JBUON 2019; 24(2): 838-843
ISSN: 1107-0625, online ISSN: 2241-6293 • www.jbuon.com
E-mail: editorial_office@jbuon.com

ORIGINAL ARTICLE

A dosimetric comparison between volumetric-modulated arc therapy and dynamic conformal arc therapy in SBRT

Sotirios Stathakis[1], Ganesh Narayanasamy[1,2], Anna Laura Licon[1], Pamela Myers[3], Ying Li[1], Richard Crownover[1], Niko Papanikolaou[1]

[1]Department of Radiation Oncology, Mays Cancer Center, University of Texas Health San Antonio, TX 78229, USA; [2]Department of Radiation Oncology, University of Arkansas for Medical Sciences, Little Rock, AR 72205, USA; [3]Baylor College of Medicine, Houston, TX

Summary

Purpose: *The purpose of this study was to investigate the dosimetric equivalency of dynamic conformal arc therapy (DCAT) against volumetric modulated arc therapy (VMAT) plans in stereotactic body radiation therapy (SBRT) of lung and liver lesions and to examine if efficiency can be increased.*

Methods: *Nineteen patients previously treated for lung and liver cancer lesions with SBRT were included. Organs at risk (OAR) and targets were contoured by a single radiation oncologist. All plans were optimized by the same dosimetrist using ELEKTA Monaco treatment planning system version 5.0 for 6MV flattening filter free (FFF) photon beam in a VersaHD (ELEKTA, Crawley, UK). A VMAT and DCAT plan was optimized using the same objectives using coplanar arcs of 225° arc span.*

Results: *All plans have achieved the target and OAR planning objectives. The target dose conformity was comparable (mean VMAT PTVr=1.3 and DCAT PTVr=1.4), and the low dose spillage were similar (mean VMAT R50=4.5 and DCAT R50=4.6). However, monitor units (MU) for DCAT plans were lower by 2.5 times on average than VMAT plans. It was observed that in 75% of cases where OARs overlapped with the PTV, maximum doses to OAR were higher in VMAT than DCAT plans, but the difference was not significant. Patient specific quality assurance (QA) plans were measured using the Scandidos Delta4 phantom and gamma analysis performed using 2mm distance to agreement (DTA) and 2% dose difference yielded more than 95% passing rates on both VMAT and DCAT plans.*

Conclusions: *DCAT delivery for lung and liver SBRT is a dosimetrically equivalent and an efficient alternative to VMAT plans.*

Key words: *DCAT, Lower MUs, OAR sparing, SBRT, VMAT*

Introduction

Radiotherapy is an important modality in the treatment of lung and liver cancer either with curative or palliative intent. In non-small cell lung cancer (NSCLC), while curative radiotherapy is indicated for patients with inoperable early stage cancer, patients with locally advanced stage disease are treated with radiotherapy in combination with concomitant chemotherapy. Curative radiotherapy in combination with chemotherapy is also indicated for limited stage small cell lung cancer [1,2]. In recent years, stereotactic body radiation therapy (SBRT) has emerged as a promising tool in the treatment of hepatocellular carcinoma (HCC) [3,4]. With SBRT, high dose radiation is delivered precisely to a small target volume in few (up to five) fractions. Using SBRT, high tumoricidal doses can be given to precisely ablate the tumor, while minimizing normal tissue damage.

Correspondence to: Sotirios Stathakis, PhD. Departments of Radiation Oncology and Radiology, University of Texas Health San Antonio, 7979 Wurzbach Rd, MC 7889, San Antonio TX 78229-4427, USA.
Tel: +1 210 450 1010, Fax: +1 210 450 1076, E-mail: stathakis@uthscsa.edu
Received: 28/09/2018; Accepted: 02/10/2018

The introduction and wide usage of intensity-modulated radiation therapy (IMRT) over the last two decades has led to great improvements in radiotherapy delivery [3,4]. IMRT allows for better sparing of healthy organs and a higher dose to the tumor. IMRT may involve smaller beamlets where intensity segments do not encompass the entire treatment volume. For those targets that are subject to motion, the interplay between the movement of the multileaf collimator (MLC) leaves and the target (e.g., due to breathing motion) may lead to either over-dosage or under-dosage of the treated volume and the healthy tissue. The concern about the interplay between the MLC and organ motion is most noted in IMRT, in all of its delivery forms, such as step-and-shoot, dynamic MLC, volumetric modulated arc therapy (VMAT) and helical tomotherapy. A patient motion study has shown that the dose delivered to a moving target varied due to the MLC and organ motion interplay [5]. Dose delivered with solid IMRT compensators showed the most temporally uniform dose to the moving target, while any form of MLC based intensity modulation exhibited the least amount of dose non-uniformity. The same study [5] concluded that gated delivery improved the accuracy of the dose delivered to the target as planned. In addition, patient setup error could result in discrepancy between the planned dose and the delivered dose especially in steep dose gradient region.

Recently, there has been a renewed interest in using SBRT techniques with dynamic conformal arc therapy (DCAT) [6-8,10]. When using DCAT, the motion interplay effect in the context of subvolume irradiation is not relevant, since the field aperture is dynamically changed to encompass the full projection of the treated volume at each gantry angle. The DCA has been shown to be a viable delivery option for SBRT treatments because of the shorter treatment time and the reduced MLC-target motion interplay effect [3,4].

The Monaco treatment planning system (TPS), version 5.0 by ELEKTA (Crawley, UK) allows for a modified conformal arc therapy option, where the MLC not only conforms to the projection of the target but allows for variable gantry speed and dose rate during delivery. Furthermore, the DCAT optimization allows the MLC to partially block the PTV if there is overlap with critical structures that have been assigned a higher priority.

The purpose of the present study was to ascertain whether the dose distribution in a DCAT plan is as clinically acceptable as the corresponding VMAT plan and if it can be used more efficiently, specifically for SBRT lung and liver cancer treatments.

Table 1. Disease and treatment features

Pt #	*Site*	*Location*	*PTV vol (cc)*	*Rx (Gy)*	*# fractions*
1	Liver	-	82.9	55	5
2	Lung Right	M	24.8	55	5
3	Lung Left	U	25.4	55	5
4	Lung Left	M	24.8	55	5
5	Lung Left	U	19.2	54	3
6	Lung Left	U	12.1	55	5
7	Lung Right	U	11.1	54	3
8	Liver	-	26.0	50	5
9	Liver	-	28.5	45	9
10	Liver	-	50.9	54	3
11	Lung Left	U	42.2	55	5
12	Lung Right	U	9.3	55	5
13	Lung Right	M	66.9	55	5
14	Lung Left	M	20.9	50	5
15	Lung Right	L	71.2	55	5
16	Lung Right	U	11.9	50	5
17	Lung Left	M	9.2	54	3
18	Lung Right	M	35.5	54	3
19	Lung Right	M	15.7	50	5

For abbreviations see text

Table 2. Objective functions used in treatment plan optimization

Objective name	*Objective function*	*Objective parameters*
PTV	Target Penalty	99% of Rx Dose
PTV+4cm	Quadratic Overdose	50% of Rx Dose 1.2cm from PTV with 5cGy RMS
Ribs	Serial	30Gy
Body	Maximum Dose	130% of Rx Dose

Methods

Patient selection

Nineteen patients previously treated for lung and liver cancer lesions with SBRT were included in this study. All patients' organs at risk (OAR) and planning target volume (PTV) were contoured by a single radiation oncologist. The patients' treatment site, target location and volume, prescription dose (Rx), and number of fractions are shown in Table 1.

Treatment plan generation

All patient plans were optimized by the same dosimetrist using the ELEKTA Monaco treatment planning system for 6MV flattening filter free (FFF) photon beam in a VersaHD (ELEKTA, Crawley, UK). In both VMAT and DCAT plans, coplanar arcs of 225° arc span were used during optimization. To ensure that no planning bias was introduced by the dosimetrist, the same template of PTV and OAR objectives was used for both plans without any further optimization. The dosimetric objectives used for all plans were derived from published data and national protocol guidelines (Table 2).

Templates in Monaco

A common template was used for all lung and liver cancer patients for each of the VMAT and DCAT paired plans. The template included the starting angle and span of the arcs, the arc sectors, the prescription, the OAR objectives and the dose calculation parameters. The templates were altered based on prescription requirements and patient anatomy on a patient-to-patient basis. Common planning objectives were applied to both DCAT and VMAT plans.

To control the dose fall off and conform the dose to the target, an auxiliary structure was created for each plan. This was done by expanding the PTV by 4 cm. Due to the nature of the Monaco optimizer, the structures that were encompassed within the PTV+4cm structure were prioritized with higher weights in the list of constraints so that they were considered during optimization. With the use of templates we ensured that all patient plans were created similarly and consistently.

Plan quality metrics

Comparison between the DCAT and VMAT treatment plans included several evaluation metrics. Two metrics for plan quality were calculated, namely the ratio of the PTV volume to the 100% isodose volume (PTVr) and the ratio of the PTV volume to the 50% isodose volume (R50). The closer the PTVr to unity, the better the conformity of the prescription dose to the target and a high R50 value indicated steep fall-off gradient outside of the PTV, resulting in reduced healthy tissue irradiated volume. The calculated PTVr, R50 and MUs for both VMAT and DCAT plans were plotted against the PTV volume to reveal any possible correlation between them. In addition, the number of monitor units (MU) was recorded for each case as it correlated with the treatment time.

Closest distance between PTV and the OAR

Critical organ dose sparing has remained as an important criterion for clinical acceptability, especially when OAR was adjacent to the target. In this study, the maximum and mean doses to OAR such as ribs, chest wall, heart, stomach and bowel, were evaluated in both VMAT and DCAT plans. The association of OAR dose with the shortest distance between the OAR and PTV was examined. Special attention was paid to OARs that overlapped with PTV, including ribs in lung tumor and stomach in liver tumor.

Statistics

The normality of the data was evaluated using Shapiro-Wilk test in the R statistical package [9]. For normally distributed data, a paired two-sample Student's t-test was used to check the hypothesis that the difference between two means is considered significant. Tests for statistical significance were based on a threshold p value of 0.05. A Wilcoxon signed-rank test was used for those distributions that failed the normality test.

Patient specific QA

For each plan that was created, a corresponding patient specific QA plan was also created for measurement in a Scandidos Delta4 phantom. The gamma index passing rate was calculated with criteria set to 2% dose difference and 2 mm distance-to-agreement (DTA) for all dose points measured above a threshold 10% of the global maximum dose.

Results

Overall, all plans have achieved the planning objectives that were set prior to optimization. The target coverage was equivalent between VMAT and DCAT plans (average values of VMAT PTVr=1.3 and DCAT PTVr=1.4, respectively). The same was ob-

served for the R50 average values for VMAT and DCAT (4.5 and 4.6, respectively). These were shown to be statistically insignificant when a paired two sample t-test was used to check the hypothesis that the two means have no difference (p>0.1). Figure 1 shows the PTVr, R50 values for VMAT and DCAT as a function of PTV volume. Table 3 tabulates the 100% and 50% isodose volumes and MUs for each patient. The VMAT PTVr average was 1.33±0.1 and the DCAT was 1.42±0.15. The respective R50 were 4.5±0.7 and 4.6±0.8 respectively as shown in Figure 1. However, it was observed that the higher values of R50 were calculated for smaller PTV and that R50 remained relatively uniform for PTV volumes of 40cc and higher. DCAT R50 values were higher than VMAT R50 in 13 of 19 cases. Though not significantly different, the average difference was 4.7±7.8%.

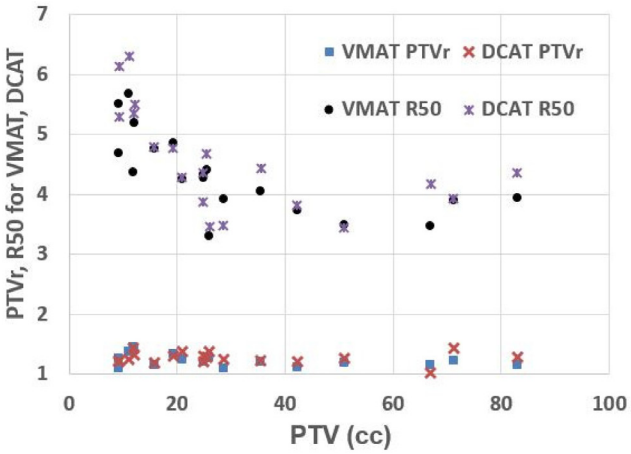

Figure 1. Comparison of PTVr and R50 values between VMAT and DCAT plans.

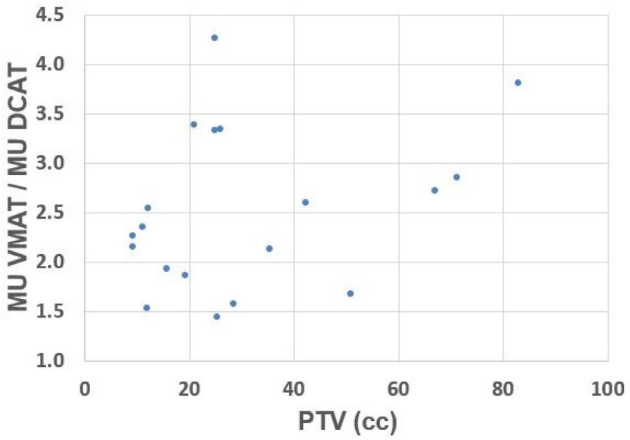

Figure 2. MU ratio of VMAT to DCAT plans versus PTV volume.

Table 3. MU and isodose volumes for the 19 pairs of patient plans

Pt #	*PTV vol (cc)*	*# Arcs*	*100% Isodose line*		*50% Isodose line*		*MU*	
			VMAT	DCAT	VMAT	DCAT	VMAT	DCAT
1	82.9	2	95.4	107.1	375.3	467.0	6854.8	1800.6
2	24.8	2	29.8	32.5	129.3	141.5	7503.2	2252.9
3	25.4	2	32.0	32.5	141.3	151.8	3263.0	2259.7
4	24.8	2	29.8	30.2	127.3	117.3	7271.3	1705.0
5	19.2	2	25.8	24.9	125.2	118.8	7379.2	3954.9
6	12.1	2	17.0	16.1	88.4	88.5	4858.1	1911.4
7	11.1	2	15.3	13.8	86.9	87.1	8062.0	3425.8
8	26.0	2	33.6	41.1	111.2	145.0	5142.0	1537.1
9	28.5	2	31.3	37.8	122.8	136.4	1646.7	948.3
10	50.9	2	60.9	64.7	213.0	223.1	6049.2	3597.1
11	42.2	2	47.2	51.1	176.3	195.1	4970.5	1913.3
12	9.3	2	10.2	11.3	48.0	59.6	4266.8	1979.2
13	66.9	2	77.5	69.0	269.0	298.4	5417.7	1994.8
14	20.9	2	26.3	34.8	111.8	150.7	6332.3	1872.2
15	71.2	1	87.9	102.6	343.2	402.5	5812.3	2034.7
16	11.9	1	17.2	17.1	75.4	91.0	2677.8	1743.4
17	9.2	1	11.8	11.4	64.8	69. 8	7619.7	3360.2
18	35.5	1	43.0	43.5	174.7	193.1	6954.7	3262.5
19	15.7	1	18.142	18.662	86.569	89.586	3345.2	1726.9

For abbreviations see text

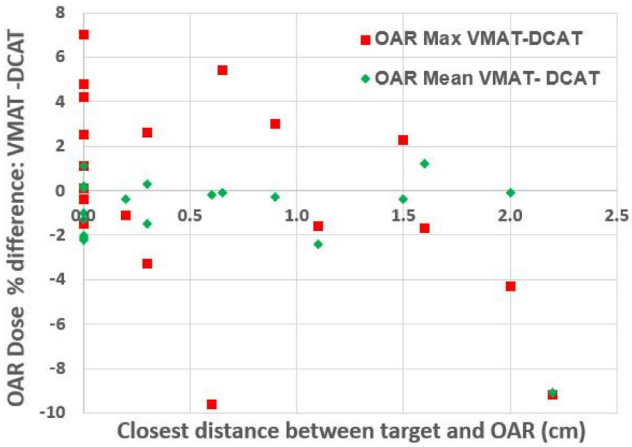

Figure 3. Mean and maximum dose differences to the most proximal OAR for the VMAT and DCAT plans.

On average, the VMAT MUs per fraction were 5549±1849 and the DCAT MUs per fraction were 2282±813 or lower by 59% (Figure 2). The MUs for the DCAT plans were significantly lower by an average of 2.5 times when compared against the VMAT plans ($p<0.001$). No correlation was observed on the number of MUs versus PTV volume.

In Figure 3, the percent maximum and mean OAR dose difference (VMAT – DCAT) was plotted against the closest distance between the OAR and PTV. A few observations can be inferred on the maximum doses to the OAR. VMAT plans had a higher maximum dose to OAR than the corresponding DCAT plans in 6 out of the 8 cases where OAR and PTV overlapped. The average difference in maximum doses to the OAR was computed to be 2.2±2.9%. However, no significant difference was discerned ($p>0.05$), possibly due to lack of statistical power.

Delivery accuracy

The patient specific plans were measured using the Scandidos Delta4 phantom. The measured 3D dose distributions were compared against the calculated ones using 2mm DTA and 2% dose difference for the gamma index calculation. More than 95% of the evaluated points met the gamma index criteria for all plans.

Discussion

With the SBRT delivery, the goal is to ablate the tumor by a significant dose per fraction in a few fractions (usually 2 to 5 fractions). Such prescriptions inevitably result in long treatment times because the combination of the large fractional dose and typically small field sizes result in a large number of MUs required to deliver the prescribed dose. With the introduction of the VMAT technique, the treatment delivery time was significantly shortened when compared to the traditional multi beam IMRT. This was achieved without compromising the dose coverage, however, the MUs needed are still high due to the large number of small segments required to modulate the beam. In this study, we have shown that the DCAT solution in MONACO can be a dosimetrically comparable but more efficient alternative treatment method to VMAT. With the DCAT approach, the beam aperture is open for a large part of treatment to cover the entire PTV and consequently, the MUs per fraction are lower than both VMAT and the traditional static IMRT delivery. Furthermore, the DCAT solution as presented here, is able to vary the dose rate and the gantry speed in an attempt to optimize the dose distribution and provide a highly conformal target coverage comparable to VMAT treatments. Moreover, during the DCAT optimization, a partial PTV irradiation was introduced by the optimizer when necessary to spare nearby OARs. The overall optimization of DCAT provides a faster delivery while maintaining high plan quality standards.

In this study we observed differences in the maximum dose to OARs between VMAT and DCAT plans when OARs were overlapping with the PTV, e.g. ribs in the case of lung or stomach in liver cases. In 6 of 8 such instances, the DCAT plans had lower maximum dose to the OAR than the corresponding VMAT plan by an average of 2.2±2.9%. However, the difference in maximum OAR dose was not significant, most likely due to lack of statistical power. All the other plan quality indices of DCAT plan were comparable to the corresponding VMAT plan. No further optimization would be necessary to improve them, which was out of the scope of this study since we did not allow for preferential planning method. The differences in maximum OAR dose could be explained by the dynamic conformity of MLCs around the target which allows for sparing critical organs in DCAT while producing plans of equivalent quality as a VMAT plan. No one planning technique was found to be superior in terms of sparing the nearby OARs.

The overall reduction in MUs by 2.5 times on average and the consequent savings in time, could potentially be considered to use deep inspiration breath hold (DIBH) for delivery. DCAT MUs were calculated to be about 2300 on average. Using a 6MV FFF (1200MU/min) beam the delivery would take less than 2 min of beam-on time for both arcs. In such cases, the benefits of DIBH would be even higher since we would be able to reduce the ITV and the PTV volumes. Moreover, if during delivery

an intra-fraction CBCT was obtained, repositioning of the patient if necessary, such CBCT, could be performed prior to each arc for improved localization accuracy. Additionally, chances of internal organ motion are reduced in DCAT plan due to faster delivery making the on-board imaging more robust. The lower treatment times required for treatment using DCAT will improve patient comfort and increase throughput.

As MLCs sweep across the field in a VMAT plan, there is considerable interplay between MLC motion, jaw motion, gantry rotation, and target motion during free-breathing treatments. This complexity could lead to substantial dosing discrepancies in VMAT plan especially due to high dose per fraction in SBRT. DCAT remains immune to the effect of MLC interplay.

In a SBRT plan the accuracy of patient setup for treatment is crucial irrespective of the planning method (VMAT or DCAT). While steep dose gradients between target and OARs associated with VMAT plans can be advantageous, the resulting deviation due to any treatment setup error could be significant. There is less chance of a deviation in DCAT plan from the prescribed dose due to setup error, as observed by Morales-Paliza et al. [10]. The authors studied the variation in tumor dose coverage by moving the isocenter 2 mm away and observed less sensitivity of DCAT delivered dose than the corresponding VMAT dose.

Considering all these factors, DCAT plans seem to a dosimetrically equivalent and, in certain circumstances, a better alternative to the VMAT plans in SBRT of lung and liver cancer lesions.

Conclusion

DCAT delivery for lung and liver SBRT treatments is a viable alternative to VMAT plans. While maintaining plan quality, DCAT deliveries use on average 2.5 times less number of MUs that could save treatment time by a substantial amount. DCAT plans showed comparable plan quality compared to the VMAT plans when OARs overlap with the PTV volume, but showed better OAR dose sparing. Both VMAT and DCAT plans were accurately delivered on a static IMRT QA phantom and had excellent gamma index passing rates (>95% using 2%, 2mm criteria).

Acknowledgements

This project was partially funded by ELEKTA, Inc. The authors appreciate the proofreading provided by Ms Kathryn Bates, University of Arkansas Medical School, Little Rock Arkansas, USA.

Conflict of interests

The authors declare no conflict of interests.

References

1. Merrow CE, Wang IZ, Podgorsak MB. A dosimetric evaluation of VMAT for the treatment of non-small cell lung cancer. J Appl Clin Med Phys 2012 doi:10.1120/gacmp.v14i1.4110.
2. Guerrero E, Ahmed M. The role of stereotactic ablative radiotherapy (SBRT) in the management of oligometastatic non small cell lung cancer. Lung Cancer 2016. doi:10.1016/j.lungcan.2015.11.015
3. Bignardi M, Huscher A, Centurioni M et al. SBRT for liver metastases from low grade neuroendocrine tumors Radiother Oncol 2016 DOI:https://doi.org/10.1016/S0167-8140(16)32520-8.
4. Bignardi M, Barbieri D, Smussi I, Galelli M. SBRT for liver tumors with biological-based VMAT planned by Monaco treatment planning system. Radiother Oncol 2012 DOI:hhttps://doi.org/10.1016/S0167-8140(12)71110-6.
5. Ehler ED, Nelms BE, Tomé W. On the dose to a moving target while employing different IMRT delivery mechanisms. Radiother Oncol 2007. doi:10.1016/j.radonc.2007.02.007
6. Rauschenbach BM, Mackowiak L, Malhotra HK. A dosimetric comparison of three-dimensional conformal radiotherapy, volumetric-modulated arc therapy, and dynamic conformal arc therapy in the treatment of non-small cell lung cancer using stereotactic body radiotherapy. J Appl Clin Med Phys 2014. doi:10.1120/jacmp.v15i5.4898
7. Rao M, Yang W, Chen F et al. Comparison of Elekta VMAT with helical tomotherapy and fixed field IMRT: Plan quality, delivery efficiency and accuracy. Med Phys 2010. doi:10.1118/1.3326965
8. Takeda A, Kunieda E, Sanuki N et al. Dose Distribution Analysis in Stereotactic Body Radiotherapy Using Dynamic Conformal Multiple Arc Therapy. Int J Radiat Oncol Biol Phys 2009;74:363-9.
9. R Development Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2008.
10. Morales-Paliza MA, Coffey CW, Ding GX. Evaluation of the dynamic conformal arc therapy in comparison to intensity-modulated radiation therapy in prostate, brain, head-and-neck and spine tumors. J Appl Clin Med Phys 2011;12:5-19.