Root Cause Analysis of IMRT QA Outliers

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IMRT QA

As we understand……

Can evaluate :

- The fidelity of a treatment planning system commissioning process
- The fidelity of a delivery system for IMRT delivery

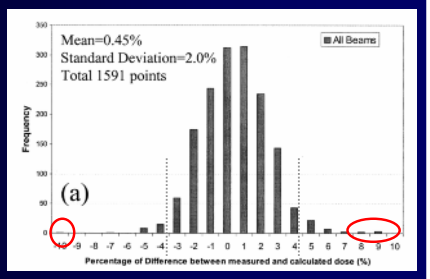
However, it does not and can not fully establish the accuracy of dose delivered to patients with IMRT

- *Uncertainties target delineation*
- *Uncertainties in patient/target positioning*

QA Outliers

7 Points outside 4σ

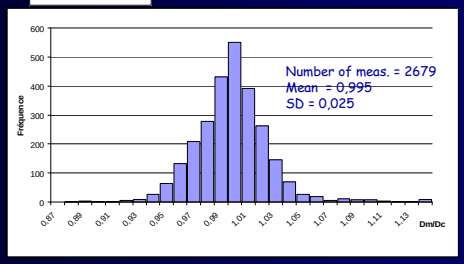
In 1591 observations



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

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

12 Centres- 118 patients



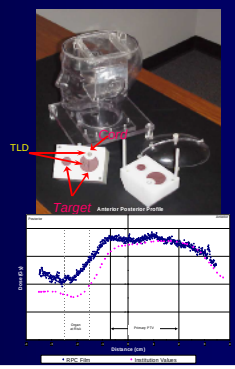
M. Tomsej et al. Cancer/Radiothérapie, 8, 2004

Eleven patients are outside 4σ……..

RPC Credentialing: IMRT

RPC criteria of acceptability:
7% for Planning Target Volume
4 mm DTA for the Organ-at-Risk

250 irradiations of
H&N phantom
28% had failed …



What could be the reason???

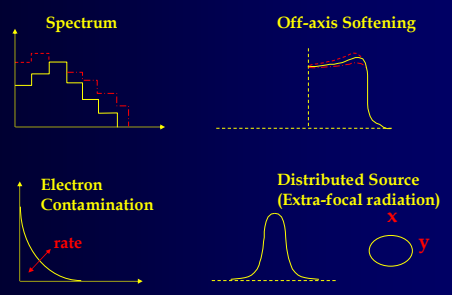
- It could be delivery error
  - Mechanical Errors?
    - MLC Leaf Positioning
  - Fluence and Timing?
    - Orchestration of MLC and Fluence
- It could be algorithmic errors
  - Source Model, Penumbra, MLC Modeling
- It could be dosimetry artifacts
  - Some measurement Problem?

More than likely a conspiracy of effects, each with its own uncertainty…….
Impossible to isolate them all……

Potential Sources of Errors in Radiation Delivery

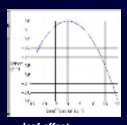
- MLC positional and leaf speed accuracy (MLC positional and leaf speed inaccuracies can cause significant dose delivery uncertainties)
- Linac performance for small MU delivery (low MU per segment and high dose rate can be an issue in IMRT dose delivery accuracy)
- MLC control issues (Large number of segments per field can be an issue for some delivery systems)
- MLC physical characteristics (leaf transmission, leaf-end leakage, and inter-leaf leakage can be an issue)
- Leaf sequencing algorithms (need to be optimized for smoothness of intensity distribution, number of segments, mechanical limits of MLC, MU efficiency, leaf travel, and delivery time)

Modeling of the Delivery System Dosimetric Characteristics in TPS



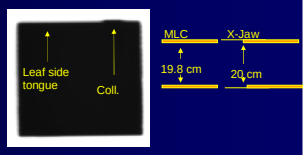
Additional Modeling Parameters

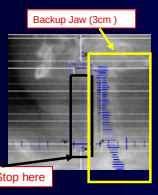
(MLC-based IMRT)



MLC round leaf end modeling

MLC leaf side modeling



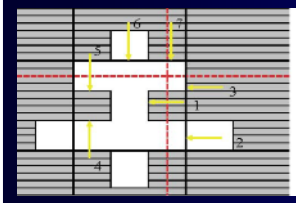


MLC transmission

Backup Jaw transmission

Penumbra values

(80%-20% dose distance)



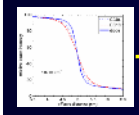
1: Leaves only:	5.8 mm
2: Back-up (Y) collimator only:	4.8 mm
3: Leaves + back-up (Y) collimator:	4.2 mm
4. Side of leaves (left):	3.8 mm
5. Side of leaves (right):	3.5 mm
6: X-collimator only:	3.6 mm
7: X-collimator + leaves:	3.4 mm

From: ESTRO Booklet # 9: Guidelines for the verification of IMRT_2008

What if the beam modeling in TPS is ideal?

–Will there be IMRT QA outliers?

•Probably yes…..

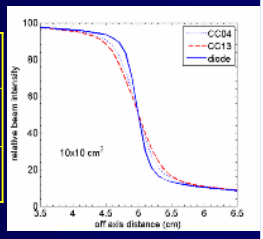


Treatment Planning System Commissioning

Garbage in, Garbage out !!!

An Example

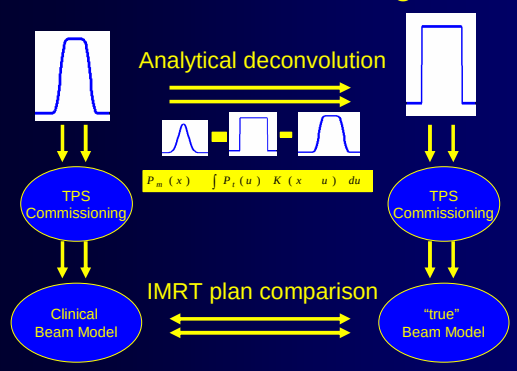
	Diode	CC04	CC13
Detector	0.8x0.8 mm²	4 mm	6 mm
Penumbra 20%~80%	4.0 mm	6.1 mm	7.2 mm



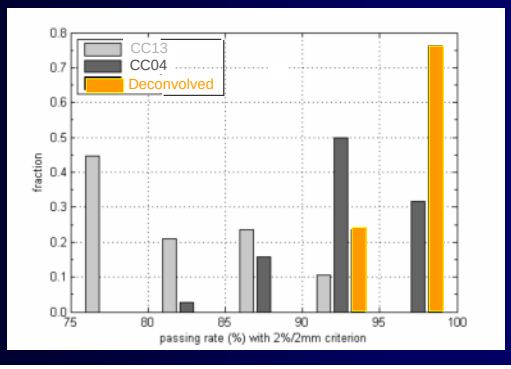
TPS commissioned with beam data measured with three different detectors

Yan et. al. :University of Florida
WE-C-AUD C-1@ 10:00 AM

TPS commissioning



IMRT QA results-DTA 2%/2 mm



IMRT QA results-DTA analysis

	CC13-based Beam Model	CC04-based Beam Model	"Truth-based" Beam Model
2%/2mm	81.6±7.8	92.6±3.3	96.8±2.3
3%/3mm	93.8±4.1	98.9±1.0	99.4±0.6

IMRT QA pass rate increased dramatically when "truth-based" data were used for beam modeling

Take home message #1

- *Understand and quantify uncertainties and their bounds in data used for TPS commissioning*
  - –overall accuracy of IMRT dose distribution is strongly correlated to the accuracy of input data and tolerance values used in TPS commissioning

Stay tuned for the availability of benchmark golden dosimetry data sets measured on modern day linear accelerators *(Establishment Of Benchmark Data Sets For Radiotherapy Quality Assurance: SBIR Contract No. HHSN261200522014C: Simon PI)*

- *These data sets will have declared uncertainty bound for each reported measurement*

Take home message #2

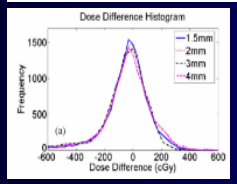
Understand the effect of dose calculation grid size on IMRT dose distributions

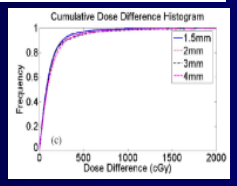
- overall accuracy of computed IMRT dose distribution is correlated to the dose calculation grid size resolution (if it is not Nyquist-Shannon sampling theorem limited)

Dose Calculation Grid Effect

Dose difference between measurement and calculation

Grid size	95% region	90% region	85% region
1.5 mm	681.2 cGy (12.6%)	381.2 cGy (7.1%)	261.2 cGy (4.8%)
2 mm	706.7 cGy (13.1%)	386.8 cGy (7.2%)	266.8 cGy (4.9%)
3 mm	766.7 cGy (14.2%)	466.8 cGy (8.6%)	286.8 cGy (5.3%)
4 mm	767.7 cGy (14.2%)	426.8 cGy (7.9%)	306.8 cGy (5.7%)





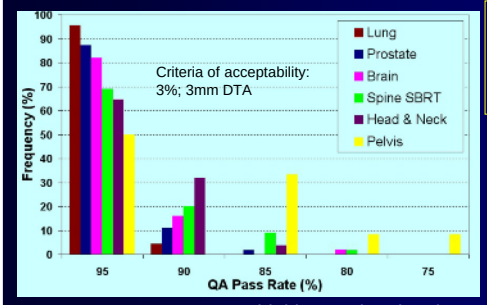
Chung, H., H. Jin, J. Palta, T. Suh, and S. Kim, Phys. Med. Biol. 51, pp.4841-4856, 2006

Take home message #3

Accuracy of IMRT dose distribution is inversely proportional to the complexity of IMRT plan (in terms of MU efficiency, number of sub-fields, size of each sub-field etc.) for a set of tolerance values for each dosimetry parameter.

IMRT QA Data

(University of Florida:2006)



Lung (68)
Prostate (155)
Brain (55)
Spine (65)
H&N (437)
Pelvis(24)

Lower pass rate highly correlated to the complexity of the treatment plan

Take home message #4

Clearly define and document the process of IMRT used in your clinic (imaging through delivery).

Quantify and document uncertainties in each step of the process.

Sources of uncertainties

STEP 1 — Imaging

-Image acquisition
-Delineation of anatomical structures
-Image resolution - Image artifact and distortion
-Conversion of a CT number to electron density
- Patient setup

STEP 2 — Planning

-Treatment margins
-Intra/inter-personal dependence of planning parameters
-Calculation algorithm (modeling of scattering and transmission of collimators/MLCs)
- Calculation grid size
- Modeling of leaf sequencing

STEP 3 — Delivery

-External patient motions
-Internal organ motions
-Misalignment of mechanical components of linacs
-Beam geometry / complexity
-Source position
-Variation in radiation generation
-Patient setup

Imaging modality and simulator commissioning

Planning system & Machine Commissioning

IMRT Process Uncertainty Analysis

	Prostate								Head and Neck/CNS							
	Voxel Size (mm)			Mean Displacement (mm)			Item Uncertainty (mm)	Process Uncertainty (mm)	Voxel Size (mm)			Mean Displacement (mm)			Item Uncertainty (mm)	Process Uncertainty (mm)
Imaging CT	X	Y	Z	X	Y	Z			X	Y	Z	X	Y	Z		
	0.94	0.94	3.00	0.47	0.47	1.50	0.87	0.87	0.94	0.94	1.50	0.47	0.47	0.75	0.55	0.55
Planning RTP																
Data							1.00	1.22							1.00	1.22
Input																
Calculation							0.50								0.50	
Non-dosimetric							0.50								0.50	
Delivery																
Machine																
Isocenter				0.50	0.50	0.75	1.03	1.44				0.50	0.50	0.75	1.03	1.44
MLC							1.00								1.00	
Setup																
Inter-fraction							2.00	7.35							0.50	1.12
Intra-fraction							5.00								1.00	
Organ motion							5.00								0.00	
	Overall Uncertainty (mm)							7.60	Overall Uncertainty (mm)							2.85

Palta et. al.. *Tolerance limits and action levels for planning and delivery of IMRT*. p. 593-612 *in* J. R. Palta and T. R. Mackie (ed.), *Intensity-Modulated Radiation Therapy*. Medical Physics Publishing. 2003.

Take home message #5

One can a priori *predict overall uncertainty in planning and delivery for a given set of tolerance limits for the commissioning parameters*

An uncertainty model

$$U(r) \quad \sqrt{w_1 SOU^2 \quad w_2 NOU^2 \quad w_3 SOU \quad NOU}$$

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 =0,

Dose Uncertainty

Space-oriented

$$SOU(\quad _{sou}) \quad \vec{G}(\vec{r}) \quad _{\vec{r}}$$

Non-space-oriented

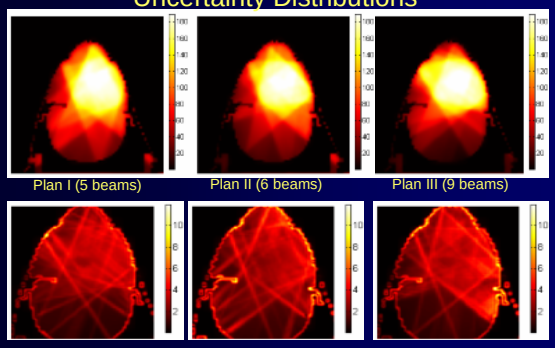
$$NOU(\quad _{nou}) \quad \frac{1}{\sqrt{D}}$$

Uncertainty sources

$$\sqrt{\quad ^2_{sou} \quad ^2_{nou}}$$

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

IMRT Plans with Corresponding Dose Uncertainty Distributions



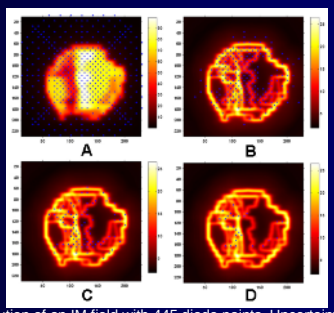
Plan I (5 beams) Plan II (6 beams) Plan III (9 beams)

Dose uncertainty distribution

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

Correlation Between Failed Points and Dose Uncertainty Distribution

MapCheck IMRT QA



A) A computed dose distribution of an IM field with 445 diode points. Uncertainty maps overlaid with failed points of gamma test using **B**) 1%-1 mm, **C**) 2%-2 mm, and **D**) 3%-3 mm criteria. (scale bar unit: % of maximum dose level)

Summary

- Accurate measurement of dosimetry data is crucial for accurate IMRT
  - Compare the measured data with golden benchmark data
- Accurate modeling of the delivery system dosimetric characteristics in the TPS will improve overall accuracy of IMRT
  - Establish a criteria of acceptability for each parameter
- Set the threshold for minimum field size for subfields and minimum MU/subfield that will ensure acceptable uncertainty in dose output/computation
  - 2 cm square; 2MU
- Use Nyquist limited dose calculation grid size resolution for dose computation
  - 2mm or less for H&N and 4 mm or less for pelvis
- It is extremely important to understand the limitations of the TPS in handling different clinical situations.
  - TPS estimates dose distributions
    - Quantify uncertainties in the dose distributions