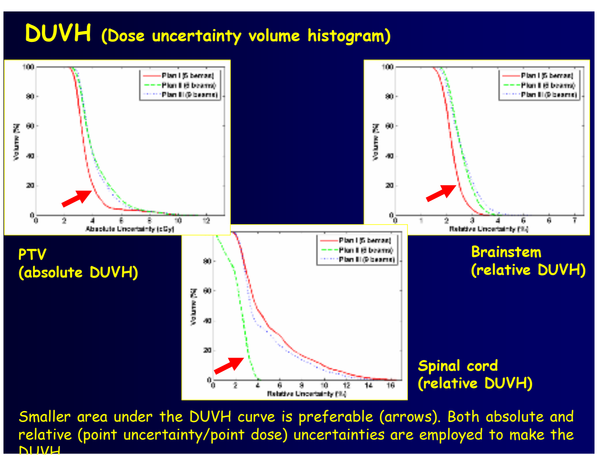

Confidence -weighted Dose Distributions (CWDD)
Plan 1
Uncertainty distribution
Isodose lines [Upper bound]
Calculated dose distribution
Isodose lines
CWDD
Uncertainty distribution
Isodose lines [Lower bound]
Plan 2

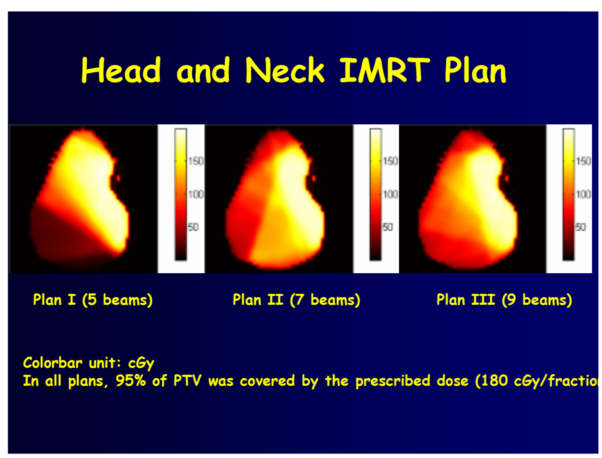

Clinical Application of the Uncertainty Model
Application 1: Dose Uncertainty Volume Histogram (DUVH)
IMRT Plan 1
3D dataset of NOU
3D dataset of SOU
Uncertainty Prediction model
3D uncertainty distribution
X
Binary map of organ of interest
3D uncertainty distribution of organ of interest
Volume
Plan 1
Uncertainty
Dose Uncertainty Volume Histogram (DUVH)
Making DUVHs with different IMRT plans for the same target
Plan 2
Plan 1
Plan 3
Plan evaluation
Applying other evaluation methods (e.g. DVH, isodose lines)
Plan 3 is selected due to minimal uncertainty in PTV and OARs
Plan selection


Head and Neck IMRT Plan
Plan I (5 beams)
Plan II (6 beams)
Plan III (9 beams)
Colorbar unit: cGy (1 SD))
In all plans, 95% of PTV was covered by the prescribed dose
(180 cGy/fraction).

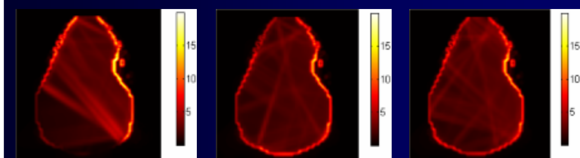

Dose uncertainty distribution
Plan I (5 beams)
Plan II (6 beams)
Plan III (9 beams)
Colorbar unit: cGy (1 SD)
SOU: 1 mm of a SD for spatial displacement
NOU: 1 % of a SD for a relative dose uncertainty at 180 cGy


Confidence-weighted dose distributions
95% confidence interval
Plan I (5 beams)
Plan II (6 beams)
Plan III (9 beams)
180 cGy (Red)
160 cGy (purple)
120 cGy (skyblue)
80 cGy (green)
40 cGy (yellow)
PTV (green)
Spinal cord (brown)
Right parotid (yellow)


DUVH (Dose uncertainty volume histogram)
PTV
(absolute DUVH)
Brainstem
(relative DUVH)
Spinal cord
(relative DUVH)
Smaller area under the DUVH curve is preferable (arrows). Both absolute and relative (point uncertainty/point dose) uncertainties are employed to make the DUVH.


Head and Neck IMRT Plan
Plan I (5 beams)
Plan II (7 beams)
Plan III (9 beams)
Colorbar unit: cGy
In all plans, 95% of PTV was covered by the prescribed dose (180 cGy/fractio

Dose uncertainty distribution



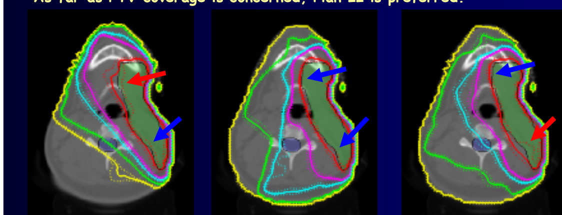
Plan I (5 beams) Plan II (7 beams) Plan III (9 beams)

Colorbar unit: cGy (1 SD)
SOU: 1 mm of a SD for spatial displacement
NOU: 1 % of a SD for a relative dose uncertainty at 180 cGy

Confidence-weighted dose distributions

95% confidence interval

As far as PTV coverage is concerned, Plan II is preferred.

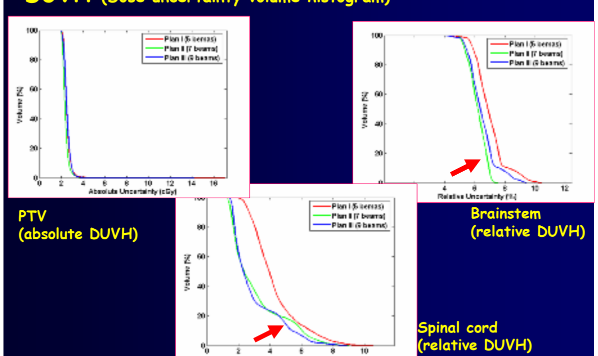


Plan I (5 beams) Plan II (7 beams) Plan III (9 beams)

180 cGy (Red)
140 cGy (purple)
120 cGy (skyblue)
80 cGy (green)
40 cGy (yellow)

PTV (green)
Spinal cord (brown)

DUVH (Dose uncertainty volume histogram)



PTV (absolute DUVH)

Brainstem (relative DUVH)

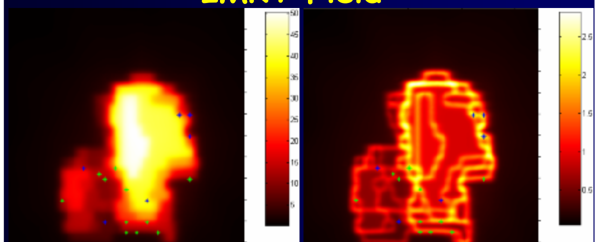
Spinal cord (relative DUVH)

Smaller area under the DUVH curve is preferable (arrows). Both absolute and relative (point uncertainty/point dose) uncertainties are employed to make the DUVH.

MapCHECK™ Analysis

- A binary test using dose difference and distance-to-agreement (DTA)
- Criteria
  - Dose difference: 3%
  - DTA: 3 mm
- Points less than 10% of reference dose were excluded

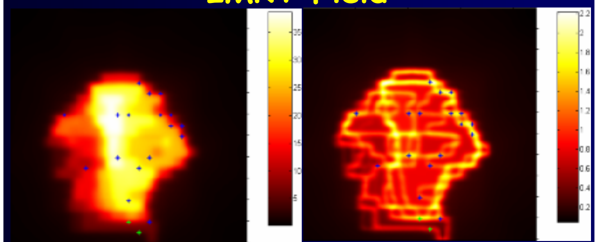
Planar Dose Distribution for an IMRT Field



Dose Distribution Uncertainty Distribution

Colorbar unit: cGy
Blue: calculation is higher, green: measurement is higher
Uncertainty distribution: 1 SD

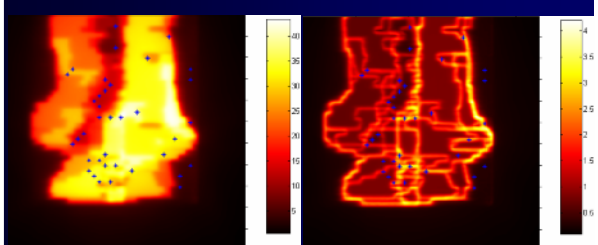
Planar Dose Distribution for an IMRT Field



Dose Distribution Uncertainty Distribution

Colorbar unit: cGy
Blue: calculation is higher, green: measurement is higher
Uncertainty distribution: 1 SD

Planar Dose Distribution for an IMRT Field



Dose Distribution Uncertainty Distribution

Colorbar unit: cGy
Blue: calculation is higher, green: measurement is higher
Uncertainty distribution: 1 SD

Summary

- ✓ The tolerance limits and action levels proposed in this presentation for the IMRT delivery system QA have justifiable scientific rationale
- ✓ The tolerance limits and action levels proposed in this presentation for the IMRT planning and patient specific QA also have justifiable scientific rationale.
  - ✓However, all commonly used metrics (ΔD, binary difference, gamma index etc.) for dose plan verification have limitations in that they do not account for space-specific uncertainty information
- ✓ The proposed plan evaluation metrics will incorporate both spatial and non-spatial dose deviations and will have high predictive value for QA outliers