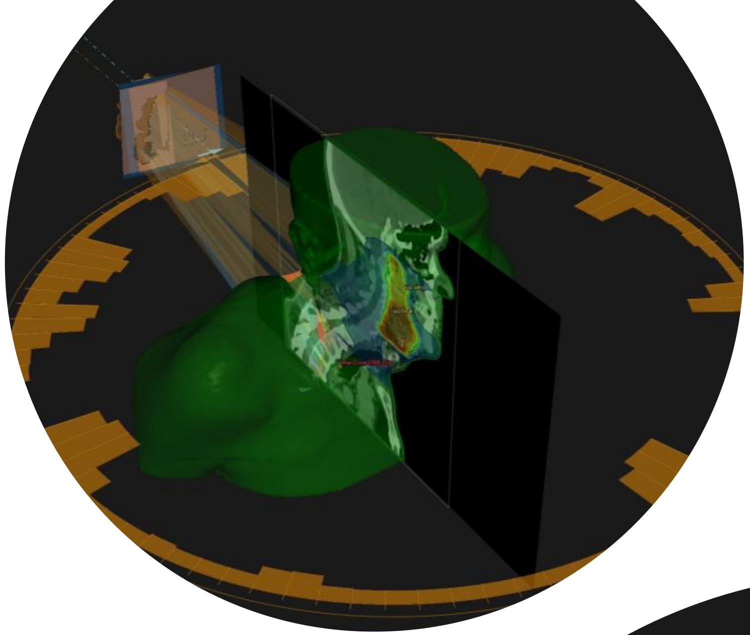
ICTP School of Medical Physics for Radiation Therapy:
Dosimetry and Treatment Planning for Basic and Advanced Applications
Trieste, 11-22 september 2023.

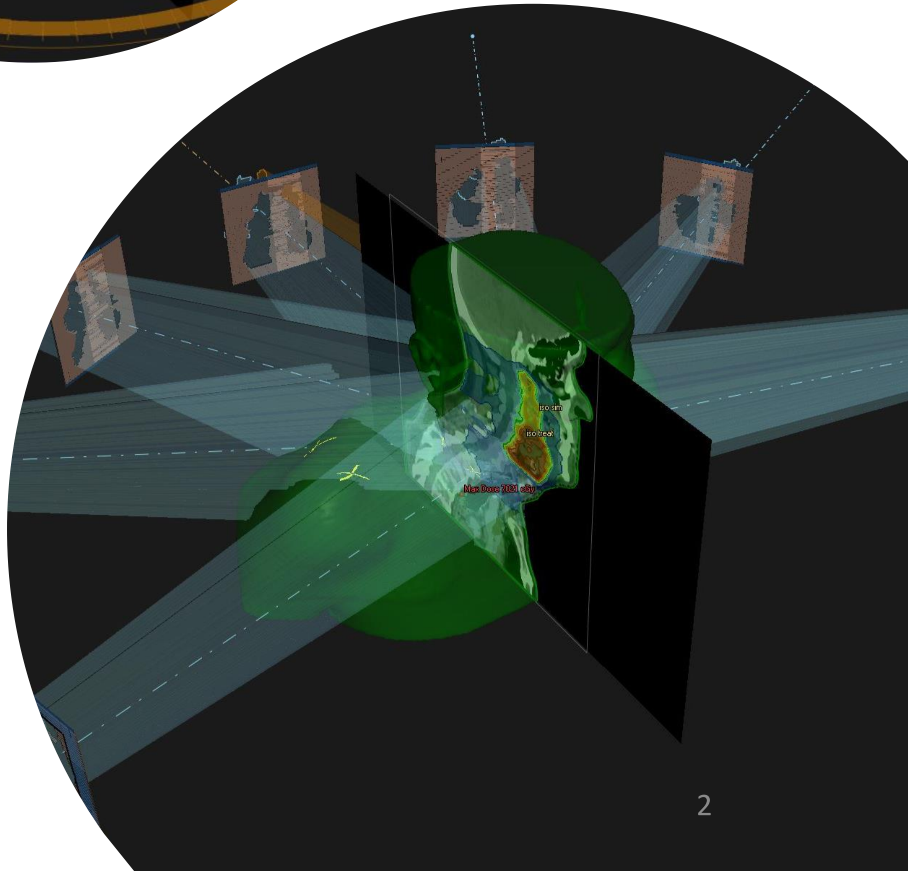
IMRT/VMAT: commissioning

Dr. Gianfranco Loi
Novara University Hospital ‘Maggiore della Carità’

Objectives



- Provide an overview of the main issues related to the commissioning of IMRT/VMAT techniques.
- Offer guidelines for safe and accurate implementation of IMRT/VMAT in clinical routine.
- To discuss the strategies and QA necessary to avoid the potential pitfalls affecting the dose delivery

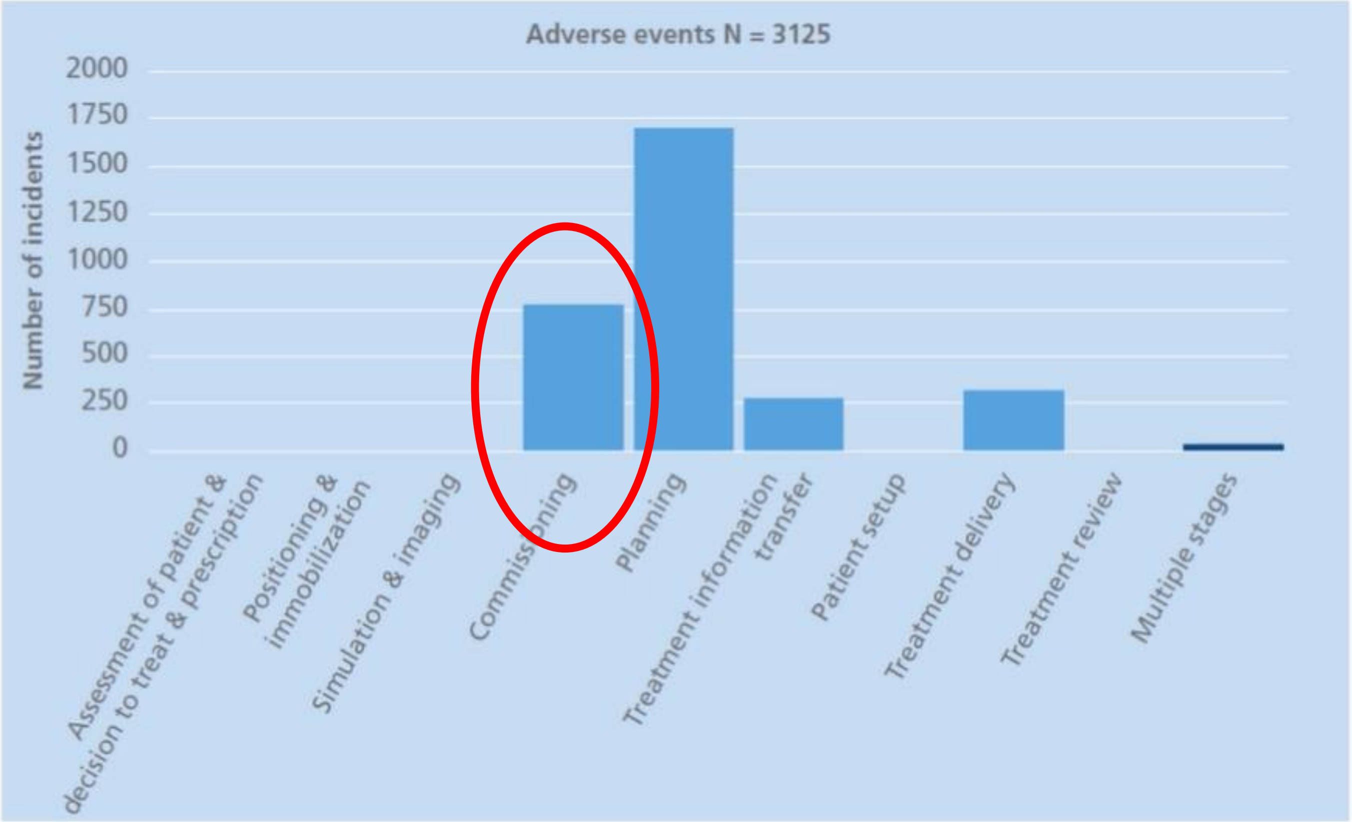


Opening statement

- The accuracy of dose calculation and delivery is paramount for safe and effective RT treatments.

- Commissioning of a new irradiation techniques such as IMRT must ensure that:
  - The delivery system meets the accuracy/precision requirements for their clinical implementation (ATP/QA)
  - Radiation beams and machine parameters are adequately modeled in the TPS and properly validated.

Radiotherapy incidents (1976-2007) by the stages of the process

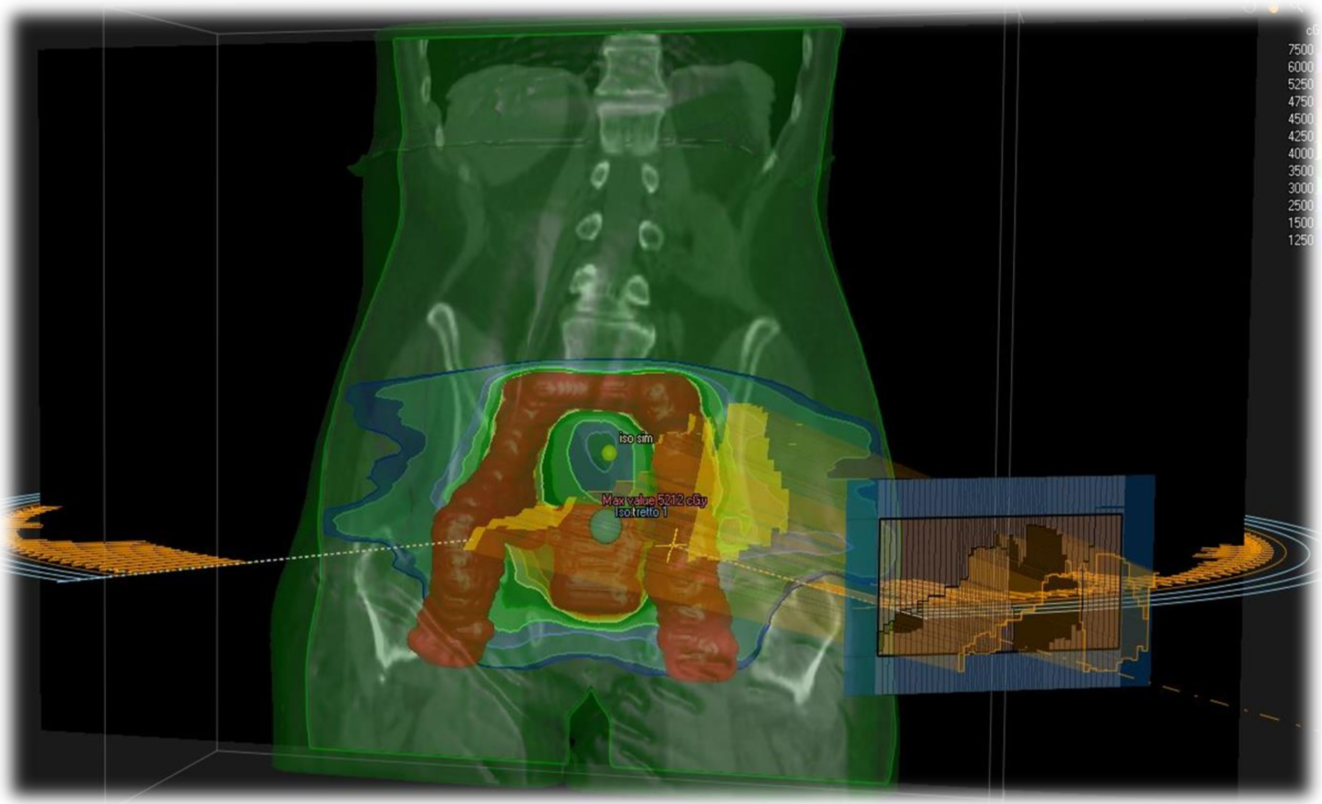


Reference : Radiotherapy risk profile. Technical manual. Geneva, Switzerland. WHO Publishing 2008

Commissioning of Intensity modulation is complicated !

Compared to conventional RT:

- ➢Higher dimensionality (4D vs 3D)
- ➢Demand for higher dosimetric/geometric accuracy (small field sizes, MLC transmission, dosimetric leaf gap…)
- ➢Increased DOF/plan complexity (leaves move, variable dose rates/gantry speed)
- ➢Multiple failure modes



As a consequence accurate commissioning IMRT is challenging!

results from IROC Houston

- 82% of the institutions passed the end-to-end test using rather lenient DD% and DTA criteria of 7% and 4 mm, respectively.
- Only 69% percent of the irradiations passed a narrowed TLD DD% of 5%.

Dosimetric errors were related to:

1. TPS commissioning :
    1. Incorrect data input and beam modeling (OF, PDDs)
    2. Inadequate modeling of MLC parameters (penumbra, leaves position, transmission..)
2. Delivery system:
    1. MLC performances (static/dynamic)
    2. Positioning errors
    3. MU delivery errors

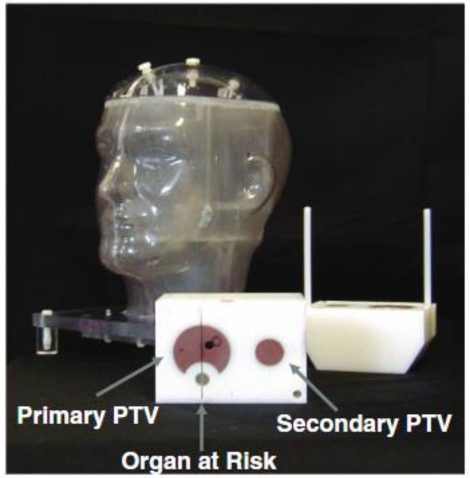


FIG. 1. RPC H&N phantom for IMRT credentialing.

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The International Journal of Medical Physics Research and Practice

Radiation measurement physics

Credentialing results from IMRT irradiations of an anthropomorphic head and neck phantom

Andrea Molineu, Nadia Hernandez, Trang Nguyen, Geoffrey Ibbott, David Followill

First published: 08 January 2013 | https://doi.org/10.1118/1.4773309 | Citations: 91

TABLE III. Comparison of pass rates for treatment planning systems with two sets of criteria.

Treatment planning system	Pass rate (%) 5%/4 mm	Pass rate (%) 7%/4 mm
Eclipse	72	88
Pinnacle[3]	56	75
TomoTherapy	79	93
XiO	54	76
Other	56	78

Passing PSQAs no good as surrogate for sucessfull IMRT commissioning.

Results*	No. of results	% Sensitivity (±SD)	% Specificity (±SD)
All results			
Institution claim	855	2 (1)	99.6 (0.2)
Evaluated by IROC Houston	745	18 (4)	91 (1)
Device			
Ion chamber + planar	91	54 (14)	79 (5)
Ion chamber	325	25 (6)	90 (2)
Film	71	33 (16)	82 (5)
MapCheck	322	14 (5)	94 (2)
Mode			
Absolute	295	3 (3)	94 (1)
Relative	97	21 (9)	91 (3)

Table 1 Sensitivity and specificity of IMRT QA results compared with IROC Houston phantom results

- ➢ Need for a comprehensive QA programs
- ➢ Importance of external audits

Physics Contribution

Institutional Patient-specific IMRT QA Does Not Predict Unacceptable Plan Delivery

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Stephen F. Kry, PhD,* Andrea Molineu, MS,* James R. Kerns, MS,*,† Austin M. Faught, PhD,*,† Jessie Y. Huang, BS,*,† Kiley B. Pulliam, MS,*,† Jackie Tonigan, MS,*,† Paola Alvarez, MS,* Francesco Stingo, PhD,†,‡ and David S. Followill, PhD*,†

**Imaging and Radiation Oncology Core at Houston, Department of Radiation Physics, The University of Texas MD Anderson Cancer Center, Houston, Texas; †The University of Texas Health Science Center Houston, Graduate School of Biomedical Sciences, Houston, Texas; and ‡Department of Biostatistics, The University of Texas MD Anderson Cancer Center, Houston, Texas*

Received Apr 18, 2014, and in revised form Aug 14, 2014. Accepted for publication Aug 18, 2014.

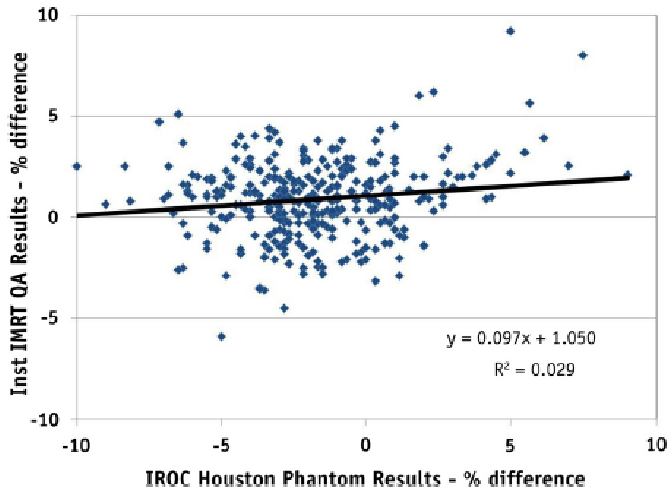


Fig. 3. Percent differences between dose measurements and treatment planning system calculations for institutional IMRT QA compared with the TLD in the IROC Houston phantom. The linear trend line should ideally have a slope of 1 but instead is nearly flat. IMRT QA = intensity modulated radiation therapy quality assurance; IROC = Imaging and Radiation Oncology Core; TLD = thermoluminescent dosimeters.

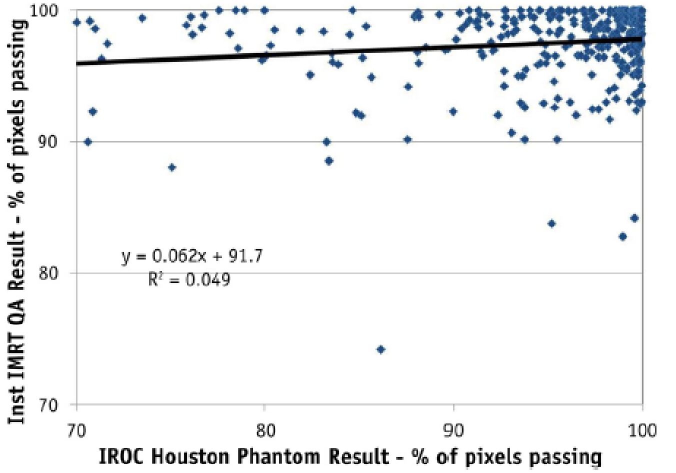
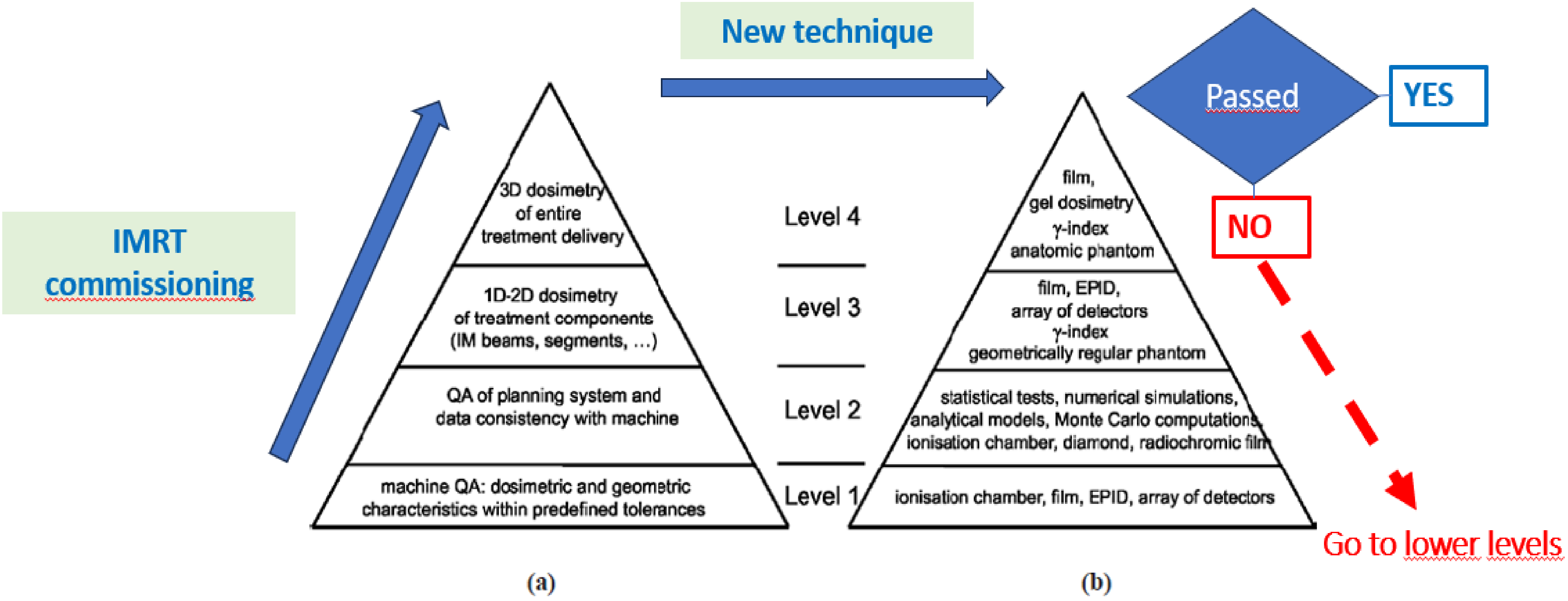


Fig. 4. Percent of pixels passing gamma for institutional IMRT QA compared with the IROC Houston phantom films. The linear trend line should ideally have a slope of 1, but instead is nearly flat. IMRT QA = intensity modulated radiation therapy quality assurance; IROC = Imaging and Radiation Oncology Core.

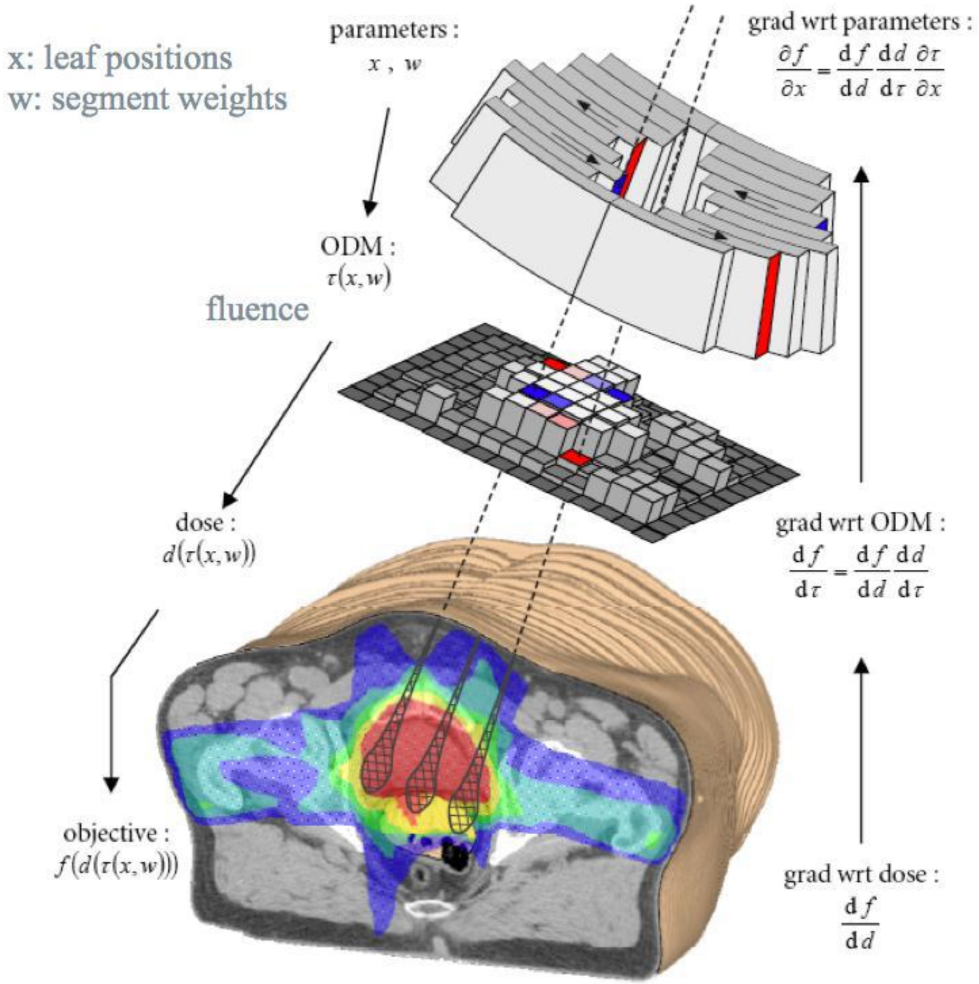
IMRT commissioning requires a multi-layered strategy:



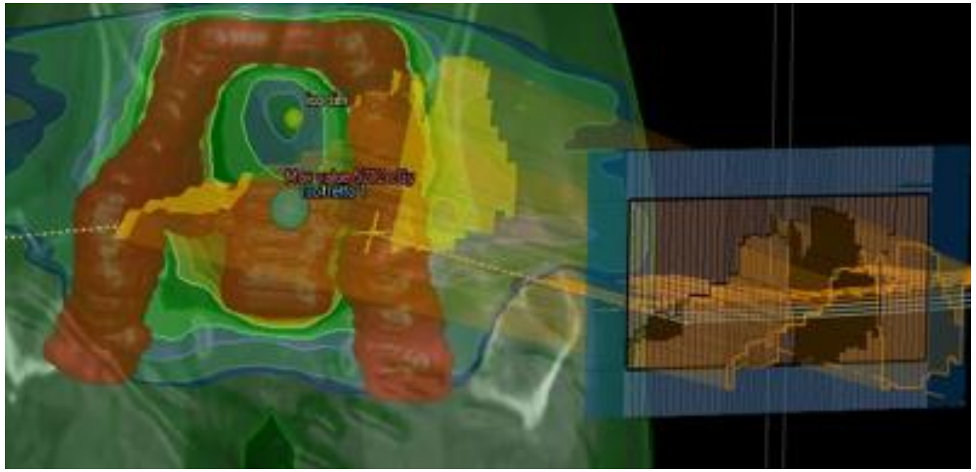
Ref. Estro Physics Booklet No 9. Guidelines for the verification of IMRT

The delivery system characterization steps:

- MLC/DMLC positional and speed accuracy
- Linac performance for small MU delivery
- MLC physical/dosimetric characteristics:
  - MLC transmisssion
  - Leaf-end / inter-leaf leakage
  - Tongue and groove effect
  - Dosimetric Leaf Gap/DMLC dynamic minimum lea
- Additional issues specific to VMAT
  - DMLC positional accuracy - rotating gantry
  - DMLC error detection test during rotation
  - DMLC dosimetric characteristics
    - changing gantry positions
    - changing gantry speed and dose rate
    - changing leaf speed during rotation
- Safety
  - Data transfer
  - Interruption/Resumption test



The positional accuracy issues



Physical and dosimetric aspects of a multileaf collimation system used in the dynamic mode for implementing intensity modulated radiotherapy

Thomas LoSasso, Chen-Shou Chui, C. Clifton Ling

First published: 13 November 1998 | https://doi-org.bvsp.idm.oclc.org/10.1118/1.598381 |

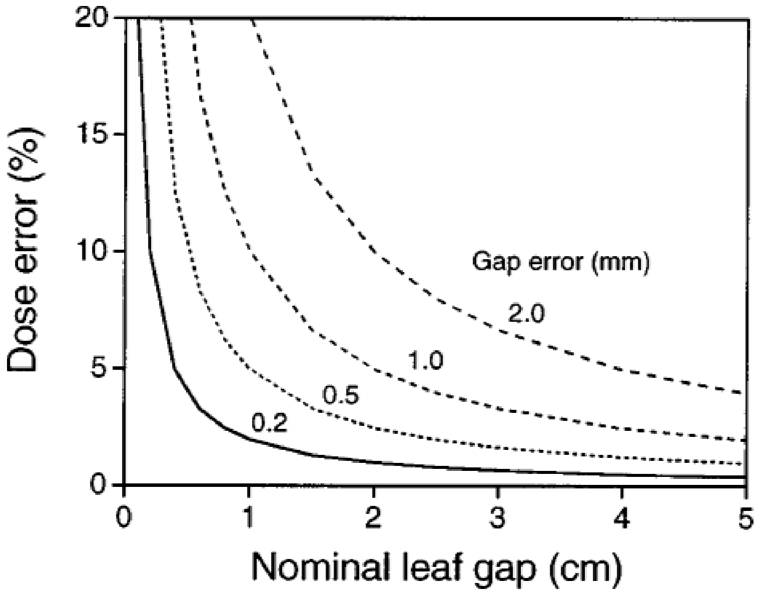


FIG. 8. Calculated results relating the error in the dose delivered to the error in the gap for a range of gap widths.

- 3DCRT: leaf position affect only the border, 1-2 mm error not clinically significant.
- IMRT: leaf positioning affects dose in the PTV, sub-millimetrical accuracy is required
- Offset (0.4- 1.1 mm) due to the rounded leaf ends.

Tests for positional accuracy

AAPM report 82

Guidance document on delivery, treatment planning, and clinical implementation of IMRT: Report of the IMRT subcommittee of the AAPM radiation therapy committee

Gary A. Ezzell, James M. Galvin, Daniel Low, Jatinder R. Palta, Isaac Rosen, Michael B. Sharpe, Ping Xia, Ying Xiao, Lei Xing, Cedric X. Yu

Picket & fence

Accuracy 0.5 mm

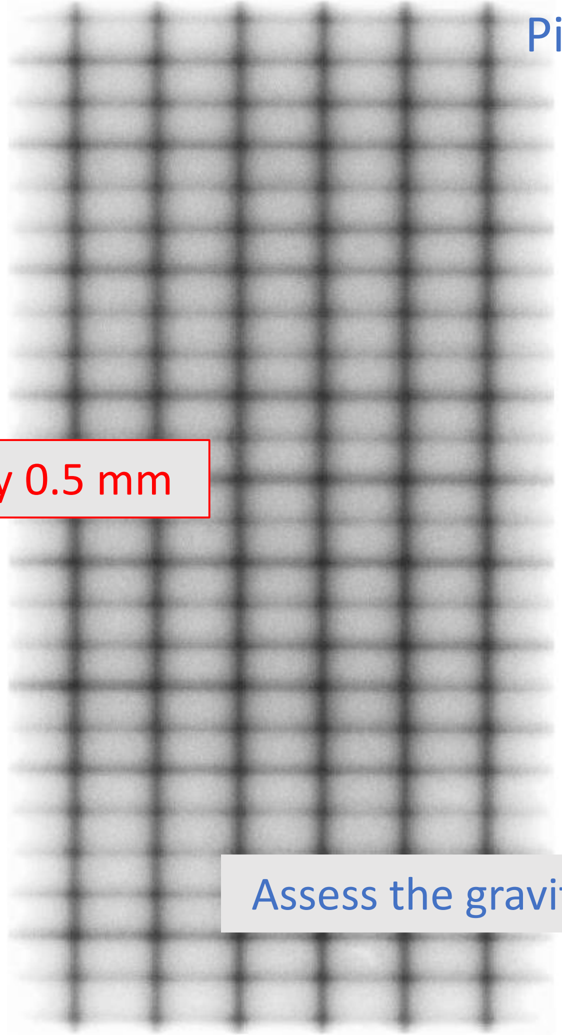
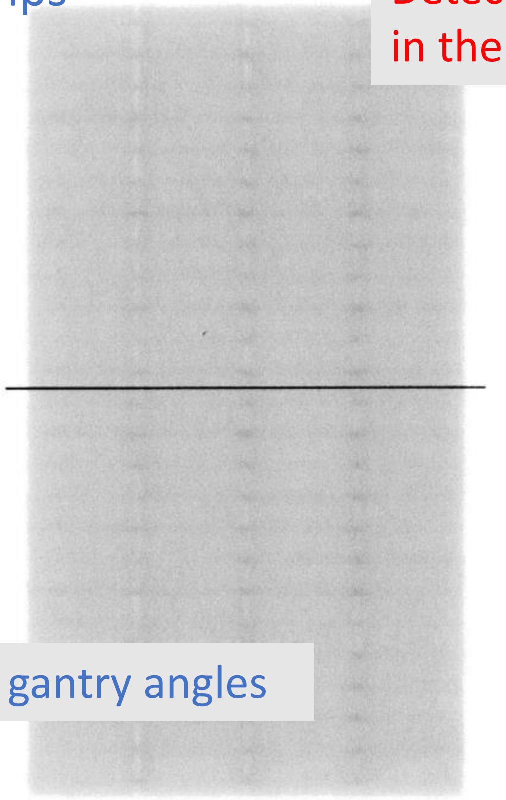
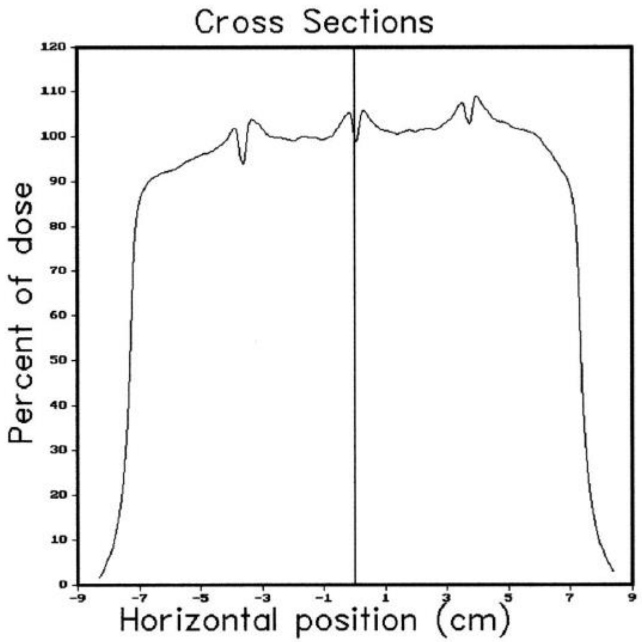


FIG. II.2. (a) MLC test pattern with a 1 mm wide strip. (b) QA film produced by moving the pattern in 2 cm intervals and irradiating in a step-and-shoot fashion. This MLC has a rounded leaf end design.

Abutting strips

Detectatibility 0.2 mm (±5% dose variation in the matchline)





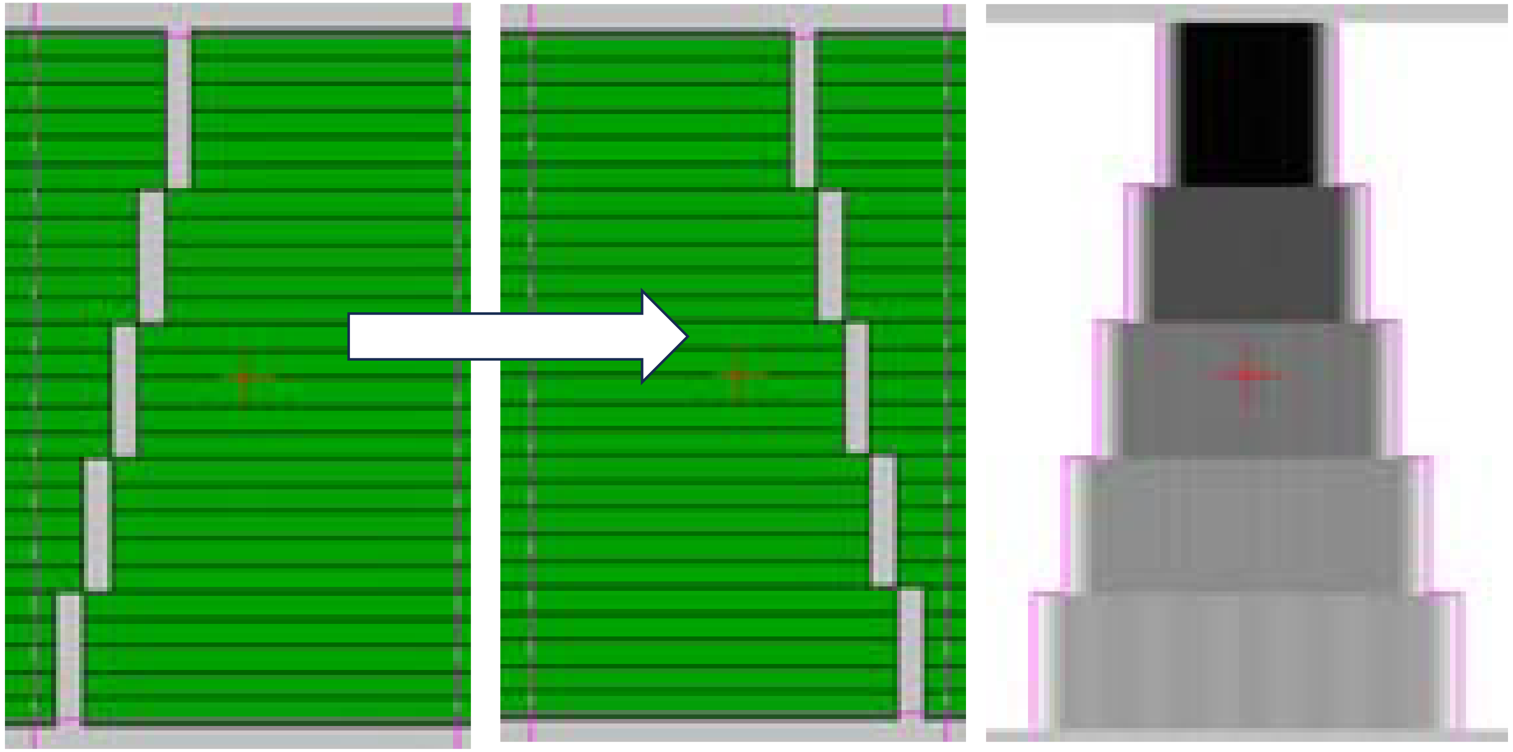
Assess the gravity effect using 90-270 gantry angles

FIG. II.1. (a) MLC test pattern with a 2 cm wide strip. (b) QA film produced by moving the pattern in 2 cm intervals and irradiating in a step-and-shoot fashion. The strips should abut at the 50% decrement lines as described in Sec. II A 1. The line on the film shows the location of the scan (c), which is used to assess the quality of the matching. This MLC has a rounded leaf end design.

… Dynamic MLC speed test:

A fixed gap moving at a uniform rate should produce a uniform fluence.

- Stability of the leaves moving at different speed can be tested delivering stepwise intensities with several leaf motion patterns on a single film/EPID.
- Ion chamber and film/Epid measurements can be combined.
- Central leaves can scan a gap across the ion chamber for a fixed number of MU, producing a constancy check.
- Film/EPID image the on/off-axis gaps moving at different rates.



Ref. AAPM report 82

Linac performance for small MU delivery

IMRT STEP&SHOOT ISSUE:

many small segments with few MUS.

- Dose-per-MU constancy should be checked.
- Similarly, the flatness and symmetry of the beam should be checked.

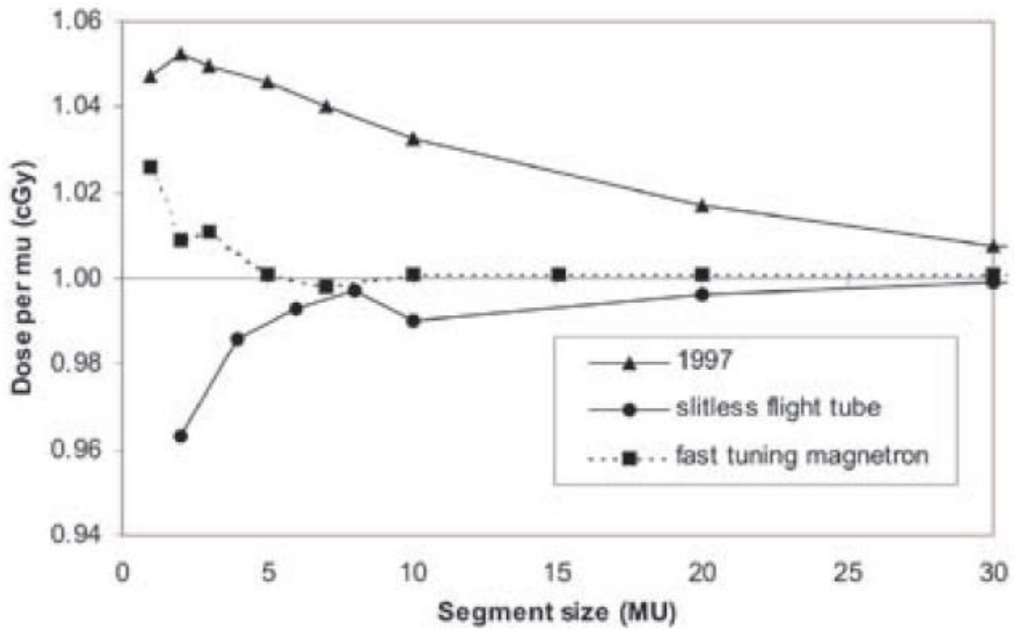


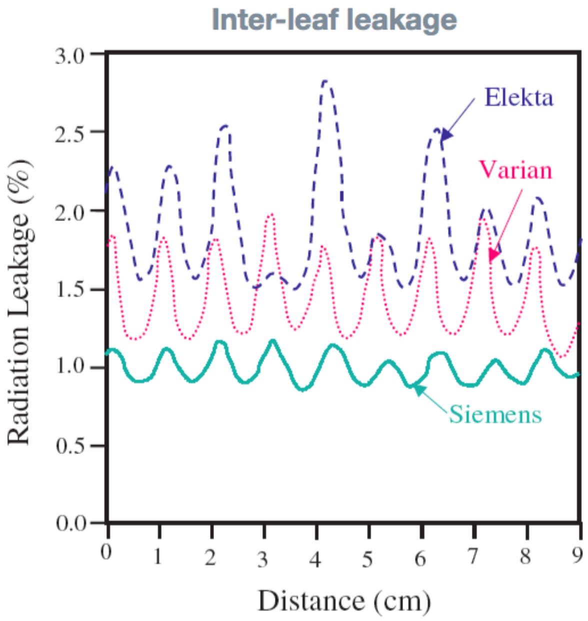
Figure 4.6 Beam calibration for a limited number of monitor units depending on the type of magnetron and steering technique for Elekta accelerators. In 1997 the feedback technique with slits was used. An improvement of this technique was the slitless flight tube, which was followed by a new design magnetron with faster tuning (Courtesy Geoff Budgell, Christie Hospital, Manchester, UK).

Ref. Estro Physics Booklet No 9. Guidelines for the verification of IMRT
Ref AAPM report 82

MLC Physical/dosimetric characteristics

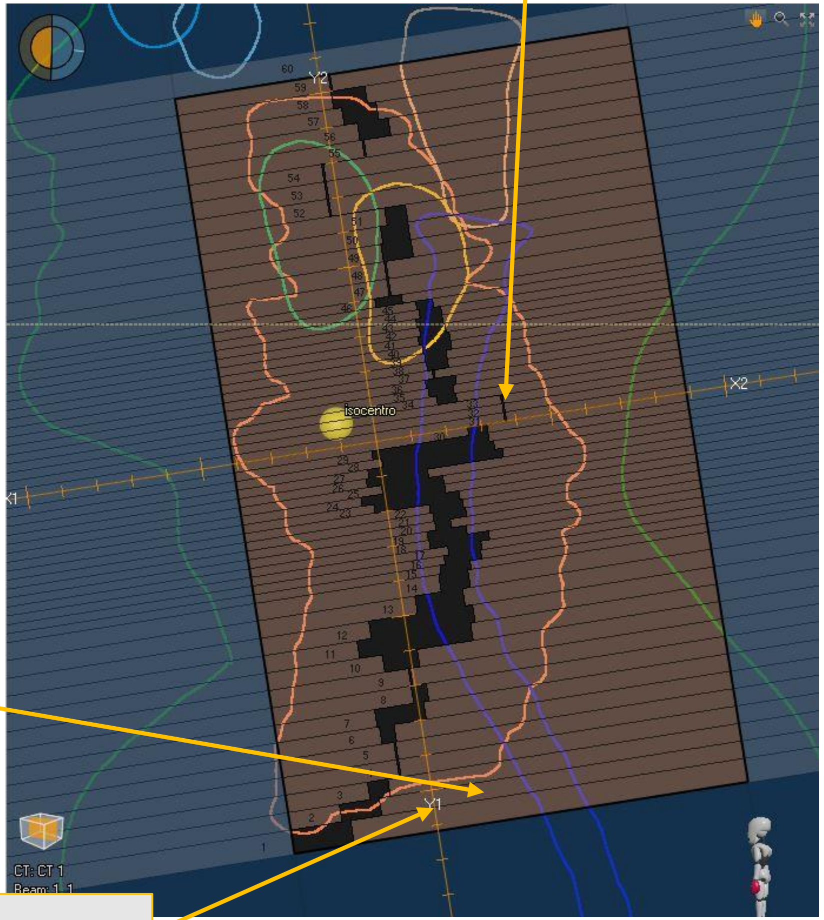
MLC leaves sweep through the PTV during irradiation, it is necessary to characterized:

- ➢ Leaf leakage:
  - Transmission through leaves
  - Intra-Interleaf leakage
  - TPS mostly require average leakage
- ➢ MLC Leaf penumbra
- ➢ Tongue and groove effect



Leakage through closed opposing leaves ~20% (rounded ends)

Leakage through leaf



Leakage between leaves

The issue of MLC penumbra

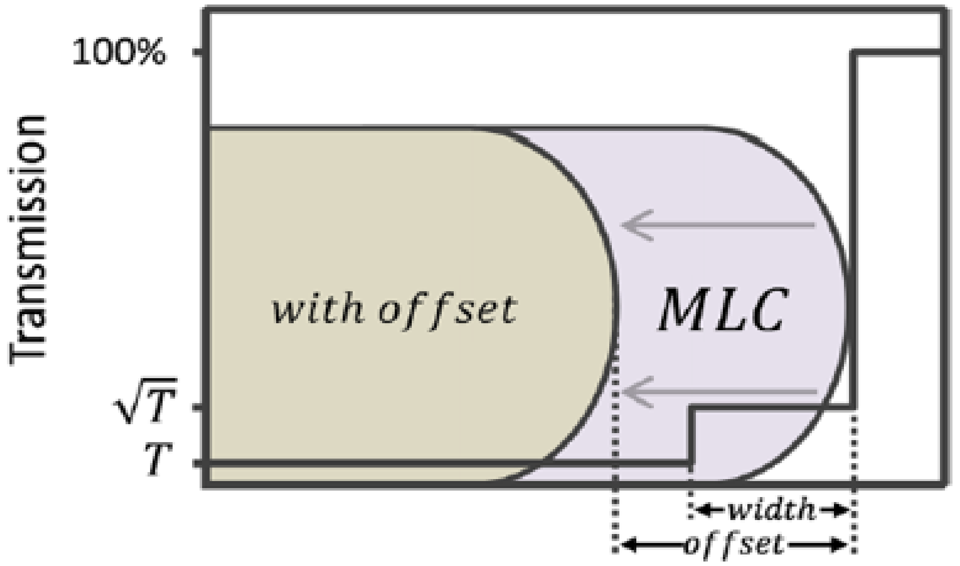
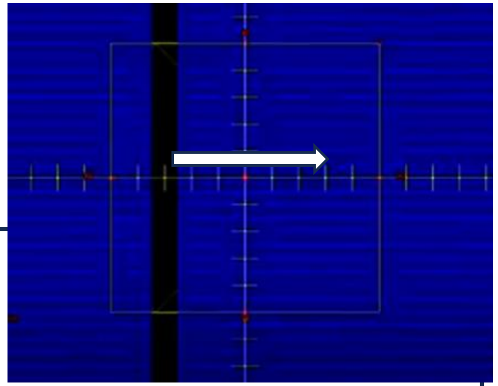


Figure from Koger et al https://doi.org/10.1002/acm2.12819

- Because of MLC leaf end design physical leaf edge differ from dosimetric leaf edge (50% isodose line).
- The distance from the nominal edge is the leaf tip offset or Dosimetric Leaf Gap (DLG). This parameter is an important factor for correct dose calculation with dMLC.
- Opposing leaves cannot be at the same position, and a minimum tip gap between opposed leaves is needed.

DLG measurement with sweeping gaps



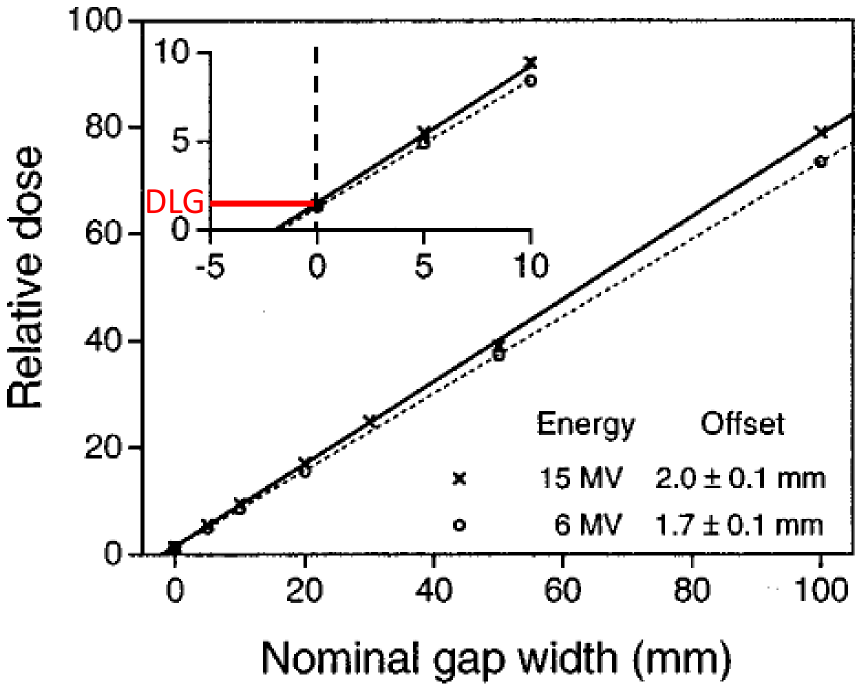
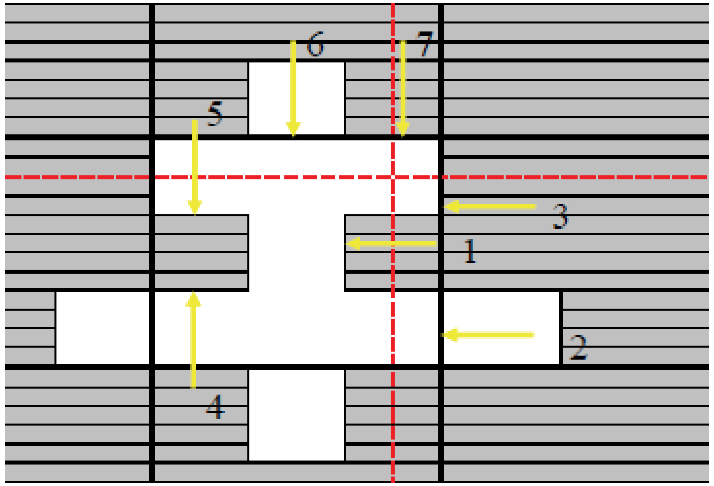


FIG. 7. Integrated dose vs MLC gap width measured in phantom with radiographic film for 6 and 15 MV x rays. The lines are linear fits to the data using least-squares regression. Extrapolation to zero integral dose determines the effective gap offset. The uncertainties are the standard errors of the data.

Figure from Lo Sasso et al https://doi.org/10.1118/1.598381

Penumbra modelling impacts strongly on Step&Shoot IMRT

- Step&Shoot : sum up many segment edges, penumbra is critical.
- Depending on MLC design and segment sequencer different components cause different penumbras.
- In dMLC techniques penumbra effects blur out.

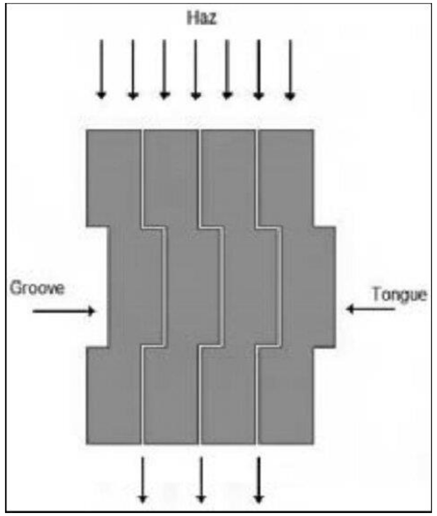


1: Leaves only:	5.8 mm
2: Back-up (Y) collimator only:	4.8 mm
3: Leaves + back-up (Y) collimator:	4.2 mm
4. Side of leaves (left):	3.8 mm
5. Side of leaves (right):	3.5 mm
6: X-collimator only:	3.6 mm
7: X-collimator + leaves:	3.4 mm

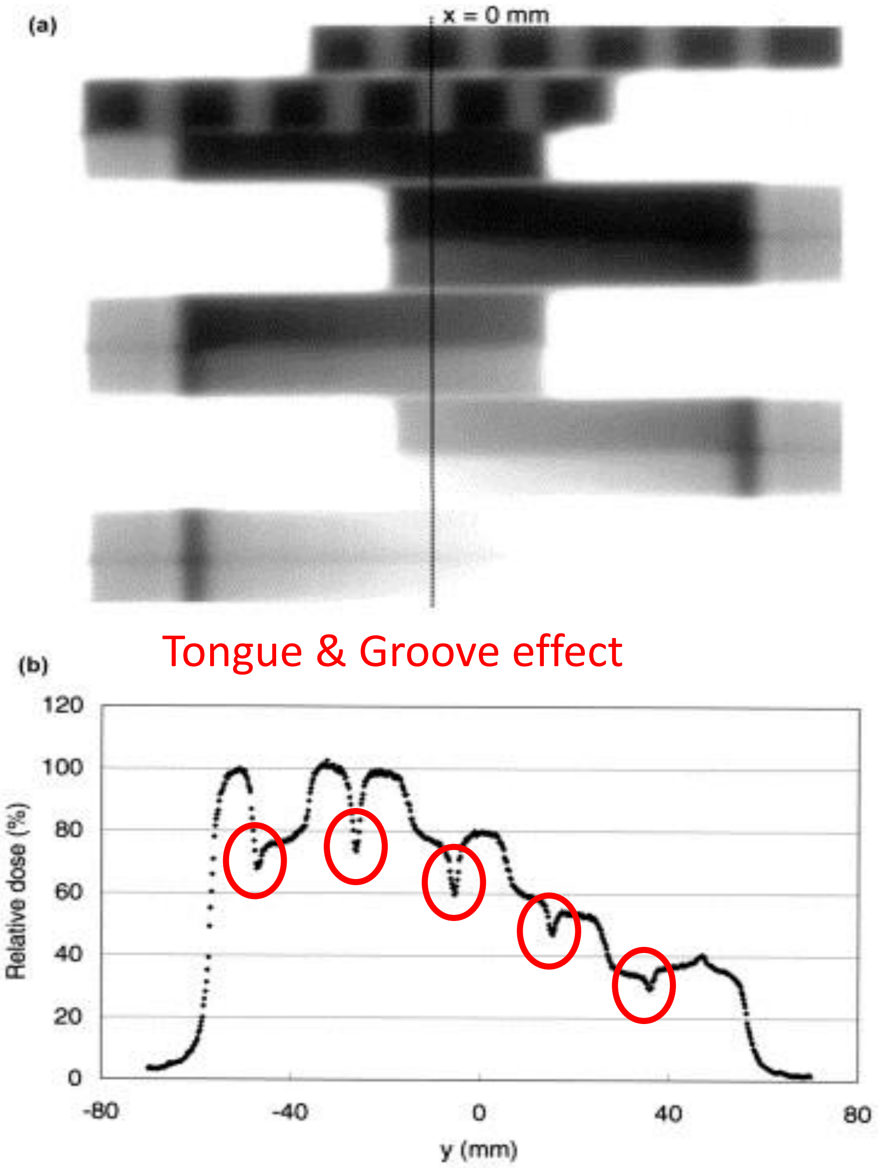
Figure 4.4 Penumbra values (80%-20% dose distance) for an Elekta MLC at the indicated positions measured with film. The arrows indicate the positions where the penumbra values were measured. The vertical and horizontal fat lines show the position of the back-up (Y) and X-collimators, respectively.

Ref. Estro Physics Booklet No 9. Guidelines for the verification of IMRT

Tongue and groove effect



- Significant underdosages in lateral leaves abutting segments
- Equally important for static MLC and dMLC based techniques.
- Depends from MLC leaf design, important factor in TPS modeling/dose accuracy



Reference: Essers M. et al. "Commissioning of a commercially available system for intensity-modulated radiotherapy dose delivery with dynamic multileaf collimation." Radiother. Oncol. 60: 215-224, 2001

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: 1.0 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 $<4\times4$ cm², 1% $\geq4\times4$ 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	
X-ray output constancy vs dose rate		±2% from baseline	
X-ray output constancy vs gantry angle		±1% from baseline	
Electron output constancy vs gantry angle		±1% from baseline	
Electron and x-ray off-axis factor constancy vs gantry angle		±1% from baseline	
Arc mode (expected MU, degrees)		±1% from baseline	
TBI/TSET mode		Functional	
PDD or TMR and OAF constancy		1% (TBI) or 1 mm PDD shift (TSET) from baseline	
TBI/TSET output calibration		2% from baseline	
TBI/TSET accessories		2% from baseline	
Mechanical			
Collimator rotation isocenter		±1 mm from baseline	
Gantry rotation isocenter		±1 mm from baseline	
Couch rotation isocenter		±1 mm from baseline	
Electron applicator interlocks		Functional	
Coincidence of radiation and mechanical isocenter	±2 mm from baseline	±2 mm from baseline	±1 mm from baseline
Table top sag		2 mm from baseline	
Table angle		1°	
Table travel maximum range movement in all directions		±2 mm	
Stereotactic accessories, lockouts, etc.	NA	NA	Functional
Safety			
Follow manufacturer's test procedures		Functional	
Respiratory gating			
Beam energy constancy		2%	
Temporal accuracy of phase/amplitude gate on		100 ms of expected	
Calibration of surrogate for respiratory phase/amplitude		100 ms of expected	
Interlock testing		Functional	

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Task group report | Free Access

Task Group 142 report: Quality assurance of medical accelerators[a)]

Eric E. Klein, Joseph Hanley, John Bayouth, Fang-Fang Yin, William Simon, Sean Dresser, Christopher Serago, Francisco Aguirre, Lijun Ma, Bijan Arjomandy, Chihray Liu ... See all a

First published: 17 August 2009 | https://doi.org/10.1118/1.3190392 | Citations: 1,033

Received: 9 February 2021 | Revised: 16 March 2021 | Accepted: 28 April 2021
DOI: 10.1002/mp.14992
AAPM SCIENTIFIC REPORT
MEDICAL PHYSICS

AAPM Task Group 198 Report: An implementation guide for TG 142 quality assurance of medical accelerators

Joseph Hanley[1] | Sean Dresser[2] | William Simon[3] | Ryan Flynn[4] | Eric E. Klein[5] | Daniel Letourneau[6] | Chihray Liu[7] | Fang-Fang Yin[8] | Bijan Arjomandy[9] | Lijun Ma[10] | Francisco Aguirre[11] | Jimmy Jones[12] | John Bayouth[13] | Todd Holmes[14]

IMRT delivery systems require tighter tollerances than 3DCRT

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

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

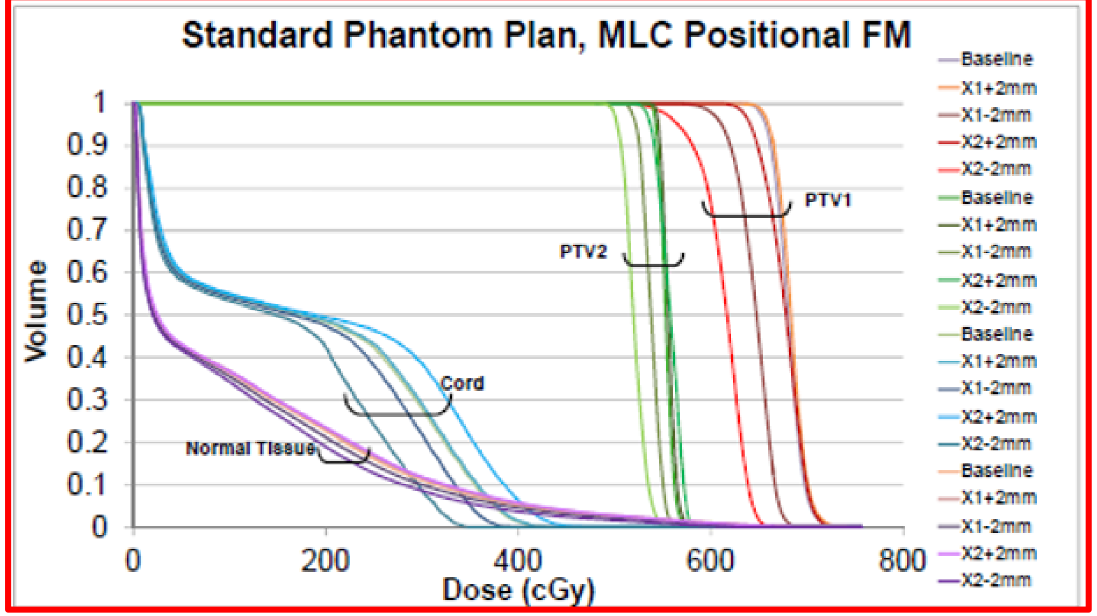
Impact of machine performances on IMRT delivery accuracy

Failure Mode	Magnitude of Failure
1. Beam energy	1% PDD_{10}
2. Beam symmetry	2%, 3.5%, 10%
3. MLC position systematic (one bank)	1 mm, 2 mm
4. Gantry angle systematic	2.0°
5. Collimator angle systematic	2.0°
6. Couch angle systematic	2.0°

Physics failure modes of step and shoot IMRT delivery near the TG-142 tolerance criteria levels have the potential for significant dose deviations in the geometry controlled IROC-Houston H&N phantom end to end tests.

Standard Phantom Plan Physical Measurement Results				
Failure Mode	Induced Error	Avg Δabs dose	ΔDTA (mm)	Δ%pp (7%/4mm)
1	+1.1%	1.3%	0.7	16%
1	-0.6%	1.7%	0.2	9%
2	3.5% in-plane	2.0%	0.2	13%
2	3.5% cross-plane	3.1%	0.3	18%
3	+ 2 mm	1.4%	0. 9	19%
4	+2°	1.8%	0.0	10%
5	+2°	0.3%	0.3	0%
6	+2°	-0.1%	0.0	1%

Table 2. Physical measurements using IROC IMRT H&N phantom with TLD and film. DTA between the primary PTV and OAR and gamma index analysis in sagittal and axial planes. Agreement of measured and calculated doses are compared for failure free irradiations and those with the listed FMs.



Reference:
Tonigan Faught et al. Clinical impact of IMRT failure modes at or near TG-142 tolerance criteria levels. AAPM Meeting 2015 https://doi.org/10.1118/1.4924540

Assessing VMAT systems capabilities

The three most important elements are:

- accuracy in DMLC position
- precise dose-rate control during gantry rotation
- accurate control of gantry speed.

VMAT control points

No.	Gantry [deg]	Cumulative MU/fx	MU/fx	Dose rate [MU/min]	Weight [%]	Delivery time [sec]	Gantry speed [deg/s]	Jaw positions [cm] X1	X2	Y1	Y2	Coll. [deg]
16	121.00	30.71	4.85	342.42	1.63	0.85	4.70	-4.12	8.90	-11.20	10.50	9.00
17	117.00	35.57	1.91	134.67	0.64	0.85	4.70	-4.12	8.90	-11.20	10.50	9.00
18	113.00	37.48	1.61	113.32	0.54	0.85	4.70	-4.12	8.90	-11.20	10.50	9.00
19	109.00	39.08	4.45	313.67	1.49	0.85	4.70	-4.12	8.90	-11.20	10.50	9.00
20	105.00	43.53	6.63	467.79	2.22	0.85	4.70	-4.12	8.90	-11.20	10.50	9.00
21	101.00	50.16	6.70	472.96	2.25	0.85	4.70	-4.12	8.90	-11.20	10.50	9.00
22	97.00	56.86	2.97	209.85	1.00	0.85	4.70	-4.12	8.90	-11.20	10.50	9.00
23	93.00	59.84	6.02	425.06	2.02	0.85	4.70	-4.12	8.90	-11.20	10.50	9.00
24	89.00	65.86	8.50	600.00	2.85	0.85	4.70	-4.12	8.90	-11.20	10.50	9.00

Show MLC table

No.	Leaf center [cm]	Width [cm]	X1 [cm]	X2 [cm]
34	0.87500	0.2500	1.88	2.43
35	1.12500	0.2500	1.68	2.38
36	1.37500	0.2500	1.63	2.49
37	1.62500	0.2500	1.87	1.92
38	1.87500	0.2500	1.74	2.35
39	2.12500	0.2500	1.73	2.34
40	2.37500	0.2500	1.70	2.51
41	2.62500	0.2500	1.62	2.51
42	2.87500	0.2500	1.70	2.44

References

ELSEVIER

Int. J. Radiation Oncology Biol. Phys., Vol. 72, No. 2, pp. 575–581, 2008

0360-3016/08/$–see front matter

doi:10.1016/j.ijrobp.2008.05.060

PHYSICS CONTRIBUTION

COMMISSIONING AND QUALITY ASSURANCE OF RAPIDARC RADIOTHERAPY DELIVERY SYSTEM

C. Clifton Ling, Ph.D.,*† Pengpeng Zhang, Ph.D.,† Yves Archambault, M.Sc.,* Jiri Bocanek, M.Sc.,* Grace Tang, M.Phil.,† and Thomas LoSasso, Ph.D.†

* Varian Medical Systems, Palo Alto, CA; † Memorial Sloan-Kettering Cancer Center, New York, NY; and ‡ University of Maryland, Baltimore, MD

ELSEVIER

Int. J. Radiation Oncology Biol. Phys., Vol. 73, No. 2, pp. 537–545, 2009

0360-3016/09/$–see front matter

doi:10.1016/j.ijrobp.2008.08.055

PHYSICS CONTRIBUTION

COMMISSIONING OF VOLUMETRIC MODULATED ARC THERAPY (VMAT)

James L. Bedford, Ph.D., and Alan P. Warrington, M.Sc.

Joint Department of Physics, The Institute of Cancer Research and Royal Marsden NHS Foundation Trust, Sutton, Surrey, UK

DMLC positional accuracy test

Tolerance: 1 mm

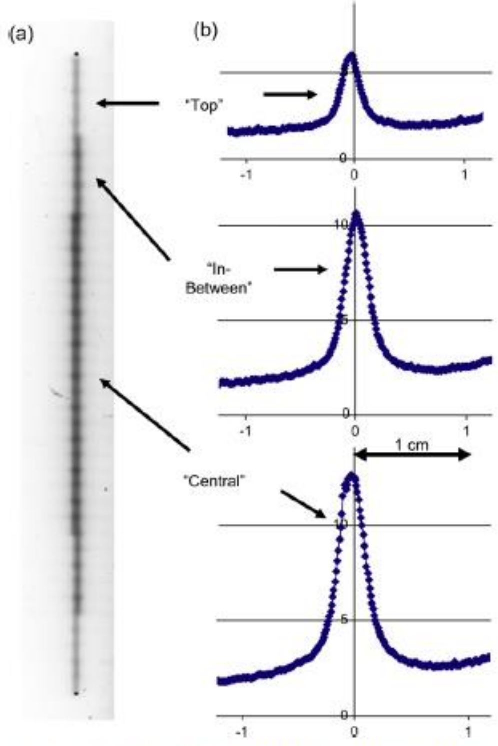


Fig. 2. (a) Image of a film mounted on the isocentric mounting fixture (IMF) and repeatedly exposed to a slit radiation field. (b) Radiation profiles of the image.

Picket fence

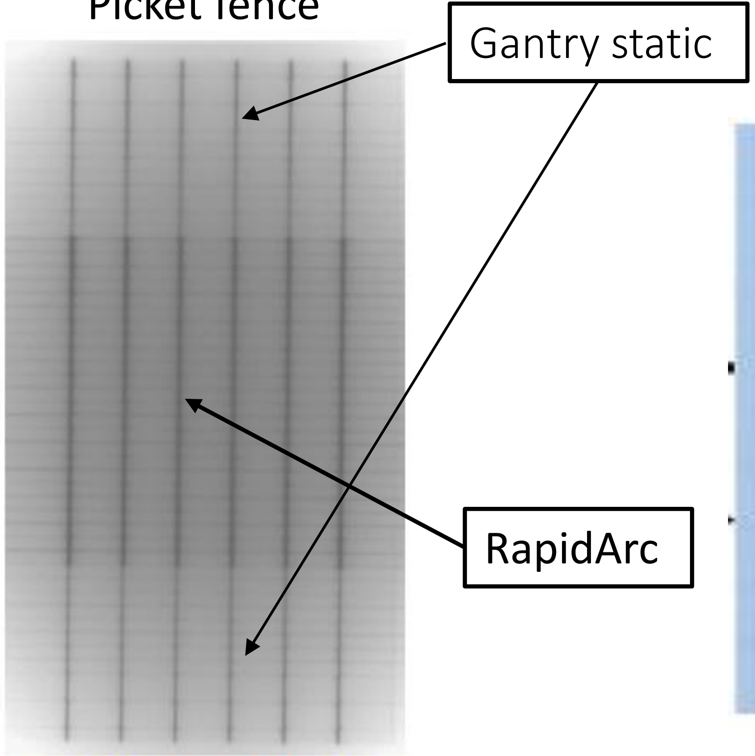
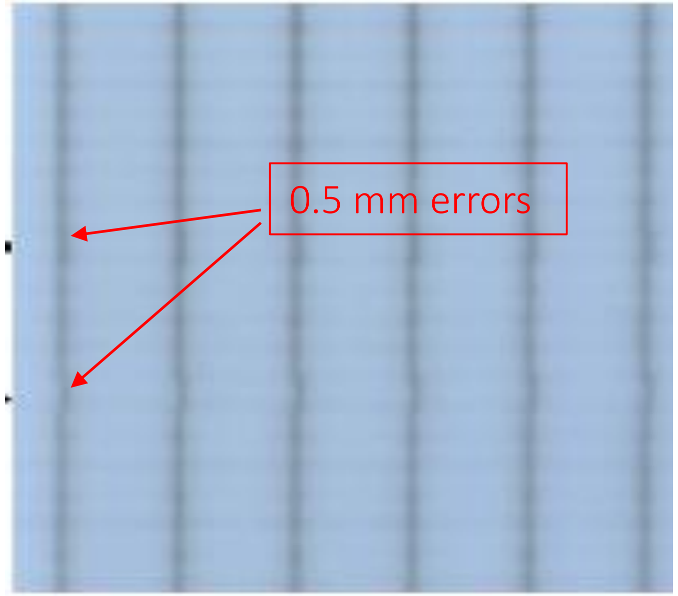
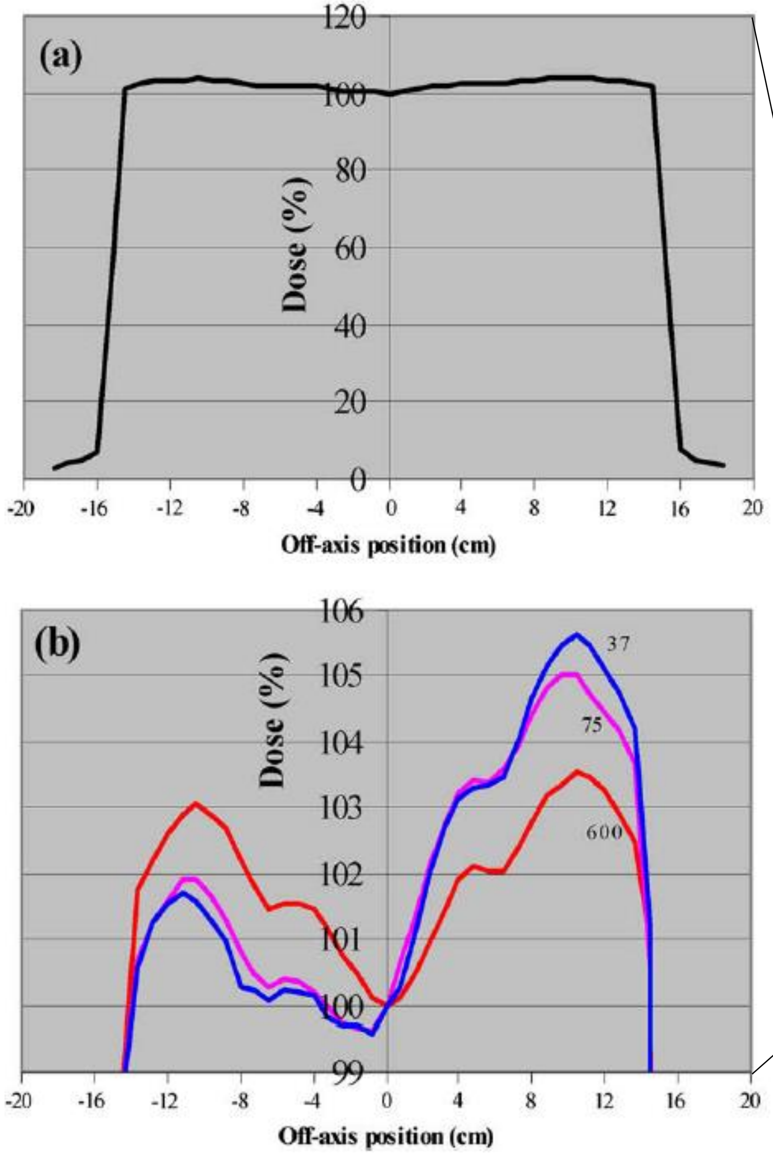


Fig. 3. Image of a film that was exposed twice to the 1-mm-wide picket fence pattern, once at stationary gantry angle and a second time in RapidArc mode.



Ling et al. IJROBP 2008

Field flatness vs gantry positions



- be sure that the beam flatness and symmetry were stable during gantry arcing and at a lower dose rate than normal

Table 1. Beam flatness and symmetry at varying dose rates

Orientation	Dose rate (MU/min)	Flatness (%)*	Symmetry (%)*
G-T	37	104.0	101.0
A-B	600	103.6	100.7
A-B	75	105.4	103.5
A-B	37	106.1	104.1

Abbreviations: A-B = perpendicular to the axis of gantry rotation; G-T = parallel to the axis of gantry rotation.

* IEC 60976 nomenclature.

Tolerance: ±3%

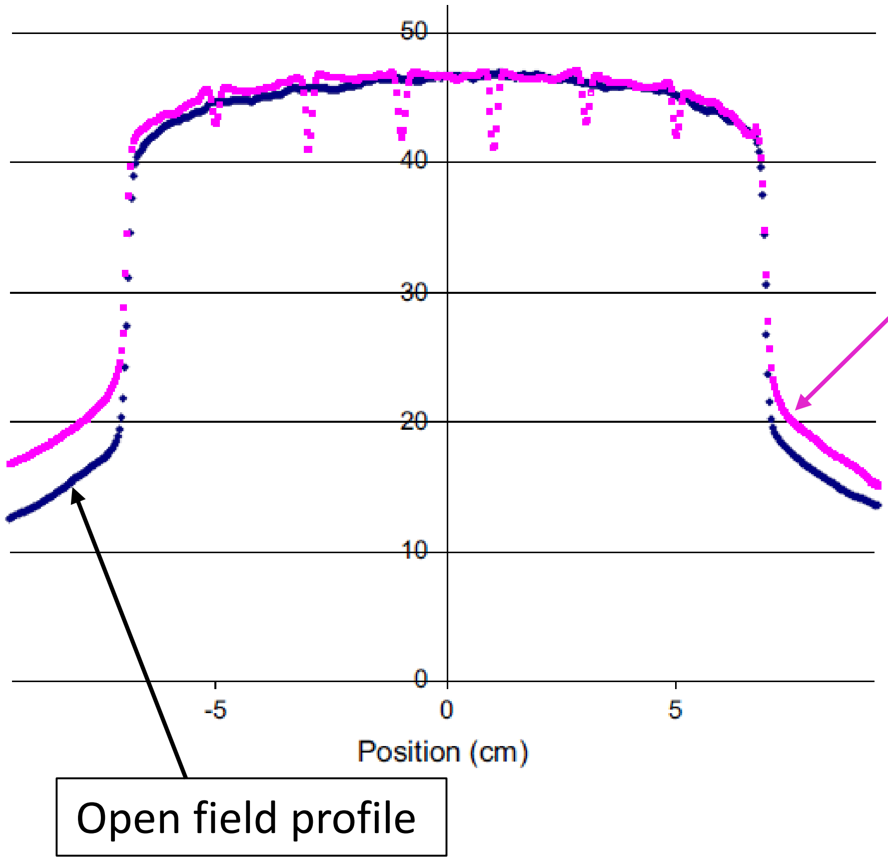
Profiles acquired with a linear array:

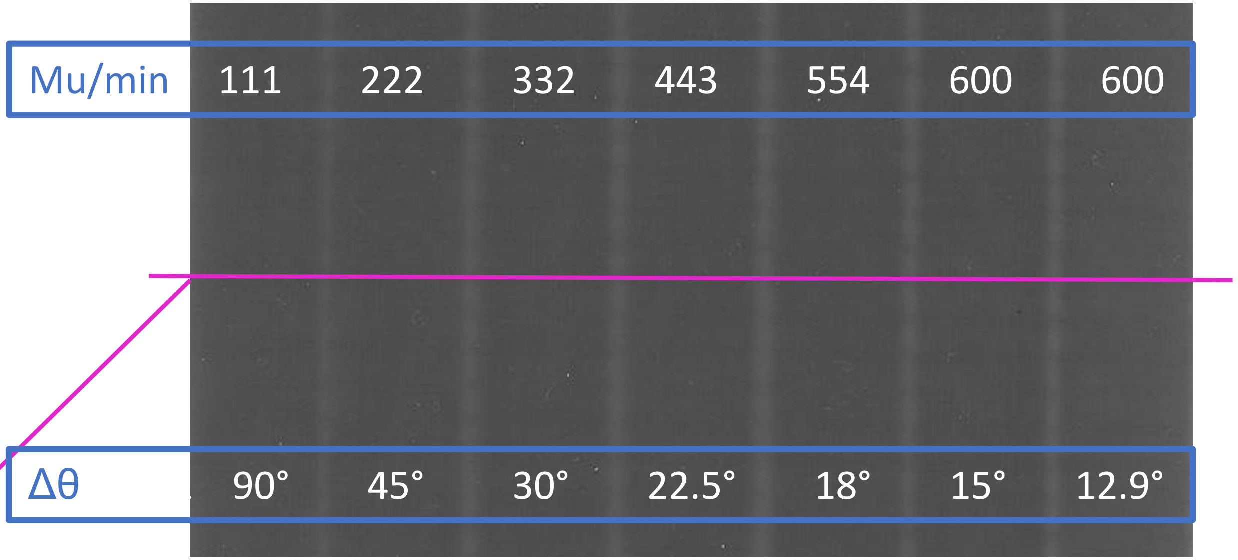
a) dose rate 37 MU/min, gantry angle 150°, clockwise motion
b) various dose rates, gantry angle 190°, clockwise motion

Bedford et al. IJROBP 2009

VMAT dose rate/ gantry speed accuracy

- Tolerance: 2%





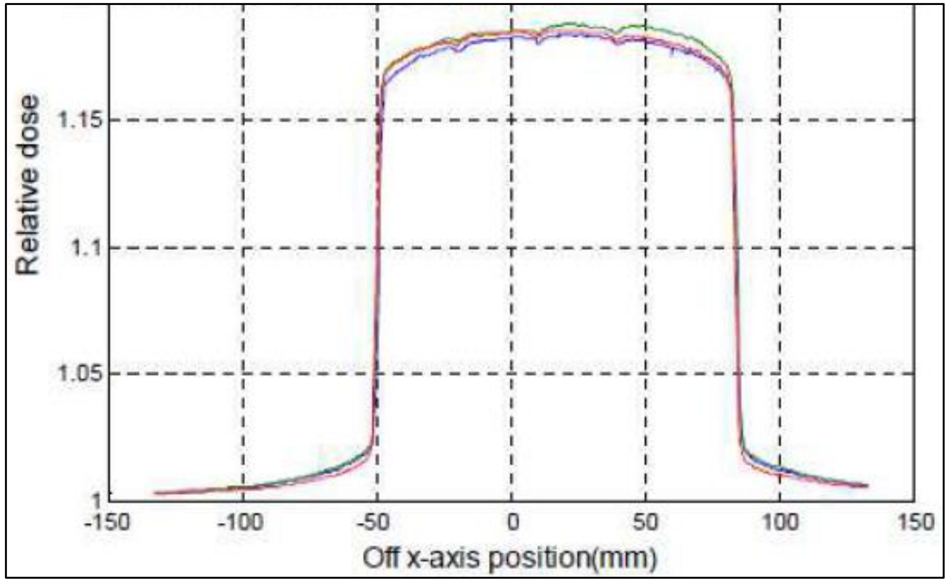
➢ Seven strips delivered with rapid arc combining different dose-rates, gantry ranges and gantry speeds to give the same MU for each portion of the field.

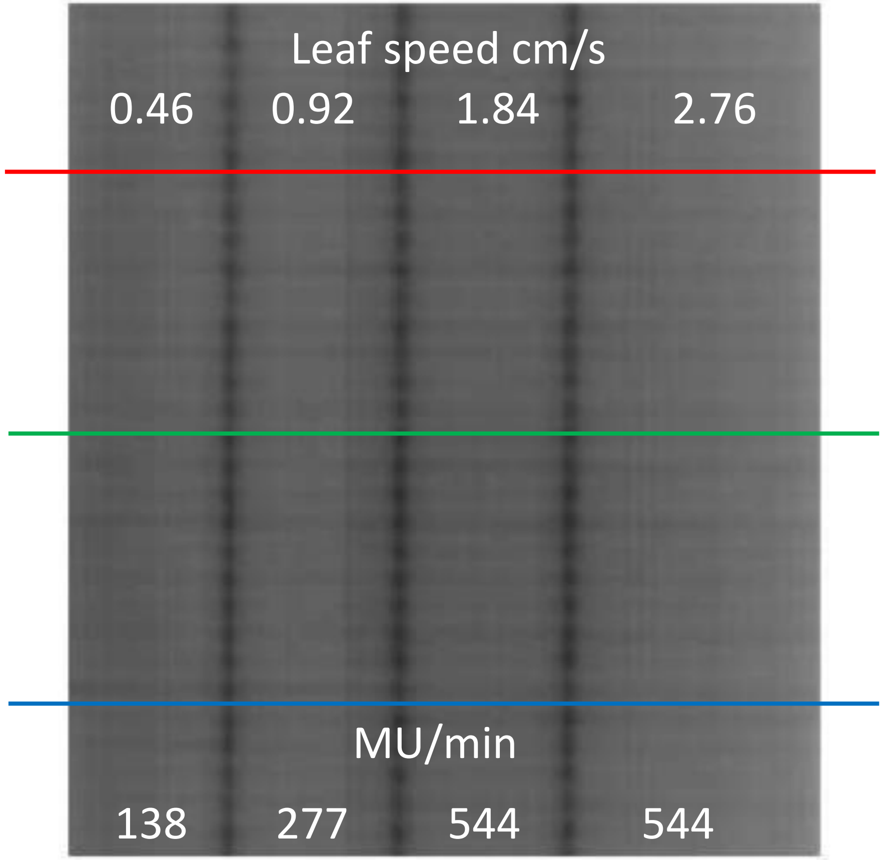
Ling et al. IJROBP 2008

VMAT dose-rate/ MLC speed accuracy

- Tolerance: 2%

➢ Repeat the previous test with four strips giving the same dose with sliding windows at different leaf speeds .
➢ Compare the profiles with the open field

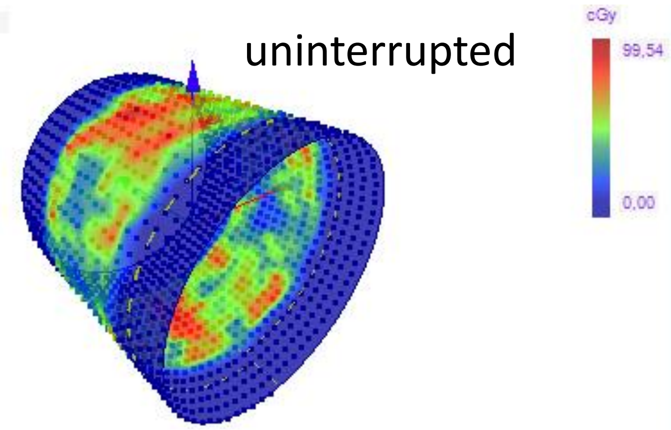


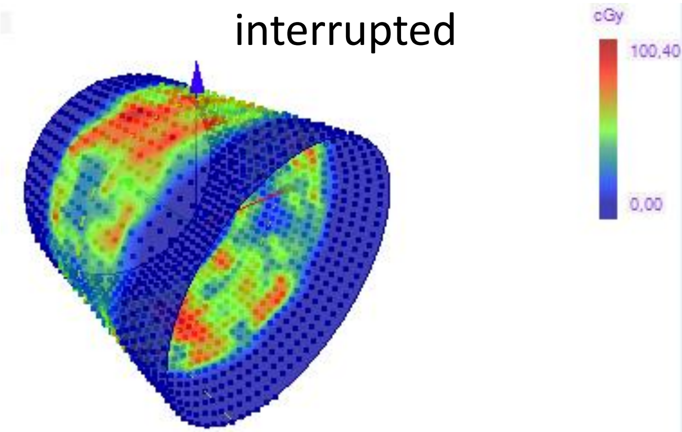


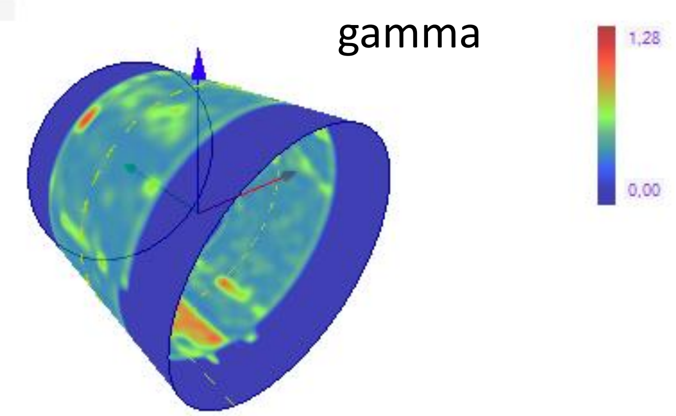
Ling et al. IJROBP 2008

Interruption/Resumption Test

- Use benchmark end-to-end test that includes measurement of dose distribution and absolute dose at a point, interrupt beam in middle of delivery and continue treatment to completion.
- Tolerance: 98% of points in agreement to 2% and 2 mm compared with reference uninterrupted delivery

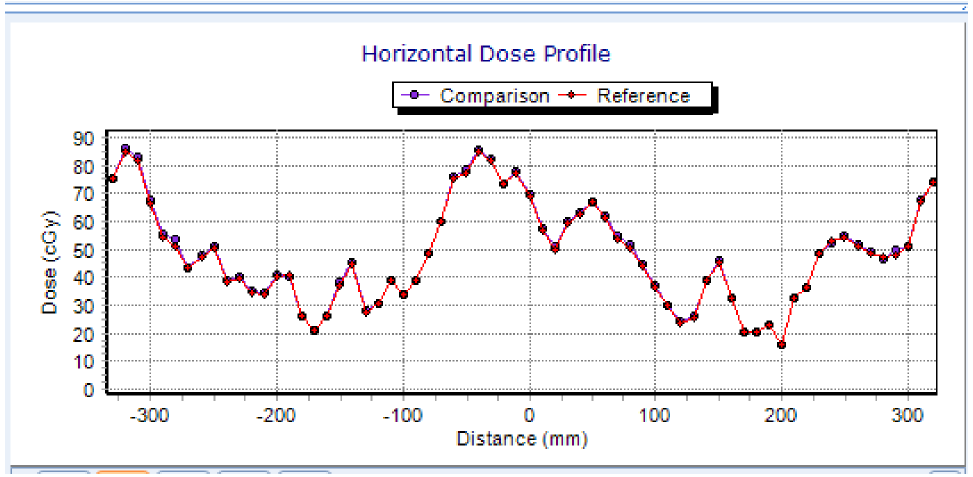






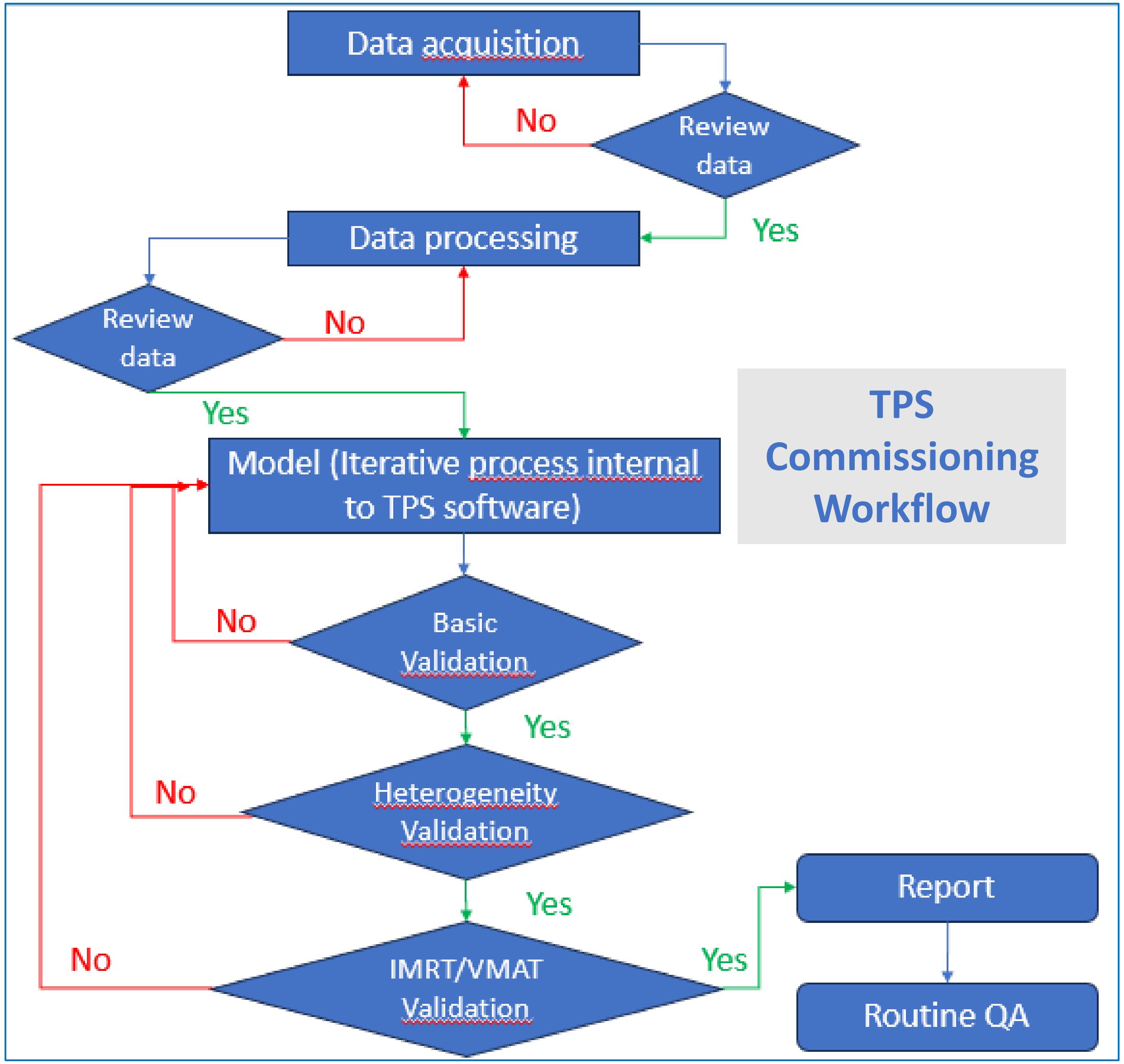
Analysis Results

Evaluated Detectors:	829
Detectors (Tγ ≤ 1):	823
Pass Rate (Tγ ≤ 1):	99,3(%)
Maximum Tγ:	1,28
Beam On (Ref):	166,55(sec)
Beam On (Comp):	167,30(sec)



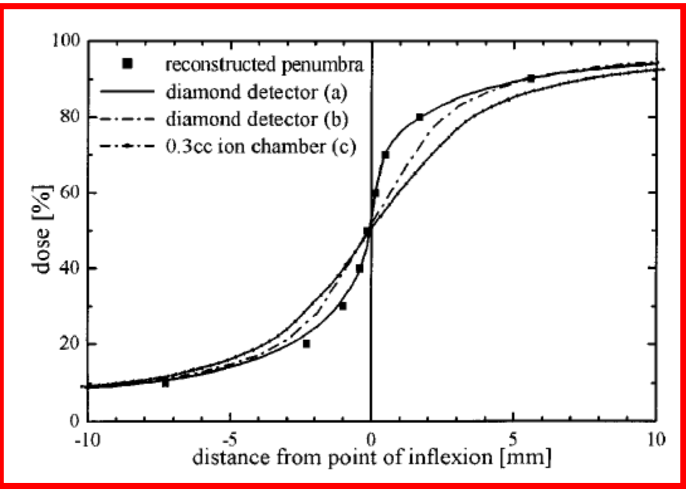
TPS commissioning

- ➢ Responsable for the majority of dose delivery failures (up to 68% , source IROC audits*)
- ➢ Intensity modulated techniques are an extension of 3D, but with additional issues related to:
  - Beam data acquisition
  - Beam modeling
  - Inverse Optimization/Leaf sequencing
  - Dose calculation.
- ➢ Guidelines:
  - IAEA TRS-430
  - AAPM TG-53, TG 119, TG-157, TG 218
  - AAPM Medical Physics Practice Guideline 5.a (TG 244)



* Carson et al. IJROBP

Data acquisition for IMRT/VMAT delivery



Minimum requirements for IMRT/VMAT TPS commissioning:

- verify both small fields and MLC characteristic :
  - PDDs down to field size ≤ 2x2 cm^2 for comparison with dose calculations
  - Small field output factors (down to 2 × 2 cm^2 or smaller) should be measured for beam modeling and/or verification.
  - Leaf-end penumbra with high resolution detector
  - MLC intraleaf and interleaf transmission and leaf gap

Detector	Use	Comment	References
Small field detectors	Small field scanning & output factors. IMRT/VMAT point measurement. MLC intraleaf measurement & penumbra	Carefully select the detector type and size to fit the application. When scanning for penumbra, diodes are recommended.	TG-106 (Das et al.) TG-120 (Low et al.) IAEA TSR 483
Large ion chamber	Aggregate dose transmission	Interleaf transmission	Lo Sasso et al.
Film and/or array detector	2D dose distribution including planar fluence maps, intraleaf measurements	Absolute dosimetry preferred; relative dosimetry adequate. Desirable if the device can be mounted on the gantry and/or in a phantom at different geometries	TG-106 (Das et al.) TG-120 (Low et al.) IAEA TSR 430

Detectors suitable for TPS commissioning

References: AAPM TG 244

Review of data

- Acquired data must be reviewed for potential setup and measurement errors
- Data should be compared, if possible, to a reference dataset from the same type of, or nearly identical, machine to identify systematic anomalies
- MLC transmission factors should be compared to the published results obtained with the same MLC and energy.

OF vs different Varian machine Types (IROC)

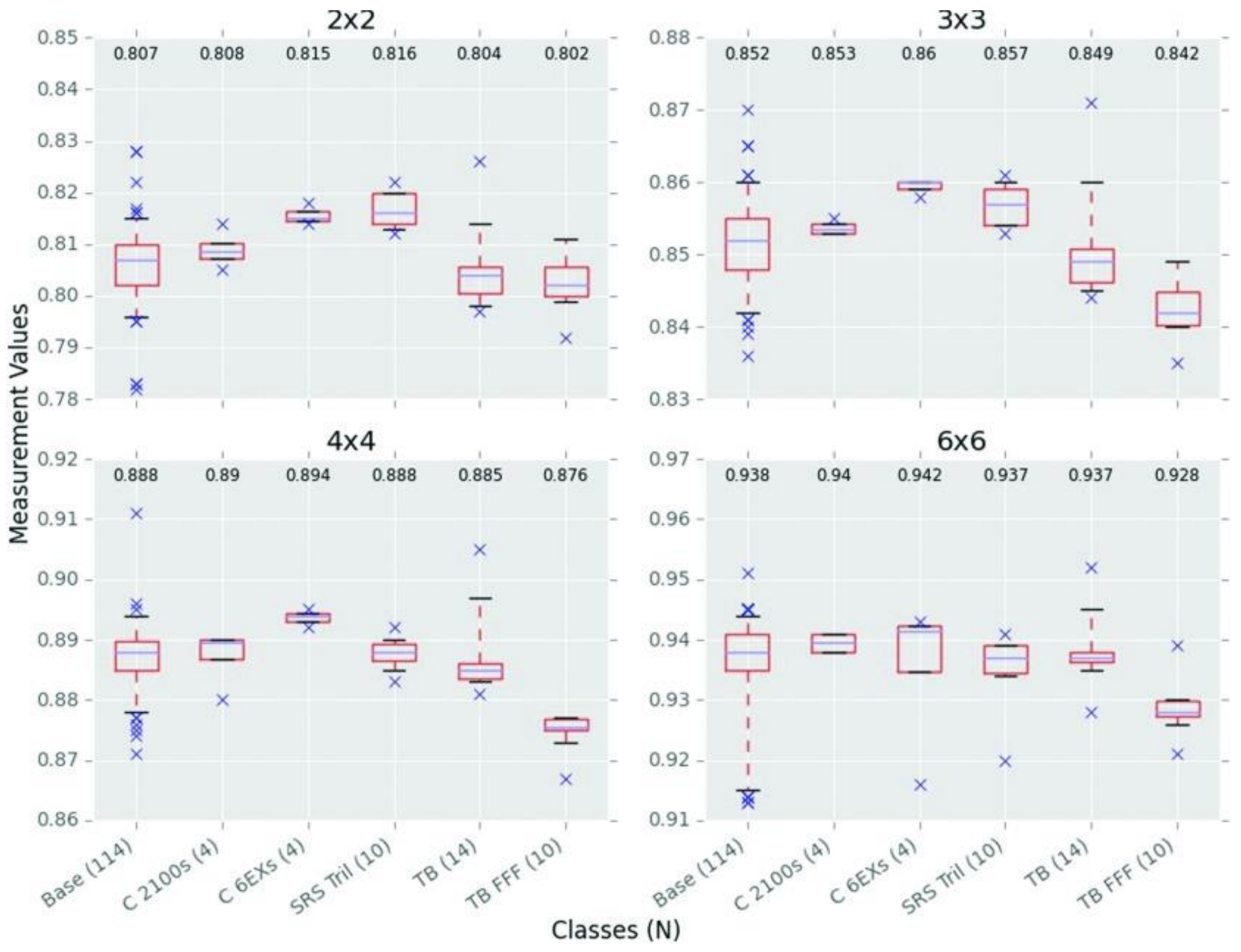
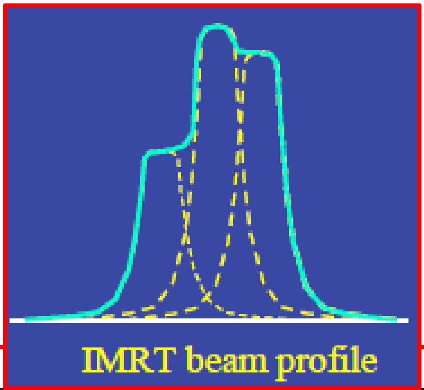


Figure from Kerns et al.Technical Report: Reference photon dosimetry data for Varian accelerators based on IROC-Houston site visit data. Med Phys. 2016. doi: 10.1118/1.4945697.



Beam modeling in TPS software

Impact on beam penumbra, OF

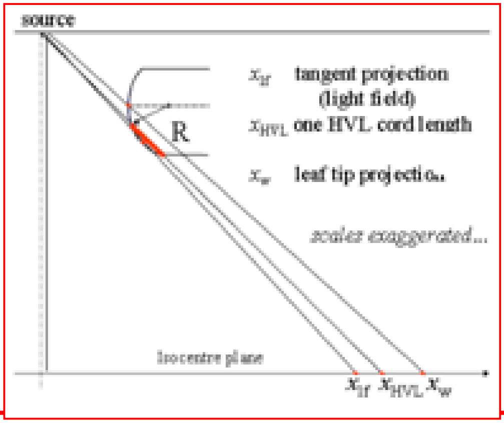
Sources

Source	Eff. dist. to source [cm]	XWidth [cm]	YWidth [cm]	Weight
Primary	-	0.070	0.090	-
Flattening filter	12.50	1.625	-	0.07632
Electrons	-	11.000	-	0.00752

Weight of flattening filter electron source: 0.004

Collimator calibration

Collimator	Offset [cm]	Gain	Curvature [1/cm]
YJaws	0.010	0.0040	0.00030
XJaws	-0.010	0.0040	0.00020
MLC x-position	0.010	-0.0040	0.00050
MLC y-position	-	0.0040	-



Positional accuracy, Critical for Step & Shoot

Collimator position

Collimator	Eff. dist. to source [cm]	Transmission
YJaws	36.70	-
XJaws	44.50	0.00100
MLC	53.50	0.01650

affects all type of intensity modulation

Additional MLC parameters

Tongue and groove [cm]: 0.025

Leaf tip width [cm]: 0.370

Important for DMLC based techniques

Modeling parameters impact differently according to the implemented technique.
A good model for IMRT Step&Shoot can be bad for dynamic/VMAT techniques

Beam modeling impacts on dosimetry errors

Original Article

Photon beam modeling variations predict errors in IMRT dosimetry audits

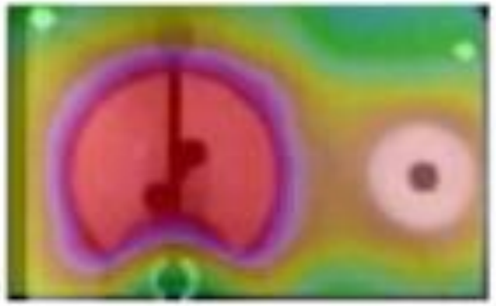
Mallory C. Glenn [a], Fre'Etta Brooks [b,c], Christine B. Peterson [c,d], Rebecca M. Howell [b,c], David S. Followill [b,c], Julianne M. Pollard-Larkin [b,c], Stephen F. Kry [b,c,*]

[a] Department of Radiation Oncology, University of Washington, Seattle; [b] Department of Radiation Physics, The University of Texas MD Anderson Cancer Center; [c] The University of Texas MD Anderson Cancer Center UTHealth Graduate School of Biomedical Sciences; and [d] Department of Biostatistics, The University of Texas MD Anderson Cancer Center, Houston, United States

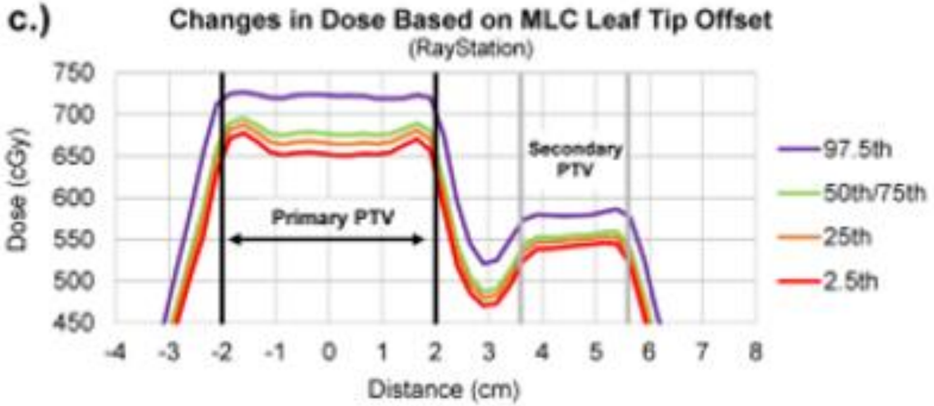
- ➢ Atypical beam modeling parameters are associated with failing phantom audits.

a.)

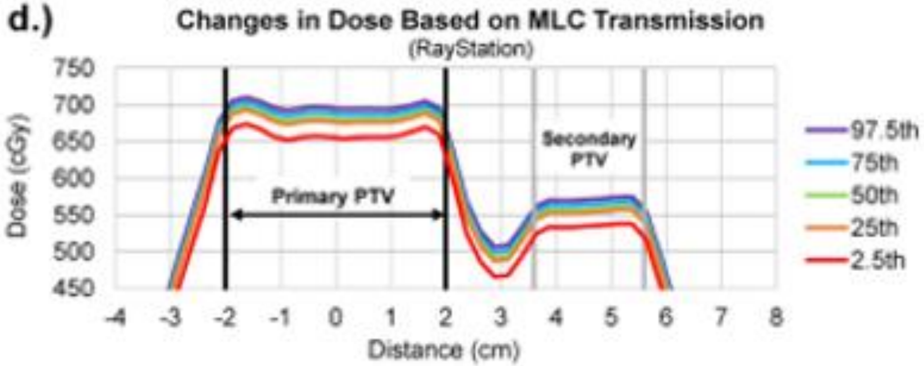
b.)



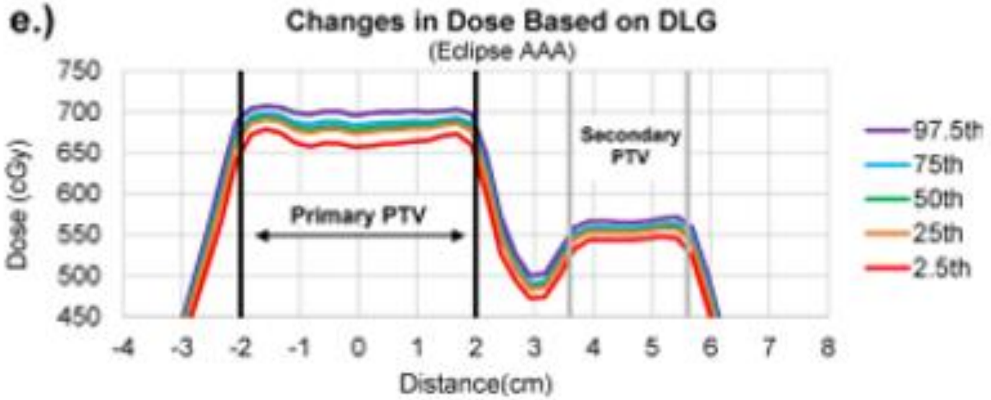
c.)



d.)

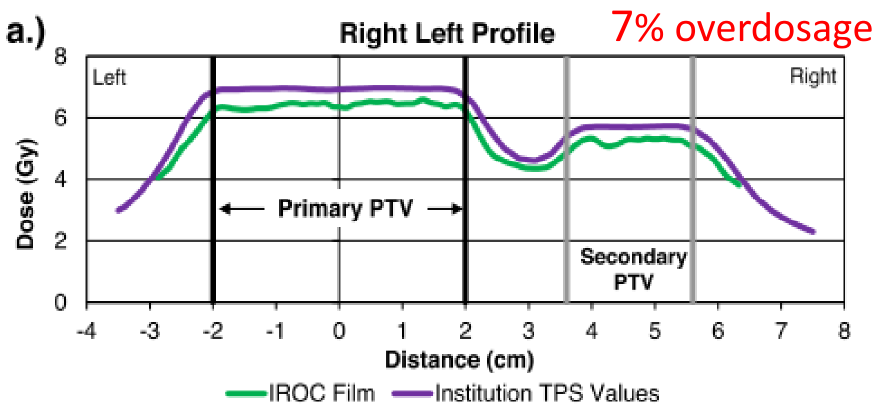


e.)



……cont

Profiles obtained varying the DLG parameters (Eclipse AAA): a) DLG 91° percentile; b) DLG lowered to 0.06 cm (1° percentile); good agreement was definetively found setting DLG to 0.125 cm



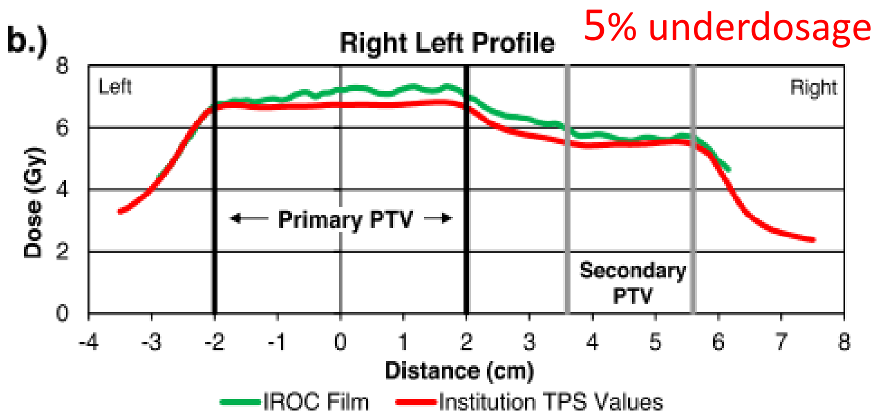
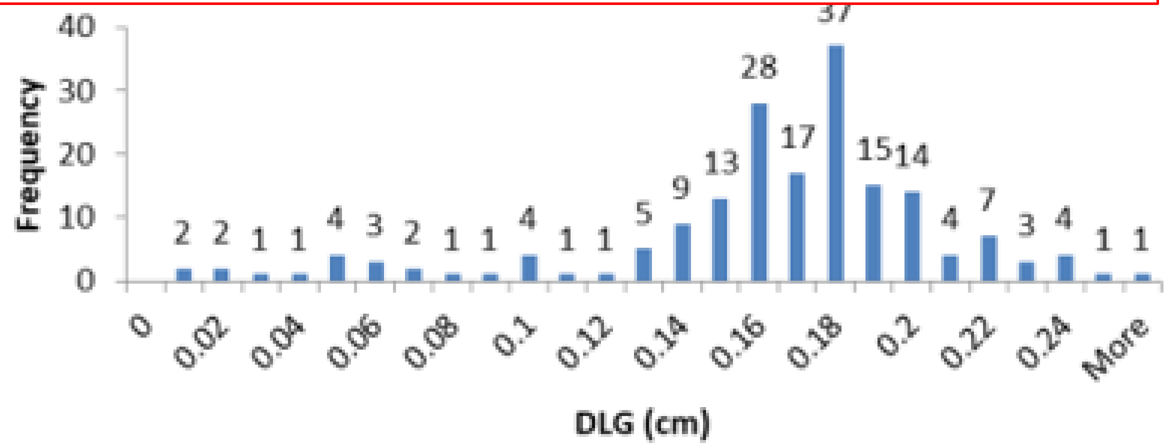


Table 1

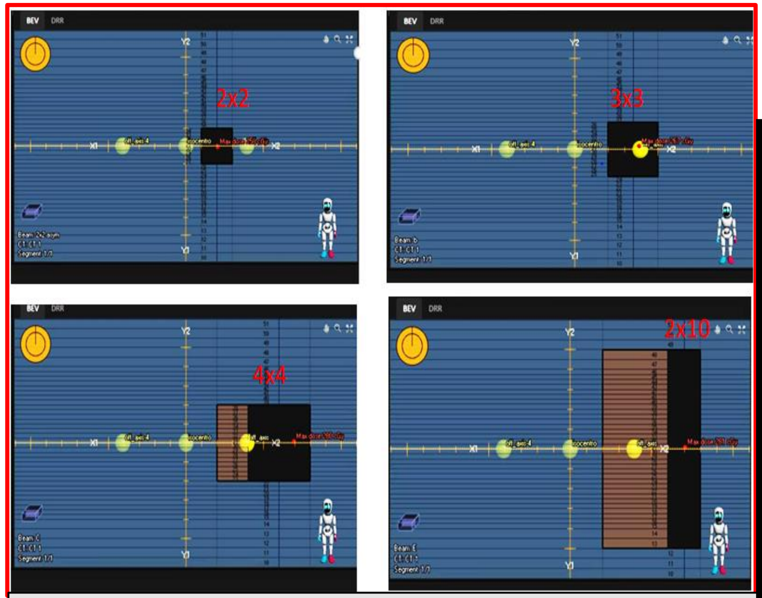
Treatment planning system beam modeling parameters requested via IROC Houston surveys and their range of dose effects (based on the reported spread in values), as previously determined by phantom dose calculations, for a common base Varian linac model equipped with Millennium120 MLC (e.g. Trilogy, 2100iX, etc.) using 6 MV photons [13,20].

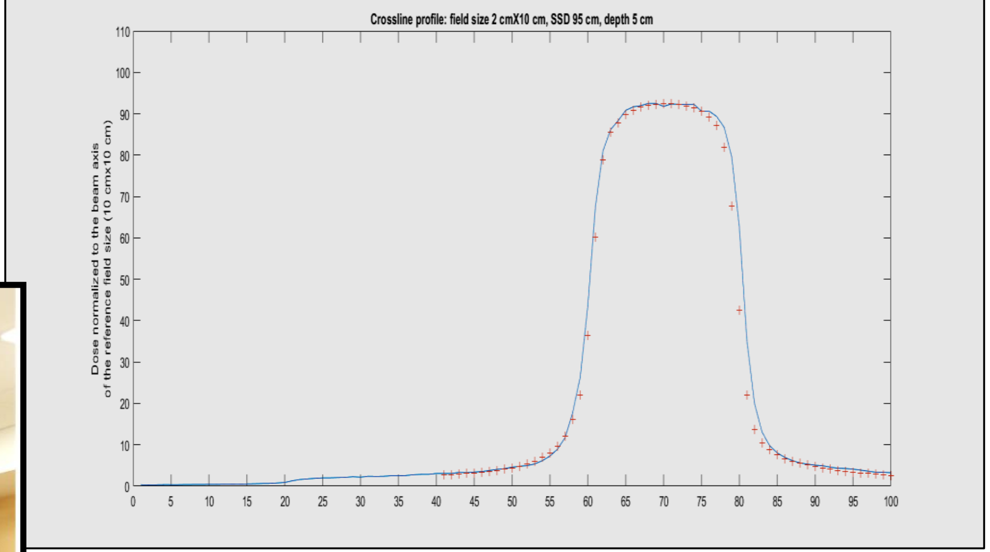
TPS Parameter	Estimated Dose Effects							
	2.5th Percentile		*10th Percentile*		*90th Percentile*		*97.5th Percentile*	
	Parameter Value	Dose Effect (vs. 50th percentile)	Parameter Value	Dose Effect (vs. 50th percentile)	Parameter Value	Dose Effect (vs. 50th percentile)	Parameter Value	Dose Effect (vs. 50th percentile)
Eclipse AAA								
Effective Target Spot Size X and Y [mm]	0.0000	0.0%	0.0000	0.0%	0.5000	0.0%	1.0000	0.0%
MLC Transmission Factor	0.0118	−1.1%	0.0134	−0.7%	0.0200	+0.8%	0.0200	+0.8%
Dosimetric Leaf Gap [cm]	0.1000	−3.6%	0.1388	−1.5%	0.2000	+1.2%	0.2300	+2.8%
RayStation								
Primary Source X Width and Y Width [cm]	0.05000	0.0%	0.04000	0.0%	0.09700	0.0%	0.12345	0.0%
MLC Transmission	0.0070	−4.0%	0.0070	−4.0%	0.0250	+2.3%	0.0250	+2.3%
Tongue and Groove [cm]	0.0100	+1.1%	0.0100	+1.1%	0.0500	−0.3%	0.0500	−0.3%
Leaf Tip Width [cm]	0.1770	−1.6%	0.1860	−1.4%	0.5000	+1.9%	0.5000	+1.9%
MLC Position Offset [cm]	0.0000	−3.6%	0.0000	−3.6%	0.1160	+6.7%	0.1160	+6.7%
MLC Position Gain	0.0000	0.0%	0.0000	0.0%	0.0150	0.0%	0.0150	0.0%
MLC Position Curvature [1/cm]	0.0000	0.0%	0.0000	0.0%	0.0010	+0.2%	0.0010	+0.2%

Take home message: Check the consistency of your parameters with other institutions



TPS verification of the basic photon model





Adjust and recheck the model with field configurations different from those used for modeling (i.e. small MLC shaped, on/off axis, different SSD…)

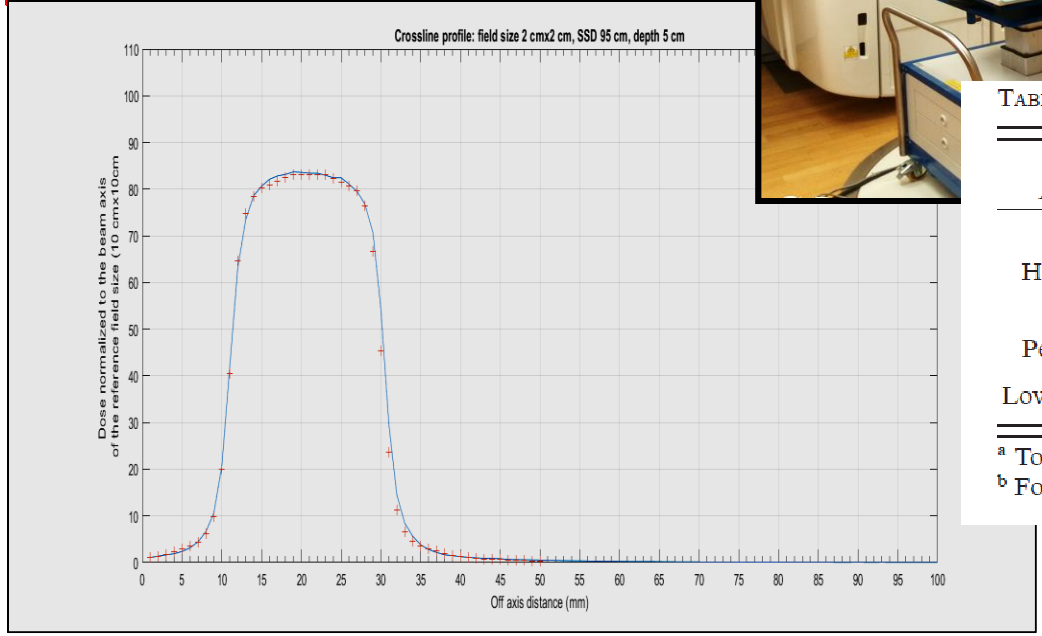


TABLE 5. Basic TPS photon beam evaluation methods and tolerances.

Region	*Evaluation Method*	*Tolerance*[a] *(consistent with IROC Houston)*
High dose	Relative dose with one parameter change from reference conditions	2%
	Relative dose with multiple parameter changes[b]	5%
Penumbra	Distance to agreement	3 mm
Low-dose tail	Up to 5 cm from field edge	3% of maximum field dose

[a] Tolerances are relative to local dose unless otherwise noted.
[b] For example, off-axis with physical wedge.

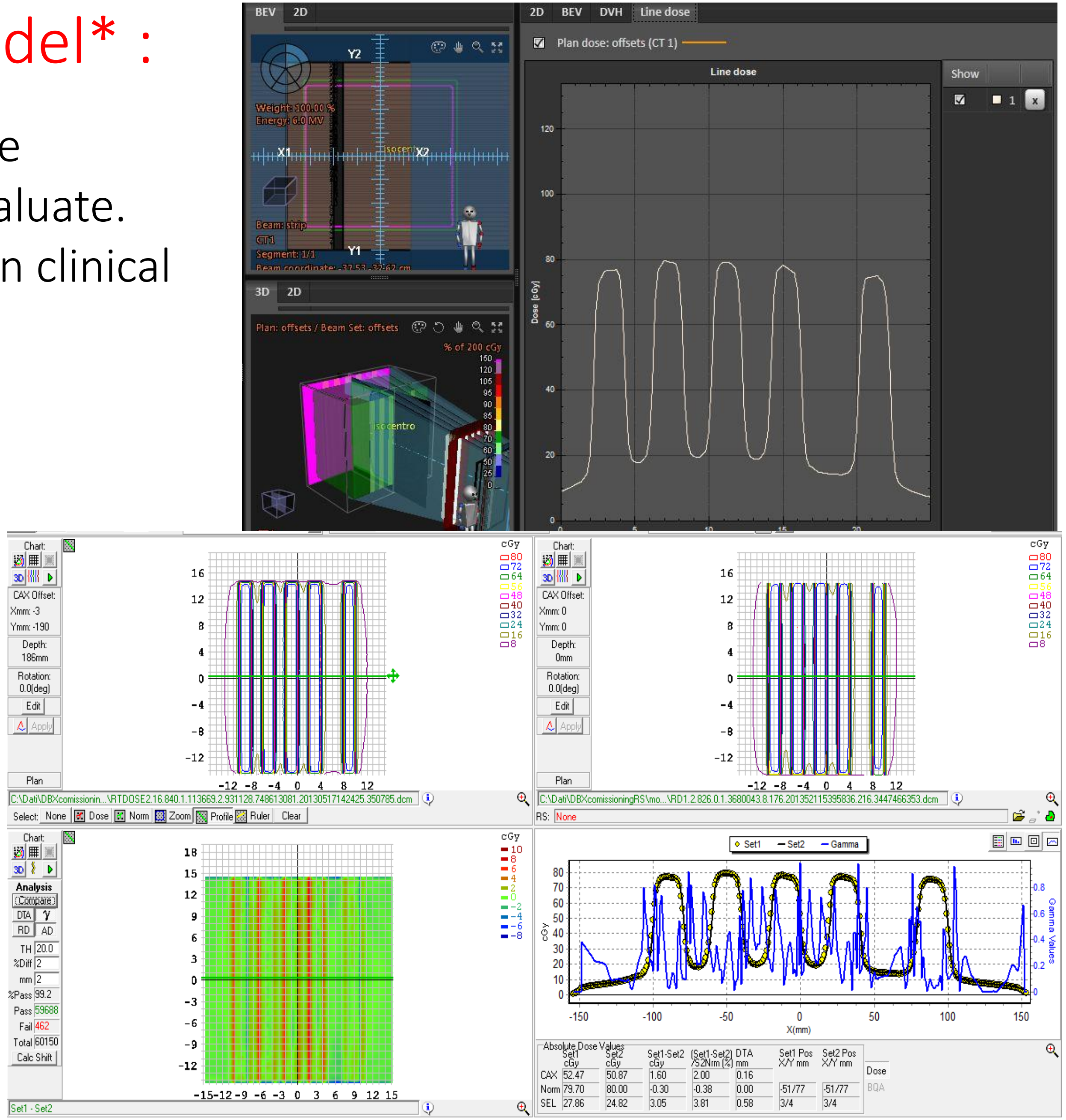
Table from AAPM Medical Physics Practice Guideline 5.a (TG 244)

Verification/tuning of the IMRT model* :

- Determine if the beam/MLC parameters are accurate using simple situations easy to evaluate.
- Determine the level of accuracy to expect in clinical situations.

Pipeline:

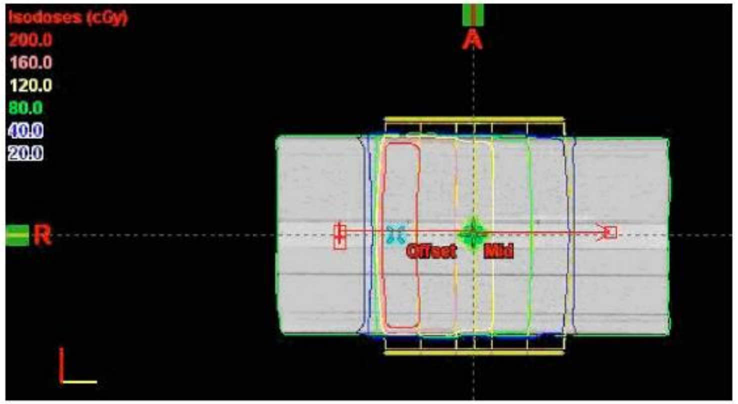
1) Start with single beams on a simple, flat phantom.
2) Progress using controlled intensity patterns for multiple beams
3) Apply multiple beams treating hypothetical targets
4) Progress to testing multiple beams treating hypothetical targets in anthropomorphic phantoms.



*AAPM TG 82 Med.Phys. 2003.DOI: 10.1118/1.1591194.

Basic verification tests for IMRT components: examples

Measure point dose with ion chambers and 2D dose distribution with films/ arrays



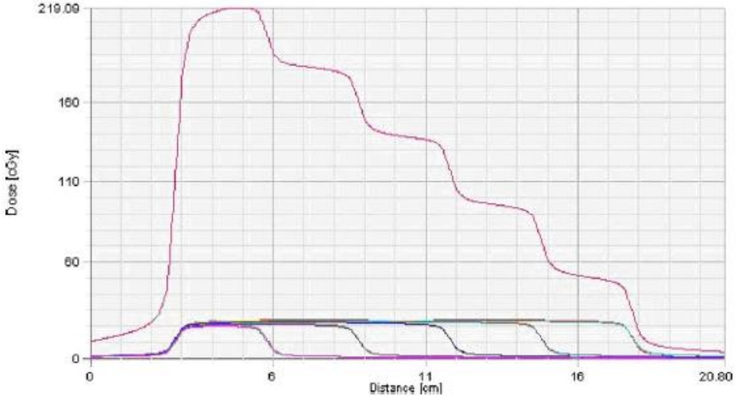


FIG. 1. Dose profile through central plane for bands. The lower curves are the individual contributions from each subfield (band); the upper curve is the summation.

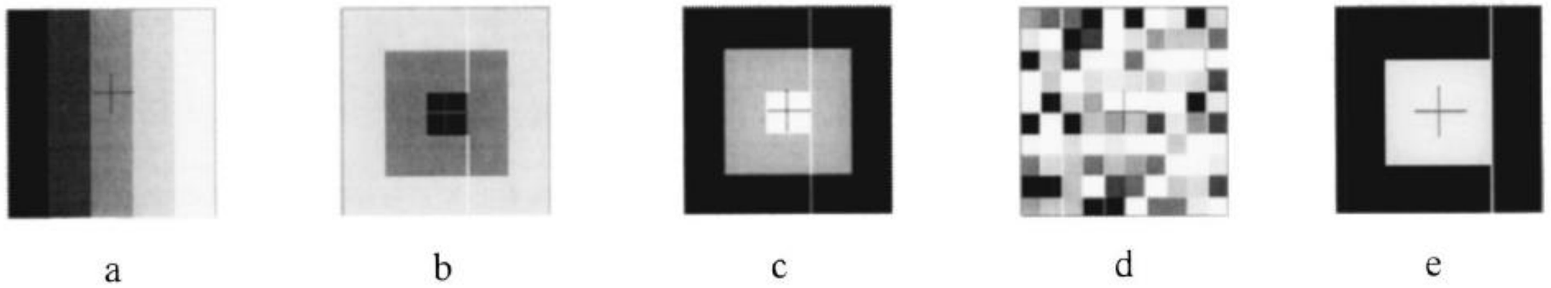


FIG. III.3. Examples of user-controlled intensity shapes used for commissioning tests.

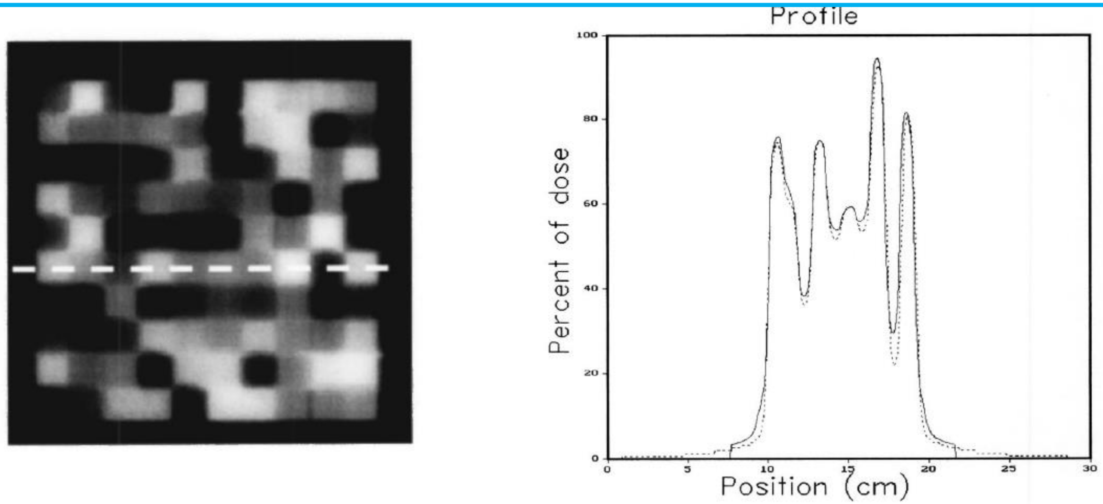


FIG. III.4. The dose profile measured with film across one line of a random intensity pattern (plan=dotted, film=solid), showing some systematic differences in low intensity regions.

AAPM TG 82 Med Phys. 2003.DOI: 10.1118/1.1591194.
AAPM TG 119 (preliminary test 2).

TPS verification procedures for IMRT/VMAT:

TABLE 7. VMAT/IMRT test summary.

Test	*Objective*	*Description (example)*	*Detector*	*Ref*
7.1	Verify small field PDD	≤ 2×2 cm^2 MLC shaped field, with PDD acquired at a clinically relevant SSD	Diode or plastic scintillator	Yunice et al.[16]
7.2	Verify output for small MLC-defined fields	Use small square and rectangular MLC-defined segments, measuring output at a clinically relevant depth for each[a]	Diode, plastic scintillator, minichamber or microion chamber	Cadman et al.[58]
7.3	TG-119 tests	Plan, measure, and compare planning and QA results to the TG119 report for both the Head and Neck and C-shape cases	Ion chamber, film and/or array	TG-119 (Ezzell et al.[37])
7.4	Clinical tests	Choose at least 2 relevant clinical cases; plan, measure, and perform an in-depth analysis of the results	Ion chamber, film and/or array	Nelms et al.[42]
7.5	External review	Simulate, plan, and treat an anthropomorphic phantom with embedded dosimeters.	Various options exist[b]	Kry et al.[39]

[a] A bar pattern scanned with a diode can be used to obtain additional absolute dose profile comparison in the direction perpendicular to MLC movement

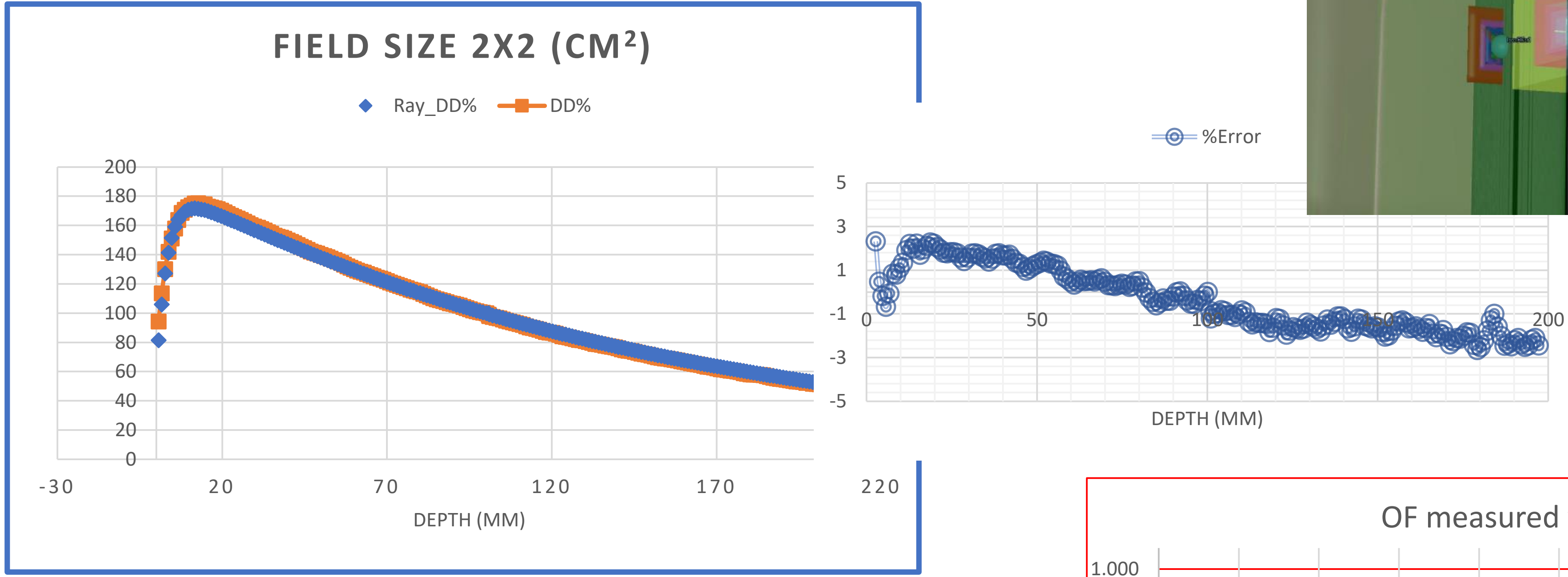
[b] If IROC Houston service is used, they typically employ TLDs and radiochromic film. Certain commercial phantoms can accommodate ion chambers for point dose measurements

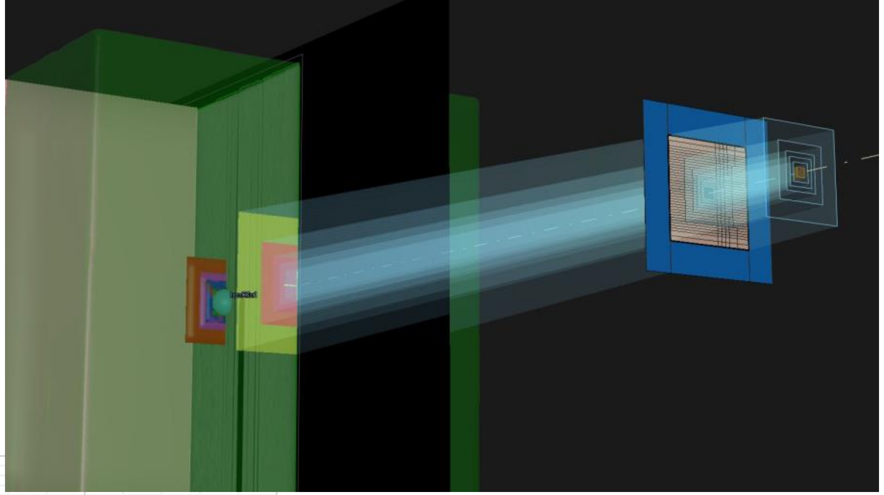
Check/adjust the source model

Check/adjust the MLC/dMLC parameters.

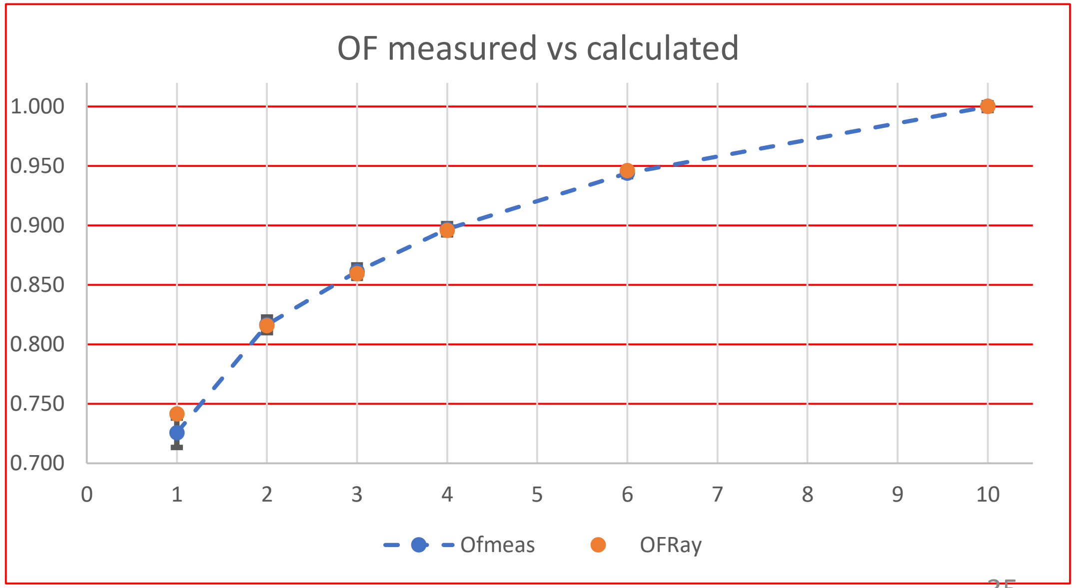
Table from AAPM Medical Physics Practice Guideline 5.a (TG 244)

IMRT validation steps 1 & 2: small MLC field PDD and OF(7.1/7.2)





Field Side (cm)	Of_{meas}	OF_{Ray}	IROC
1	0.726 ± 0.006	0.742	NA
2	0.816 ± 0.003	0.816	0.816
3	0.861 ± 0.003	0.859	0.857
4	0.897 ± 0.005	0.896	0.885
6	0.944 ± 0.003	0.946	0.937
10	1.000 ± 0.003	1.000	1.000



IMRT validation step 3: the TG 119 test suite
(http://www.aapm.org/pubs/tg119/default.asp)

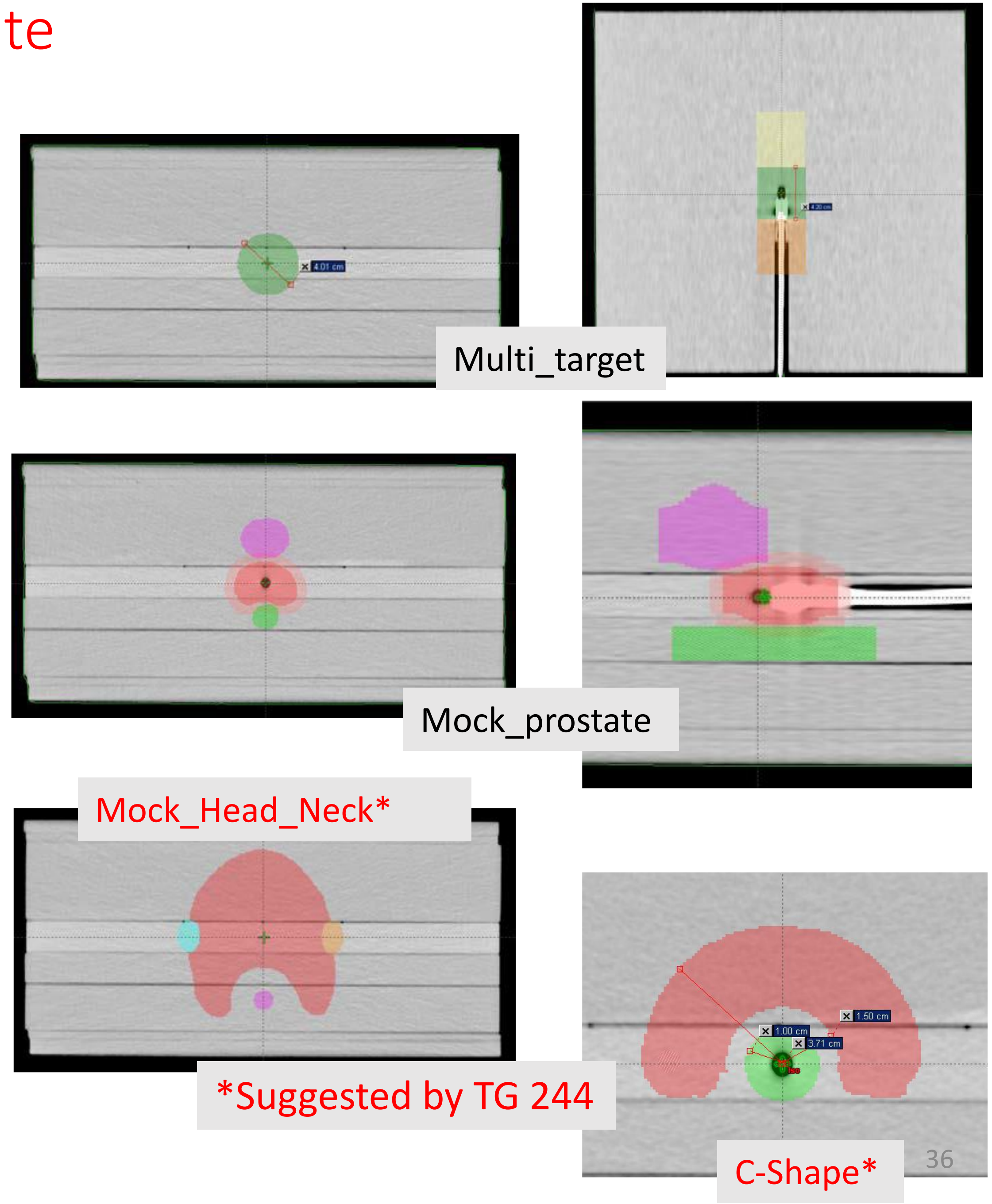
Aim: to assess the overall accuracy of planning and delivery of IMRT treatments.

The test suite includes:

- Rt-structures corresponding to Targets/OARs contoured in rectangular water equivalent slab phantom
- Objective and constraints to plan each test.
- Beam arrangement.

Dose agreement results from a multi-institutional study proposed as baseline for IMRT commissioning :

a) Point measurements with ion chamber in high and low dose regions
b) Film dosimetry in a coronal plan (gamma 3%/ 3mm)



Report from AAPM Task Group 119 Medical Physics, Vol. 36, No. 11, November 2009

TG 119 baselines

- 10 institutions passing credentialing audits
- dMLC-SMLC-binaryMLC techniques employed
- Multiple TPS (Eclipse, Pinnacle, Tomo and other…)

TABLE VII. High dose point in the PTV measured with ion chamber: [(measured dose) −(plan dose)]/prescription dose, averaged over the institutions, with associated confidence limits.

Test	Location	Mean	Standard deviation (σ)	Maximum	Minimum
Multitarget	Isocenter	0.001	0.017	0.030	−0.020
Prostate	Isocenter	−0.001	0.016	0.022	−0.026
Head and neck	Isocenter	−0.010	0.013	0.011	−0.036
CShape (easier)	2.5 cm anterior to isocenter	−0.001	0.028	0.038	−0.059
CShape (harder)	2.5 cm anterior to isocenter	−0.001	0.036	0.054	−0.061
Overall combined		−0.002	0.022		
Confidence limit=(|mean|+1.96σ)			0.045		

TABLE IX. Low dose point in the avoidance structure measured with ion chamber: [(measured dose) −(plan dose)]/prescription dose, averaged over the institutions, with associated confidence limits.

Test	Location	Mean	Standard deviation (σ)	Maximum	Minimum
Multitarget	4 cm inferior to isocenter	−0.008	0.019	0.014	−0.050
Prostate	2.5 cm posterior to isocenter	0.000	0.018	0.030	−0.025
Head and neck	4 cm posterior to isocenter	0.004	0.024	0.061	−0.017
CShape (easier)	Isocenter	0.010	0.024	0.050	−0.037
CShape (harder)	Isocenter	0.009	0.025	0.055	−0.021
Overall combined		0.003	0.022		
Confidence limit (|mean|+1.96σ)			0.047		

σ increase with plan complexity

TABLE XI. Composite film: Percentage of points passing gamma criteria of 3%/3 mm, averaged over the institutions, with associated confidence limits.

Test	Location	Mean	Standard deviation (σ)	Maximum	Minimum	Number of submissions
Multitarget	Isocenter	99.1	0.9	100	97.5	8
Prostate	Isocenter	98.0	2.24	99.8	94.2	7
	2.5 cm posterior	93.2	7.6	99.9	85	3
Head and neck	Isocenter	96.2	3.0	100	92.4	8
	4 cm posterior	97.6	1.5	98.9	95.6	4
CShape (easier)	Isocenter	97.6	3.9	100	88.9	7
	2.5 cm anterior to isocenter	93.9	5.0	99.6	87.9	5
CShape (harder)	Isocenter	94.4	6.0	99.4	86.2	5
	2.5 cm anterior to isocenter	93.0	7.2	99.9	81.3	5
Overall combined		96.3	4.4			
Confidence limit=(100−mean)+1.96σ				12.4 (i.e., 87.6% passing)		

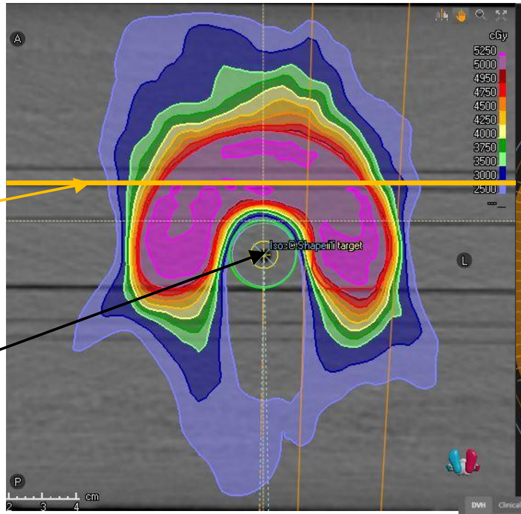
Limits:

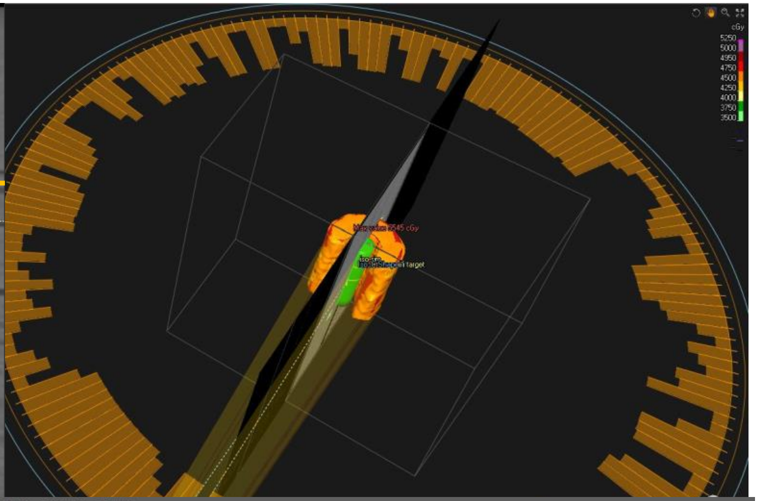
a) Passing rate criteria too lenient to detect modeling errors (Nelms et al.)
b) Not representative of real plan complexity : SIB, sizable volumes.

CShape example:

Radiochromic Film EBT3

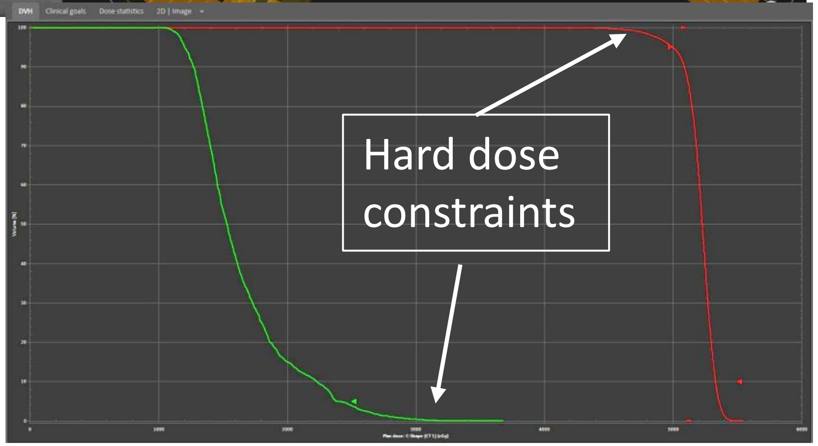
Film Passing Rate (TG 119):
γ (3%, 3 mm) : 94.5%



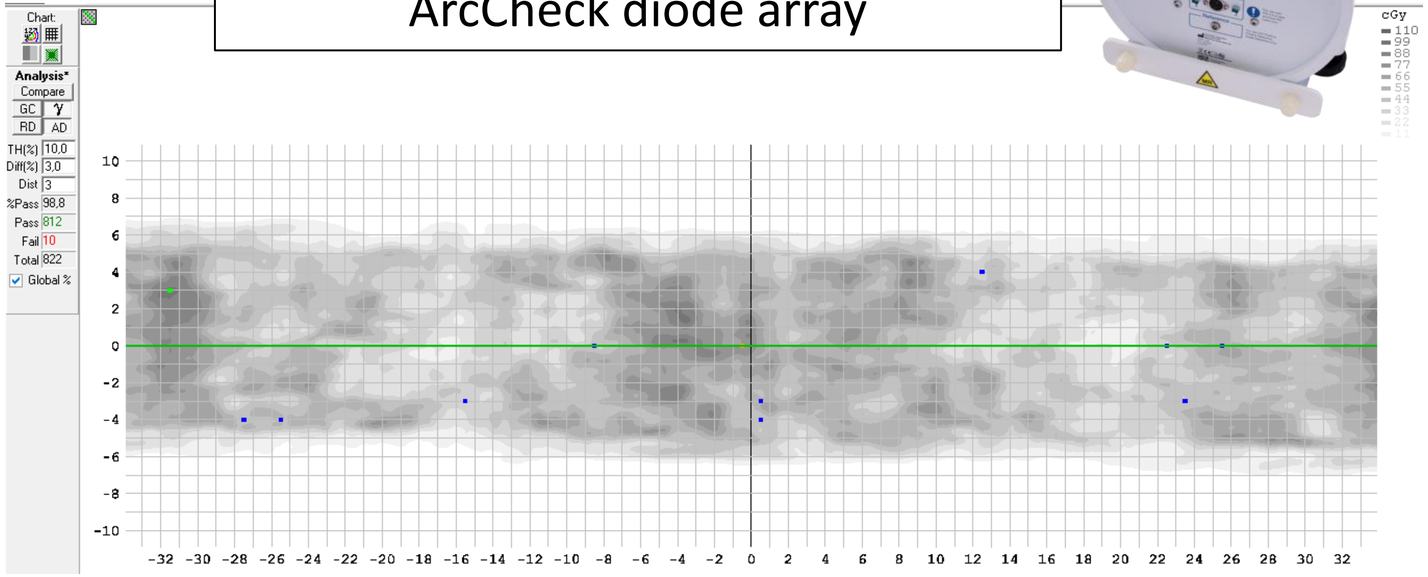


Micro IC

$Dose_{Meas}$	$Dose_{Calc}$	Δ%
58.3 cGy	57.54 cGy	1.3%



ArcCheck diode array



Passing Rate (TG 119):
γ (3%, 3 mm) : 98.8%
(visible dots represent failing points)

a) TG119 passing criteria too lenient

Inaccurate (volume-averaged) dose profiles entered into beam model

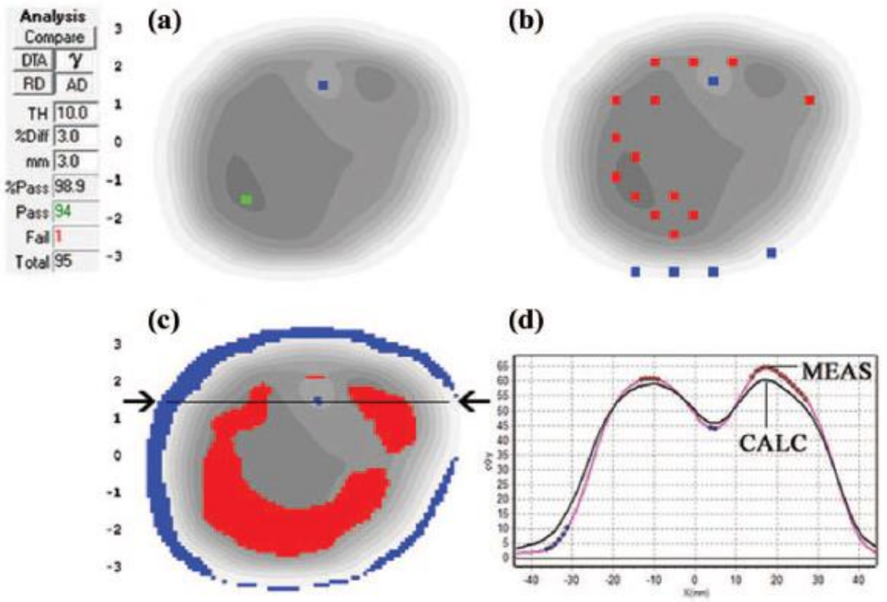


FIG. 3. (a) 3%G/3 mm gamma failing points and (b) 2%L/2 mm gamma failing points based on a diode array at 5 cm depth, 100 cm SDD. In both (a) and (b), the visible dots represent failing points. (c) 2%L/2 mm gamma failing points for EPIDose analysis at same virtual depth and (d) dose profile through the horizontal line indicated by the arrows in panel (c), with the black line extracted from the TPS dose grid and the line with dots highlighted from the measurement.

Setting in TPS causes failure to account for tongue-and-groove effects

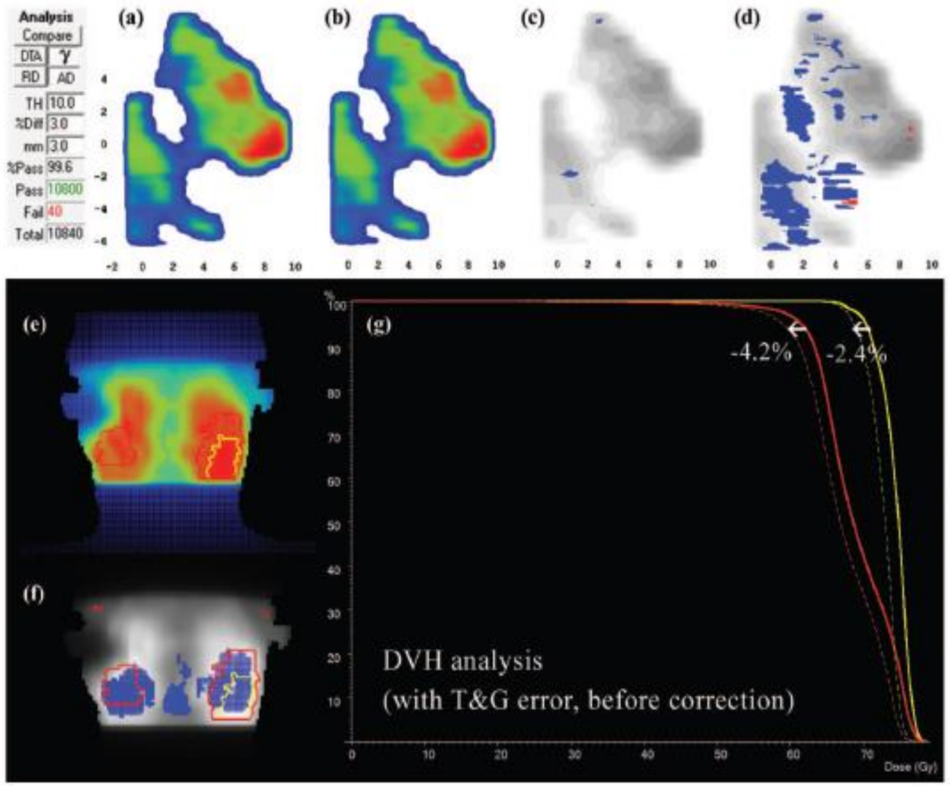


FIG. 2. Absolute dose planes at 5 cm depth, 100 cm SDD for (a) measured and (b) calculated dose. (c) 3%G/3 mm gamma with failing points shown as the shaded region over the calculated plane in grayscale. (d) 2%L/2 mm gamma failing points showing a clear pattern of meas < calc, i.e., shaded regions showing gamma failing points. (e) Patient coronal TPS plane, (f) 3DVH-estimated dose differences (3DVH–TPS), and (g) estimated DVH errors showing lower MGDR target dose compared to planned.

Examples from Nelms et al. Evaluating IMRT and VMAT dose accuracy: Practical examples of failure to detect systematic errors when applying a commonly used metric and action levels. Med Phys 40 November 2013. http://dx.doi.org/10.1118/1.4826166

IMRT/VMAT updated tolerances for commissioning:

Dose agreement evaluated by true composite approach:

TABLE 8. VMAT/IMRT evaluation methods and tolerances.

Measurement Method	*Region*	*Tolerance*
Ion Chamber	Low-gradient target region	2% of prescribed dose < 1.5% optimal
	OAR region	3% of prescribed dose
Planar/Volumetric Array	All regions	2%/2 mm[a], no pass rate tolerance, but areas that do not pass need to be investigated
End-to-End	Low-gradient target region	5% of prescribed dose

[a] Application of a 2%/2 mm gamma criterion can result in the discovery of easily correctable problems with IMRT commissioning that may be hidden in the higher (and ubiquitous) 3%/3 mm passing rates.[39]

*Evaluation by local normalization is recommended by AAPM TG218 (it highlight the failures in high dose gradient regions, useful to tune the MLC model).
*Measurements based on planar/Volumetric Array systems are allowed if appropriated spatial resolution can be achieved

Table from AAPM Medical Physics Practice Guideline 5.a (TG 244) Journal of Applied Clinical Medical Physics, Vol. 16, No. 5, 2015

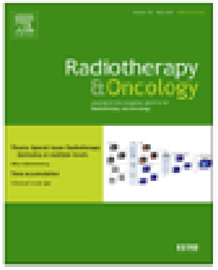
b) Need of realistic clinical scenarios: complexity matters.

Original Article

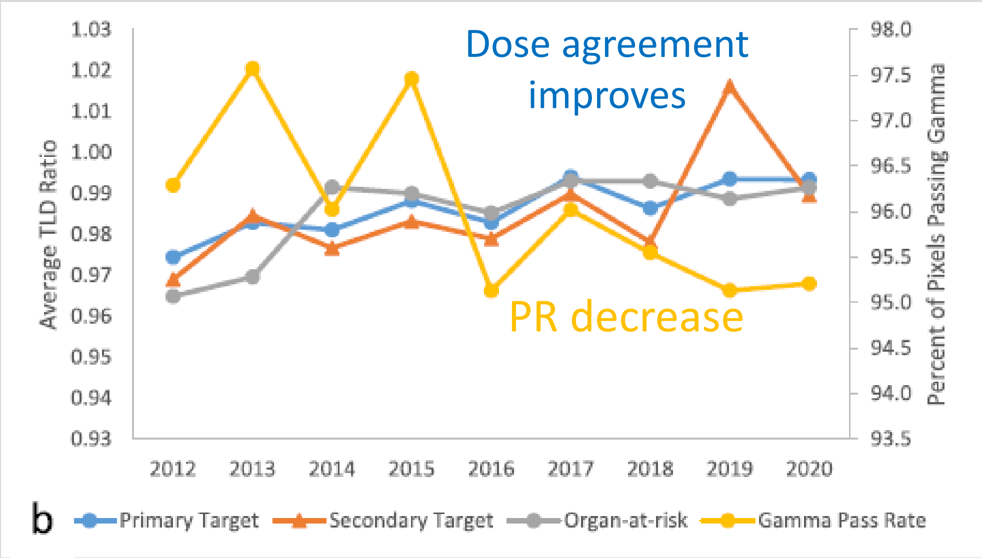
Characterizing the interplay of treatment parameters and complexity and their impact on performance on an IROC IMRT phantom using machine learning

Hunter Mehrens[a,b,d], Andrea Molineu[a,b], Nadia Hernandez[a], Laurence Court[b,d], Rebecca Howell[b,d], David Jaffray[b], Christine B. Peterson[c,d], Julianne Pollard-Larkin[b,d], Stephen F. Kry[b,d,*]

[a] IROC Houston Quality Assurance Center; [b] Department of Radiation Physics; [c] Department of Biostatistics, The University of Texas MD Anderson Cancer Center, Houston, TX, USA; and



Radiotherapy and Oncology 182 (2023) 109577



- ➢The complexity of treatment plans has increased.
- ➢Complexity metrics are significant prognostic factors for output parameters.

- ➢Need for supplementary tests that reflect the level of complexity in the clinical practice (step 4)
- ➢Need to check different anatomical sites

Table 3
Average ranking (mean ± st. dev.) of the importance of each treatment or complexity metric in terms of predicting pass versus fail (classification) or parameter value (regression).

	Classification	Regression			
	Pass/Fail	Primary Target TLD	Secondary Target TLD	OAR TLD	% of Pixels Passing Gamma
meanTGi	1.9 ± 0.6	6.2 ± 1.6	8.1 ± 1.1	6.0 ± 1.1	2.6 ± 1.3
First Quartile of MLC Gaps	1.9 ± 1.2	2.0 ± 1.2	2.4 ± 1.3	4.8 ± 1.8	2.6 ± 1.4
EM	3.1 ± 1.9	3.1 ± 2.1	4.0 ± 1.3	5.0 ± 1.3	3.4 ± 1.5
MCS	4.7 ± 1.0	4.2 ± 1.1	2.5 ± 1.2	7.1 ± 1.5	6.2 ± 1.6
Plan Irregularity	5 ± 1.3	7.6 ± 1.2	6.1 ± 1.5	1.9 ± 0.6	3.8 ± 1.4
MLC Speed Modulation	5.6 ± 1.7	6.7 ± 1.8	9.5 ± 0.7	1.3 ± 0.7	6.4 ± 0.5
Leaf Travel	5.9 ± 1.5	4.8 ± 2.0	6.0 ± 1.6	5.7 ± 2.1	2.7 ± 1.6
MI	7.9 ± 0.3	2.5 ± 1.2	3.4 ± 2.1	4.2 ± 1.5	6.6 ± 0.8
Treatment Technique	9.5 ± 0.5	11.9 ± 0.6	12.6 ± 0.5	10.3 ± 0.5	9.9 ± 0.7
Irradiation Year	9.5 ± 0.5	10.0 ± 0.5	10.8 ± 0.4	9.0 ± 0.0	9.3 ± 0.5
Treatment Machine	11.2 ± 0.4	12.9 ± 0.3	12.4 ± 0.5	12.4 ± 0.8	10.8 ± 0.4
TPS	11.8 ± 0.4	8.0 ± 1.8	4.4 ± 2.8	10.8 ± 0.6	12.0 ± 0.0
TPS Algorithm	13.0 ± 0.0	11.1 ± 0.6	8.8 ± 1.6	12.8 ± 0.6	13.0 ± 0.0
Beam Energy	14.0 ± 0.0	14.0 ± 0.0	14.0 ± 0.0	13.7 ± 0.7	14.0 ± 0.0

Step 4: clinical tests

Available from TG244: http://www.aapm.org/pubs/MPPG/TPS/

Aim: to simulate the complexity and quality of plans expected to be used clinically

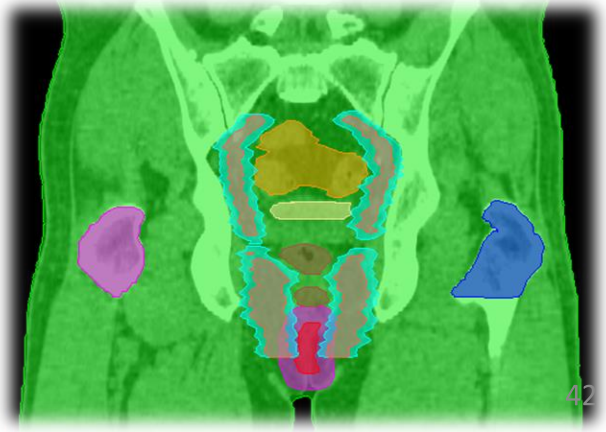
Downloadable from the TG-244 site:

- CT, Contours with sizable targets.
- Objectives/Constraints

5 typical clinical sites:

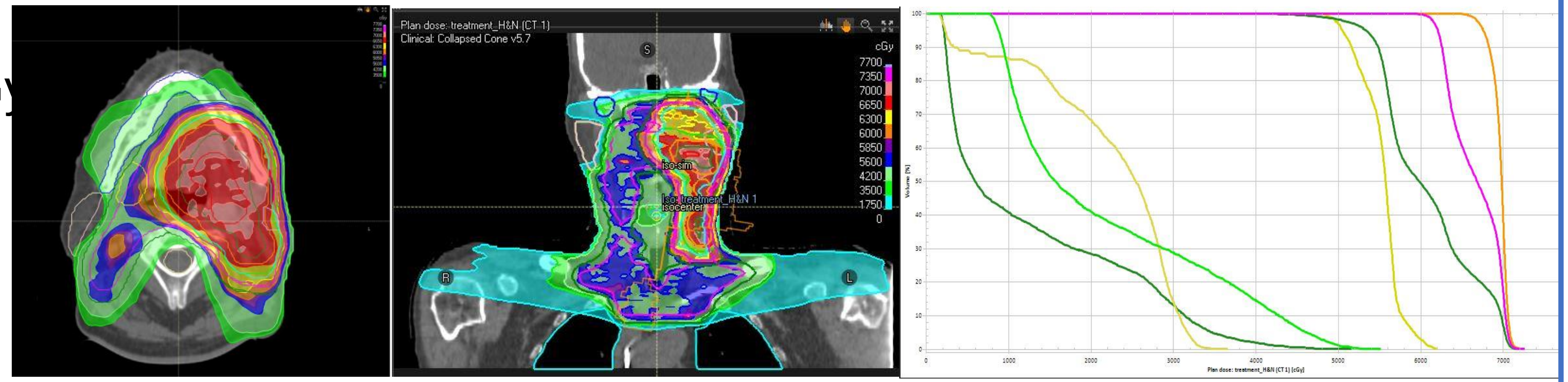
- Head&Neck (SIB)
- Abdomen (SIB)
- Anal (SIB)
- Lung (PTV 767 cc)
- Prostate bed (SIB)

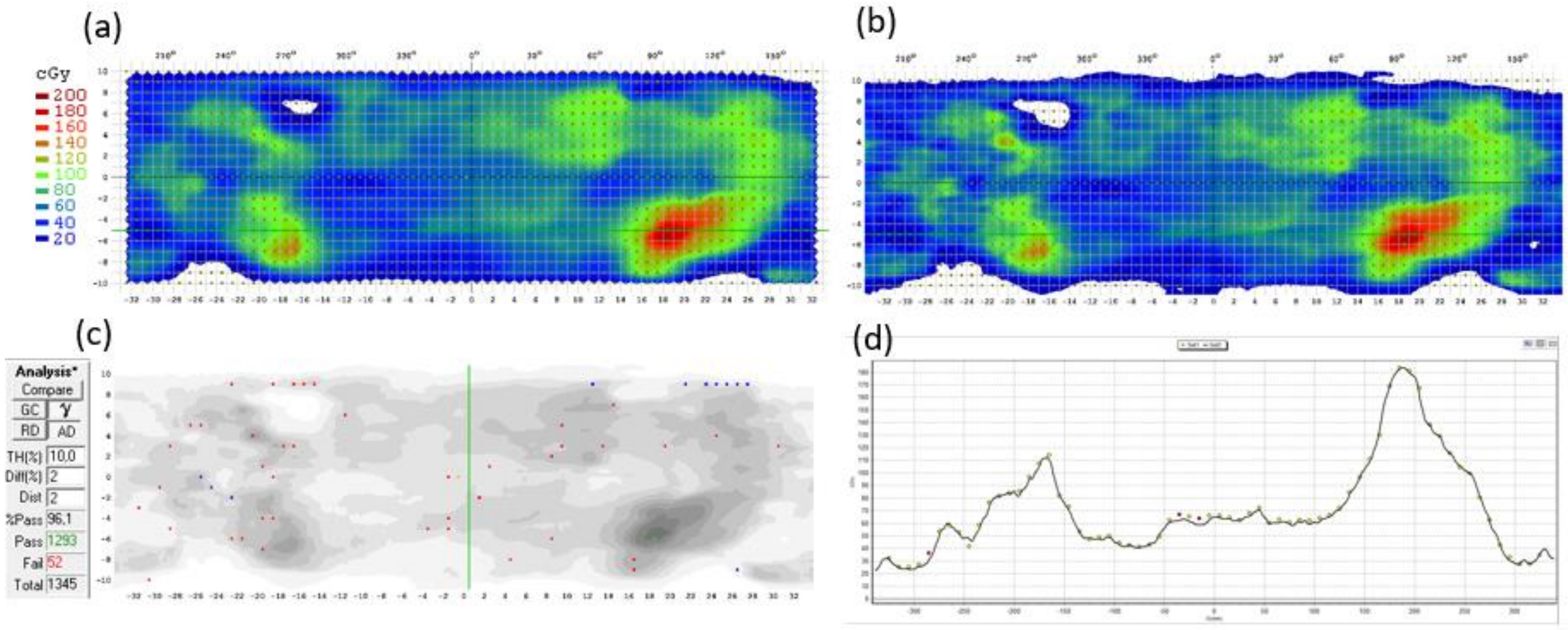
Choose at least two relevant cases (7.4)



TG 244 H&N tumor: clinically optimal plan

-VMAT SIB 56-63-70 Gy
-TPS Raystation
-X 6 MV
-Millenium HD MLC

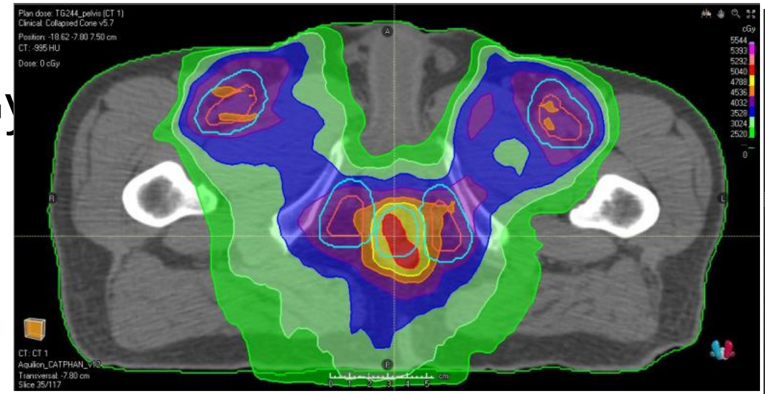


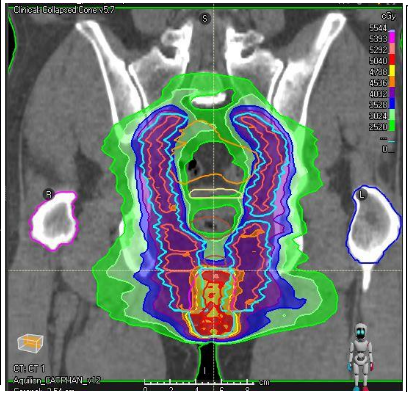


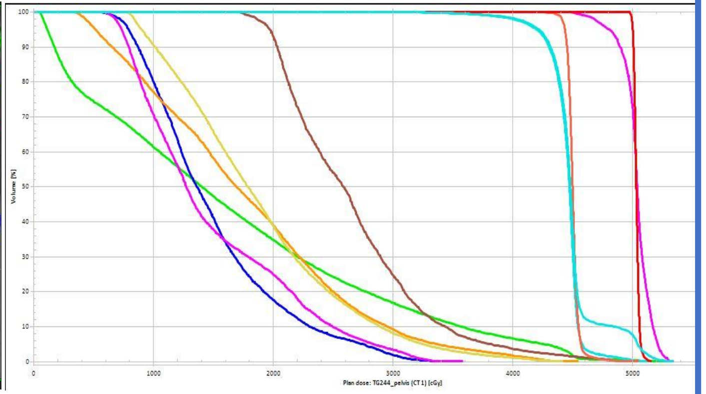
2%L/2mm gamma failing points based on the ArcCheck diode Array.
The agreement between calculated (b) and measured dose (a) is good (PR=96.1).

TG 244 anal tumor:clinically optimal plan

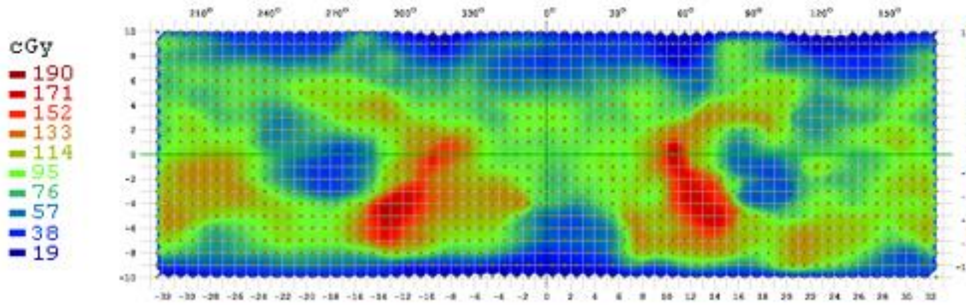
-VMAT SIB 45-50 Gy
-TPS Raystation
-X 6 MV
-Millenium HD MLC



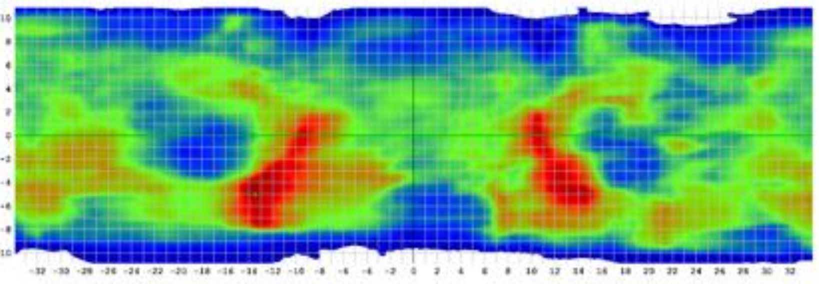




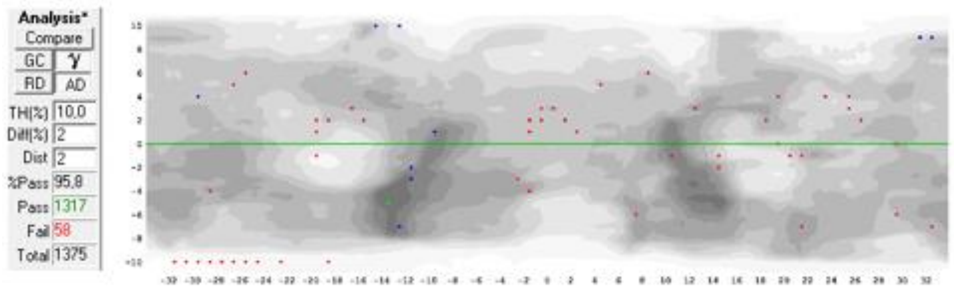
a



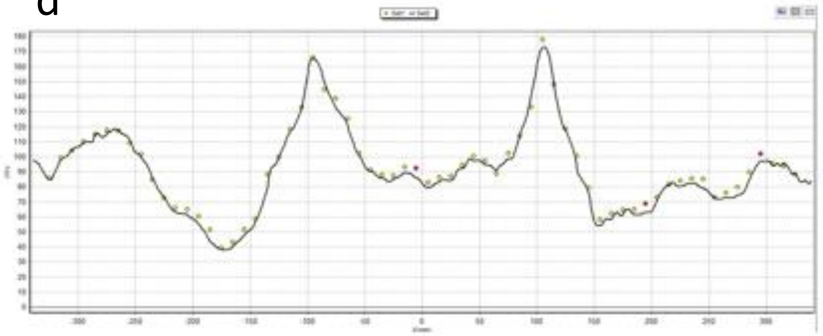
b



c

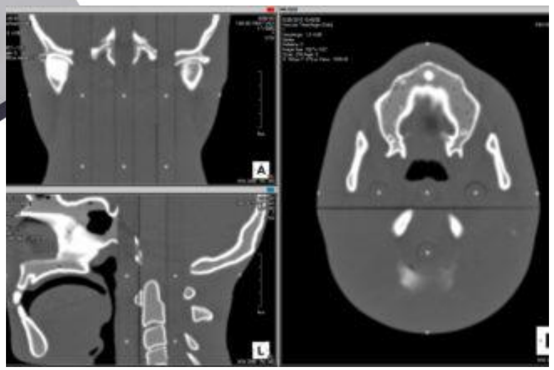


d

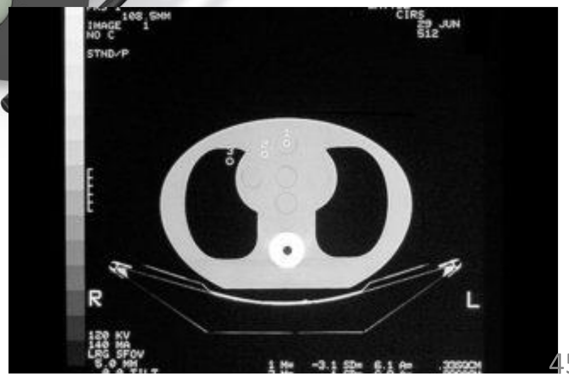


2%L/2mm gamma failing points based on the ArcCheck diode Array. The agreement between calculated (b) and measured dose (a) is good (PR=95.8). A slightly systematic underestimation of the delivered dose is visible in c) and d)

Final step: End to end test/ external review



- Closing the loop one independent end-to-end test with anthropomorphic phantoms (H&N, lung) , is recommended*
- A head and neck plan, such as the IROC Houston credentialing test, is encouraged, as complicated test plans are more likely to demonstrate possible commissioning deficiencies.
- If, not possible, the results of the end-to-end tests should be peer-reviewed by another radiation oncology center.



* AAPM Medical Physics Practice Guideline 5.a

Summary

i. **Implementation of IMRT/VMAT requires careful planning, testing, and verifications.**
ii. **It is difficult to decouple all the components of IMRT/VMAT treatment delivery and planning:**
    i. Extensive and Comprehensive QA procedures are necessary
    ii. A multi-layered strategy should be adopted to check the limits and capabilities of the delivery and TPS sub-systems
iii. **TPS commissioning is the main factor affecting the dose accuracy depending on:**
    i. Quality of the dosimetric data used to create the beam models (OF, penumbra profiles…)
    ii. Source, MLC static/ dynamic parameters.
    iii. Plan complexity in typical clinical settings
iv. **It's necessary:**
    i. TPS fine tuning and validation for different techniques/sites.
    ii. To assess the accuracy of the whole process by end to end testing with antropomorfic phantoms
v. **An indipendent peer to peer review is strongly recommended**