Phantom Investigation of Three-Dimensional, Motion-Induced Dose Discrepancy During Intensity Modulated Radiation Therapy Dose Delivery

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INTRODUCTION

Significant strides have been made in the development of external beam conformal therapy techniques capable of improving local tumor control and minimizing normal/critical tissue toxicity to acceptable levels. Most notable is intensity-modulated radiotherapy (IMRT). [1] IMRT is currently being use in dose escalation techniques such as Stereotactic Body Radiation Therapy (SBRT) of liver and lung lesions. Intensity modulated dose distributions are typically computed based on 3D computed tomography (CT) data sets. In the presence of intrafraction organ/tumor motion, accurate delivery of IMRT-based SBRT dose distributions can be compromised by tumor motion relative to the radiation beam aperture. Yang et al. [2] quantified the interplay effect in tomotherapy delivered with both continuous helical beam and sequential rotational beam, using a computer-controlled dynamic phantom to simulate tomotherapy dose delivery and single-dimension longitudinal tumor motion. Yu et al. [3] used an analytical model to simulate the interplay effect for MLC-based IMRT. In their study they simulated delivery of a single field, with the MLC leaves moving along the direction of tumor motion, to investigate parameters including the relative speed of tumor motion and MLC leaf motion, and the relative width of leaf gap and the tumor motion amplitude. Jiang et al. [4] experimentally investigated the magnitude of the interplay effect in MLC-based lung IMRT treatments where single-dimension tumor motion was instead perpendicular to MLC leaf motion. Additionally, they examined the dependence of the interplay effect on the delivery mode, dose rate and motion starting phase.

As an extension to the previously described work, we performed in-phantom dosimetric measurements on multiple-sized targets moving in clinically relevant 3 dimensional motion patterns typical of clinically observed lung lesion movement. As an added degree of clinical relevance, the targets were embedded in a prototype anthropomorphic phantom with target motion independent of the static phantom (phantom now commercially available from CIRS, Computerized Imaging Reference Systems Inc., Norfolk, VA) (fig.1).
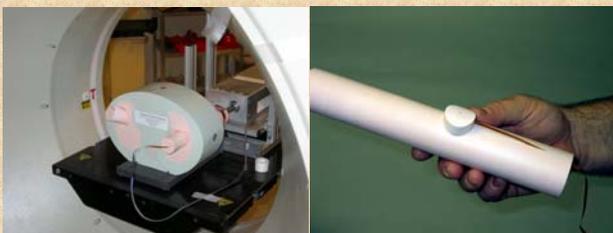

Fig. 1

Conformal Radiotherapy Technique with the MIMiC System					
Target Diameter (mm)	Target State	Mean Dose (cGy)	% Diff.	95% CI (cGy)	p-value
10 mm	Static	174	-	1.4	-
	Unsynchronized	173	-0.6	2.3	0.2380
	0	170	-1.9	1.5	0.0014
	π/2	171	-1.5	1.1	0.0030
	π	173	-0.2	1.7	0.6150
	3π/2	173	-0.3	1.9	0.6020

Fig. 2a Impact of motion on dose to the center of a 10 mm diameter target using the MIMiC-based conformal technique (i.e. non-modulated) with a prescribed dose of 1.8Gy.

The dosimetric deviation of measured versus calculated dose was quantified for: 3D conformal plans utilizing both binary and standard MLC (i.e. non-modulated), and for IMRT treatment plans using both MLC and serial tomotherapy-based delivery techniques, all in the presence of 3 dimensional target motion that was both synchronized and unsynchronized in phase with treatment beam delivery for both standard (1.8Gy) and hypofractionated (12 Gy) dose schemes.

MATERIAL and METHODS

CT-image information for two different targets (1 cm and 3.15 cm in diameter) stationary at the reference position, embedded in a prototype of a commercially available dynamic anthropomorphic thorax phantom (CIRS Inc., Norfolk, VA), were imported into a commercial TPS (Corvus Version 5.0M Rev J6, NOMOS Corporation, Cranberry Township, PA,) for inverse treatment planning. Optimized IMRT fluence maps were generated for delivery with either a dynamic MLC (DMLC) (5 x 5 mm² pencil beam size and 7 non-opposing coplanar static gantry positions, 300 MU/min,) or a MIMiC binary MLC platform (1-CM mode with gantry arc length of 340°, fluence modulation every 5°, beam intensity levels of 0-100% in 10% steps, machine dose rate of 400 MU/min). Non-modulated conformal plans were also generated and delivered using both MLC delivery techniques. Prescription doses of either 1.8Gy or 12Gy from a 6MV beam, covering at least 97% of the PTV, with the GTV receiving at least 95%, were specified. The treatment plan optimized for each delivery technique was delivered to the corresponding target when; 1) stationary, 2) moving in 3D and not synchronized in starting phase with linac motion (unsynchronized), and 3) moving in 3D, synchronized in phase with beam delivery. Four different target motion-to-linac/MLC motion initial phase relationships were used for synchronization. The 3D, target motion cycle was 4 sec long with 3D motion of ±10mm S-I, ±5mm AP, and ±2mm R-L. The MOSFET 20 patient dose verification system (Thomson & Nielsen Electronics Ltd., Ottawa, ON,) was used for point dosimetry at the center of each target. Each measurement was repeated 5 times and averaged for statistical certainty, except for the unsynchronized cases which where repeated with n=20. Measured dose results for the moving targets were compared to measured results for the static target, thus eliminating the effects of dose calculation algorithm dependent errors.

RESULTS

For both serial tomotherapy and static gantry MLC techniques, non-modulated, conformal plan maximum dose deficits of ≤ 2.4% to the center of the moving target were observed, depending on starting phase (fig. 2a and b). For the DMLC IMRT technique with either 1.8 or 12 Gy prescription dose, maximum phase dependent errors of ≤ 4.1% were observed, and similarly for the serial tomotherapy approach maximum phase dependent motion based errors of ≤ 6.2% and 8.4% were observed, for the 12 and 1.8 Gy deliveries, respectively; again dependent on starting phase. The higher maximum error for one particular phase of the low dose serial tomotherapy treatment seems understandable given that the arcing gantry moves significantly faster for the delivery of the 1.8 Gy dose, thus resulting in greater potential for synchronization errors between the fast moving gantry and moving target.

Static Gantry Conformal Radiotherapy Technique					
Target Diameter (mm)	Target State	Mean Dose (cGy)	% Diff.	95% CI (cGy)	p-value
10 mm	Static	168	-	1.6	-
	Unsynchronized	168	-0.4	2.7	0.5320
	0	165	-1.8	1.0	0.0010
	π/2	164	-2.4	0.8	0.0002
	π	169	0.4	1.1	0.4170
	3π/2	167	-0.5	1.8	0.3520

Fig. 2b Impact of motion on dose to the center of a 10 mm diameter target using MLC-based conformal technique (i.e. non-modulated) with a prescribed dose of 1.8Gy.

Target Diameter (mm)	Target State	180 cGy				1200 cGy			
		Mean Dose (cGy)	% Diff.	95% CI (cGy)	p-value	Mean Dose (cGy)	% Diff	95% CI (cGy)	p-value
10	Static	180	0.0	1.8	-	1173	0.0	5.2	-
	Unsynchronized	180	-0.3	8.3	0.816	1196	1.9	34.2	0.02
	0	175	-2.8	2.9	0.0002	1177	0.3	2.4	0.014
	π/2	182	0.8	2.3	0.052	1205	2.8	10.3	<0.0001
	π	174	-3.1	2.3	<0.0001	1213	3.4	9.7	<0.0001
	3π/2	173	-4.1	2.3	<0.0001	1194	1.8	4.7	<0.0001
31.5	Static	188	0.0	3.6	-	1264	0.0	5.0	-
	Unsynchronized	188	0.2	9.3	0.789	1280	1.3	17.4	0.0004
	0	180	-3.8	1.4	0.002	1271	0.5	18.1	0.064
	π/2	193	2.9	3.7	0.0098	1307	3.4	25.3	<0.0001
	π	188	0.3	2.3	0.717	1267	0.3	14.6	0.268
	3π/2	192	2.4	2.8	0.025	1251	-1.0	33.5	0.011

Fig. 3 Impact of motion on dose to the center of a 10- and 31.5-mm diameter targets using the DMLC IMRT technique.

Target Diameter (mm)	Target State	180 cGy				1200 cGy			
		Mean Dose (cGy)	% Diff.	95% CI (cGy)	SE (%)	Mean Dose (cGy)	% Diff	95% CI (cGy)	SE (%)
10	Static	174	0.0	3.3	-	1271	0.0	26.4	-
	Unsynchronized	168	-3.4	14.3	0.0001	1229	-3.3	52.6	0.002
	0	173	-0.5	2.0	0.16	1192	-6.2	19.6	<0.0001
	π/2	161	-7.2	1.0	<0.0001	1231	-3.2	23.8	0.001
	π	178	2.4	1.6	<0.0001	1248	-1.8	6.5	0.0054
	3π/2	168	-3.6	1.3	<0.0001	1248	-1.8	7.1	0.0057
31.5	Static	185	0.0	2.3	-	1255	0.0	16.5	-
	Unsynchronized	184	-0.8	12.6	0.33	1288	2.6	24.3	<0.0001
	0	177	-4.6	3.8	0.0006	1245	-0.8	14.9	0.223
	π/2	182	-1.9	3.0	0.0038	1281	2.1	12.3	0.064
	π	170	-8.4	2.5	<0.0001	1264	0.8	7.9	0.502
	3π/2	176	-5.3	3.1	<0.0001	1235	-1.6	26.0	0.063

Fig. 4 Impact of motion on dose to the center of a 10- and 31.5-mm diameter targets using the MIMiC-based MLC IMRT technique.

When no synchronization of beam to target motion was performed the maximum motion related delivery error was 3.4%.

CONCLUSIONS

The process of performing treatment planning on a 'static' data set and then treating a moving target results, quite obviously, in delivery errors. If no attention was paid to the starting position of the moving target at beam on time (unsynchronized) the mean dose deviation from predicted was a modest 1.7% for IMRT delivery techniques. As various and specific phase synchronization relationships between target and beam were explored, dose deviations as large as 8% could be observed when careful and consistent reproduction of synchronization to one specific phase of target/treatment beam motion was employed. While it would be highly unlikely that such distinctly unfortunate synchronizations would occur consistently for multiple fractions of a fractionated delivery scheme, such a possibility becomes, at least, more probable for hypofractionated delivery schemes, such as SBRT when using IMRT. It should also be noted that inappropriately implemented respiratory gated treatments might also provide a mechanism by which such unfortunate "mis-synchronizations" might be consistently reproduced.

REFERENCES

[1] Intensity Modulated Radiation Therapy Collaborative Working Group. Intensity-modulated radiotherapy: current status and issues of interest. *Int J Radiat Oncol Biol Phys* 2001; 51:880-914.

[2] Yang JN, Mackie TR, Reckwerdt P, et al. An investigation of tomotherapy beam delivery. *Med Phys* 1997; 24:425-36.

[3] Yu CX, Jaffray DA, Wong JW. The effects of intra-fraction organ motion on the delivery of dynamic intensity modulation. *Phys Med Biol* 1998; 43:91-104.

[4] Jiang SB, Pope C, Al Jarrah K, et al: An experimental investigation on intra-fractional organ motion effects in lung IMRT treatments. *Phys Med Biol* 2003; 48:1773-84.