Clinical impact of IMRT failure modes at or near TG-142 tolerance criteria levels

THE UNIVERSITY OF TEXAS MD Anderson Cancer Center

Jacqueline Tonigan Faught, Jennifer Johnson, Stephen Kry, Peter Balter, Laurence Court, Francesco Stingo, David Followill

IROC Houston QA Center

The University of Texas, M.D. Anderson Cancer Center, Houston, Texas

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Introduction

As advanced technologies are added to standard treatment processes, the measures required by the current quality assurance approach become increasingly burdensome. This fact, along with the necessity to mitigate every possible radiotherapy error possible, is a large motivator for better understanding the risks presented by all potential failure modes. We investigated physics failure modes of step and shoot IMRT delivery at or near commonly accepted tolerance criteria levels (shown in Table 1) through treatment planning studies and physical measurements.

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°
7. MU linearity for < 5 MU systematic	6%, up to 30%
8. MLC transmission and leakage modeling	0.5%
9. MLC tongue-and-groove modeling	0.5%
10. MLC leaf end modeling	0.5%
11. CT number to electron density table, systematic	2%, wrong table

Table 1. Physics failure modes and magnitudes of failures investigated.

Materials and Methods

Eleven step-and-shoot IMRT failure modes (FMs) were introduced into twelve Pinnacle v9.8 treatment plans. One standard and one highly modulated plan on the IROC IMRT H&N phantom and ten previous H&N patient treatment plans were used. Resultant DVHs were compared to those of failure-free plans and the severity of plan degradation was assessed considering PTV coverage and OAR and normal tissue tolerances and used for FMEA severity scoring. Six of these FMs were physically simulated and phantom irradiations performed. TLD and radiochromic film results were used for comparison to treatment planning studies.

Results

Physical Measurements

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.

Results

Treatment planning studies

Standard Phantom Treatment Planning Results			
Failure Mode	Difference from Baseline		
	PTV1 D95%	PTV2 D95%	Cord Max Dose
1	-1.98%	-0.86%	-4.75%
2	-0.38%	-1.18%	0.54%
3	-16.08%	-7.98%	8.17%
4	-0.27%	-0.09%	11.69%
5	-0.33%	-0.51%	-0.27%
6	-0.06%	-0.06%	2.43%
7	0.00%	-0.01%	0.42%
8	0.05%	0.05%	3.62%
9	-0.23%	-0.14%	2.04%
10	-0.53%	-0.85%	7.39%
11	-0.02%	-0.04%	0.11%

Table 3. Treatment planning study results from standard phantom treatment plan at dose to 95% of the primary and secondary PTVs and maximum dose to the cord.

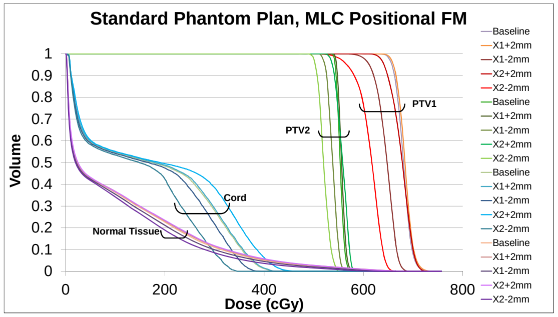

Figure 1. Deviations in standard phantom treatment plan due to systematic 2mm MLC positional errors in one bank, the largest changes seen in the phantom.

Severity Score (S)	Qualitative Definition	Quantitative Definition
1	No effect	0% - 2.9%
2	Inconvenience	3% - 3.9%
3		4% - 4.9%
4	Minor dosimetric error, suboptimal plan or treatment	5% - 6.9%
5	Limited toxicity or tumor under dose. Wrong dose, dose distribution, location, or volume.	7% - 8.9%
6		9% - 9.9%
7	Recordable event. Potentially serious toxicity or tumor under dose	10% - 14.9%
8		15% - 19.9%
9	Reportable event. Possible very serious toxicity or tumor under dose. Very wrong dose, dose distribution, location, or volume.	20%-49.9%
10	Catastrophic	≥50%

Table 4. Severity scoring scale with quantitative definition based on common dosimetric levels and published biological consequences.

Results

Based on phantom treatment planning studies, the largest clinical impact was induced by 2 mm systematic MLC shift in one bank with the combination of a D95% target under dose near 16% and OAR overdose near 8%. Cord overdoses of 5%-11% occurred with gantry angle, collimator angle, couch angle, MLC leaf end modeling, and MLC transmission and leakage modeling FMs.

Based on patient treatment planning studies, the largest clinical impact was induced by the same MLC positional error as well as 1% PDD(10) beam energy errors, with over 30% parotid gland dose errors in different patients with these failures. Angular misalignments and MLC modeling had the potential for large errors in patients similar to the phantom results.

PTV coverage and/or OAR sparing was compromised in all FMs introduced in all plans with the exception of CT number to electron density tables and MU linearity. Symmetry and MLC tongue-and-groove modeling overall had smaller dosimetric effects. Resultant severity scores from treatment planning studies are shown in Figure 2.

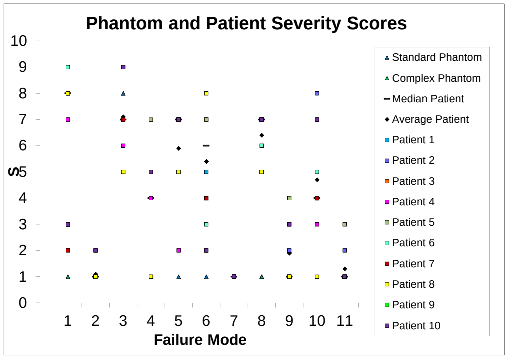

Figure 2. Severity scores assigned using our quantitative scoring scale for phantom and ten patient treatment plans for 11 physics failure modes near tolerance criteria levels.

Physical measurements did not reflect the full magnitude of the potential consequences seen in the treatment planning results. For example, symmetry errors resulted in the largest physically measured discrepancies of up to 3% in the PTVs while a maximum of 0.5% deviation was seen in the treatment planning studies.

Conclusion

Even in the simplistic anatomy of our phantom, some basic physics FMs, just outside of TG-142 tolerance criteria, appear to have the potential for large clinical implications. Phantom irradiations and treatment planning studies were unable to fully capture the variable and potentially significant clinical consequences of the tolerance criteria level physics failures investigated.

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