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Dosimetric Comparison of Flattening Filter-Free Energies for Lung SBRT

Ismail Faruk Durmus[1], Emine Dilara Atalay[2]
[1]*Department of Radiotherapy, Nisantasi University, Istanbul, Turkey*
[2]*Department of Physics, CanakkaleOnsekiz Mart University, Canakkale, Turkey*

Abstract: ***Purpose:*** *The purpose of this study is the dosimetric comparison of 6 MV flattening filter free (FFF) and 10 MV FFF energies in the lung stereotactic body radiotherapy (SBRT) plans.*
Materials and Methods: *The treatment plans of 16 lung SBRT patients were prepared using the same fields and the same physical parameters for 6 MV FFF and 10 MV FFF energies. Critical organ doses, planning target volume doses, quality of plans (gradient index (GI), homogeneity index of International Commission on Radiation Units and Measurements (HI_{ICRU}), heterogeneity index (HI), and conformity index (CI)), and monitor unit (MU) values have been compared between the two plans. The high dose volume and low dose volume outside the target volume are compared according to the Radiation Therapy Oncology Group (RTOG) 0813/0915 protocols. The verification of the plans has been performed through 2D Array IBA® MatriXX Evolution Dosimetry System for each plan.*
Results: *We have determined better CI and GI values with 6 MV FFF energy. A rapid decrease in dose in regions outside the target has been observed, when the GI value has been lower, which leads to enhancement in the protection of the healthy tissue. Lower MU values have been obtained with 10 MV FFF energy. The maximum doses of the heart and spinal cord have been similar for both energies. We have determined lower V5, V10, and V20 doses in the body and ipsilateral lung with 6 MV FFF plans. For both FFF energies and noncoplanar volumetric modulated arc therapy fields, high dose and low dose volumes are determined according to the RTOG criteria. High dose spillage, intermediate dose spillage, V5, V10, and V20 doses have been better with 6 MV FFF. Quality assurance (QA) is evaluated according to the gamma and average gamma indices in the plans prepared with both energies. Both plans that are prepared with 6 MV FFF and 10 MV FFF energies are suitable according to QA results. In addition, better gamma results have been obtained with 10 MV FFF than 6 MV FFF.*
Conclusions: *Although 6 MV FFF and 10 MV FFF are suitable for lung SBRT, 6 MV FFF has some dosimetric advantages.*
Key-words*: FFF energies, Lung SBRT, Average Gama Index*

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I. Introduction

Radiosurgery is a well‑established treatment modality used in the management of a wide variety of intracranial and extracranial lesions, in which a high dose is typically provided in a few fractions to a small and precisely localized target.[1,2] In stereotactic radiosurgery/stereotactic radiotherapy (SRS/SRT), small field sizes and increased number of beams are employed to create highly conformal dose distributions using rigidly attached stereotactic frames or a stereotactic image guidance system. This approach allows high doses to be delivered to the target in one or several fractions, while sparing critical surrounding structures.[3] Stereotactic body radiotherapy (SBRT) refers to the use of SRT on an extracranialregion, and it is a successful treatment method with limited toxicity for primary and metastatic lung cancers.[4‑6] The first SBRT implementation to patients with lung cancer was reported in 1995 by Blomgren*et al*.[7] Several studies have reported significantly improved local control and survival using SBRT in patients with Stage I lung cancer.[8‑10] SBRT administration achieves avoidance of normal tissue exposure to radiation during the planning process by providing for sharp

fall‑off dose gradients outside the target.[11,12]The clinical use of flattening filter‑free (FFF) beams has initially been driven by the attempt to reduce the long delivery time required for SRS/SBRT treatments, as removing the flattening filter increases the dose rate by a factor of 2–4.[13,14]Treatment time is reduced with high‑dose rates using FFF beams in SRS and SBRT. It also increases the efficacy and accuracy of the treatment through image‑guided radiotherapy systems, while providing fast and comfortable treatment for patients. Volumetric‑modulated arc therapy (VMAT) is a novel technique that delivers the dose, in which the linear accelerator rotates continuously around the patient. The dose rate, gantry rotation speed, and multileaf collimator (MLC) positions change dynamically during the treatment.[15]

The aim of our work is to compare physically and dosimetrically the VMAT plans prepared with 6 MVFFF and 10 MVFFF. Parameters such as lung SBRT treatments, target dose distributions, and healthy organ doses were compared for two unfiltered energies [Figure 1].

II. Materials and Method

All plans are calculated using the Monte Carlo algorithm at Elekta® Monaco 5.11 (Elekta, Crawley, England) Treatment Planning System (TPS). Monte Carlo dose calculation simulates transportation of millions of photons and particles within matter. It has been widely considered as the gold standard algorithm for calculating the dose distribution within a patient. Particle disequilibrium occurs especially in lungs and on the surfaces of heterogeneous tissues, and Monte Carlo simulations provide a significant success in calculation accuracy.[16]Low *et al*., in 1998, and Low and Dempsey, in 2003, introduced gamma index method, which is still often used at intensity‑modulated radiation therapy (IMRT)–VMAT as a computer‑based verification program.[17,18] Gamma index method is a calculation technique that is based on the criteria of dose difference (DD) and distance to agreement (DTA). DD and DTA are complementary parameters in the confirmation of dose distribution. Gamma analysis evaluation checks if the gamma index value is < 1 at all evaluation points. If the value of any point is <1, then that point is appropriate. If 90% of all assessed points are <1, the plan is suitable for treatment. The average gamma index is the average of the numerical values of the gamma analysis at all points (<0.6 indicates that the plan is good; <0.4 indicates that the plan is very good). Verification of the SRS / SRT / SBRT plans is performed by separate analysis of gamma and mean gamma values.Computed tomographic (CT) images of 16 lung SBRT patients were scanned on a Siemens® BiographmCT positron emission tomography‑CT device. Target and critical organ volumes were contoured on CT images. Two different plans were prepared using non-coplanar VMAT fields with 6 MVFFF (1400 MU/min) and 10 MVFFF (2200 MU/min) energies in Monaco 5.11 TPS. The same field arrangement and optimization parameters were used in the plans made with both energies. The parameters used in the plans are as follows: target margin: 0–1 mm, beam‑let width: 0.25 cm, fluence smoothing: high, minimum segment width: 0.5 cm, and grid spacing: 0.15 cm. Plans with 1% statistical uncertainty in dose to medium mode have been calculated using the Monte Carlo dose calculation algorithm.In this study, we have used Agility collimator system, which included 160 MLC leaves with a leaf width of 5 mm. Our target volumes were between 0.6 cc and 155.3 cc for 16 lung SBRT patients (average 28.5 cc). Quality assurance (QA) measurements were performed a by 2D‑Array IBA® MatriXX Evolution Dosimetry System for each plan.Plans for 6 MVFFF and 10 MVFFF energies are evaluated a using the following plan metrics: homogeneity index of International Commission on Radiation Units and Measurements (ICRU) (HI_{ICRU}), heterogenity index (HI), conformity index (CI), and gradient index (GI).

HI_{ICRU} denotes the index suggested for ICRU homogeneity. An HI of 0 indicates that the absorbeddose distribution is homogeneous.[19]

$$HI_{ICRU} = \frac{D_{2\%} - D_{98\%}}{D_{50\%}} \quad \text{(Eq. 3a)}$$

Where $D_{2\%}$ is the dose absorbed by 2% of target volume, $D_{98\%}$ is the dose absorbed by 98% of target volume and $D_{50\%}$ is the dose absorbed by 50% of target volume.

HI defines the heterogeneity of dose in target volume (Eq. 3b).

$$HI = \frac{D_{max}}{D95} \quad \text{(Eq. 3b)}$$

Where D_{95} is the dose absorbed by 95% of the target volume and D_{max} is the maximum dose within target volume.

CI defines the target coverage of the reference isodose line, according to J. van'tRiet*et al*.[20] (Eq. 3c).

$$CI = \frac{TV_{PIV} \, x \, TV_{PIV}}{TV \, x \, PIV} \quad \text{(Eq. 3c)}$$

Where TV_{PIV} is the target volume covered by the reference isodose, TV is the target volume, and PIV is the volume covered by the prescribed dose. GI defines the rate of dose change outside the target, according to Paddick*et al*.[21] (Eq. 3d).

$$GI = \frac{PIV_{half}}{PIV} \quad \text{(Eq. 3d)}$$

Where PIV is the volume covered by the prescribed dose and PIV_{half} half is the volume covered by half of the prescribed dose. [Table 1].

According to RTOG 0915 and 0813 reports:

- High‑dosespillage (HDS%): Thecumulativevolume of alltissueoutsidethe PTV receiving a dose>105% of prescriptiondoseshould be nomorethan 15% of the PTV volume

$$HDS(\%) = \frac{V105 - PTV}{PTV} x100 \quad \text{(Eq. 3e)}$$

- Intermediate‑dose spillage: The fall‑off gradient beyond the PTV extending into normal tissue structures must be rapid in all directions and meet the following criteria:

Location: The maximum dose in Gray (Gy) to any point 2 cm or greater away from the PTV in any direction must be no greater than D_{2cm}. [11,12]

Volume: The ratio of the volume of 50% of the prescription dose isodose to the volume of the PTV must be no greater than $R_{50\%}$.[11,12]

Statistics:

We used the Wilcoxon signed test rank test to analyze the differences between 6 MV FFF and 10 MV FFF.A $P < 0.05$ has been considered as statistically significant. In addition, lower and upper limits of 95% confidence interval (CI) have also been evaluated.

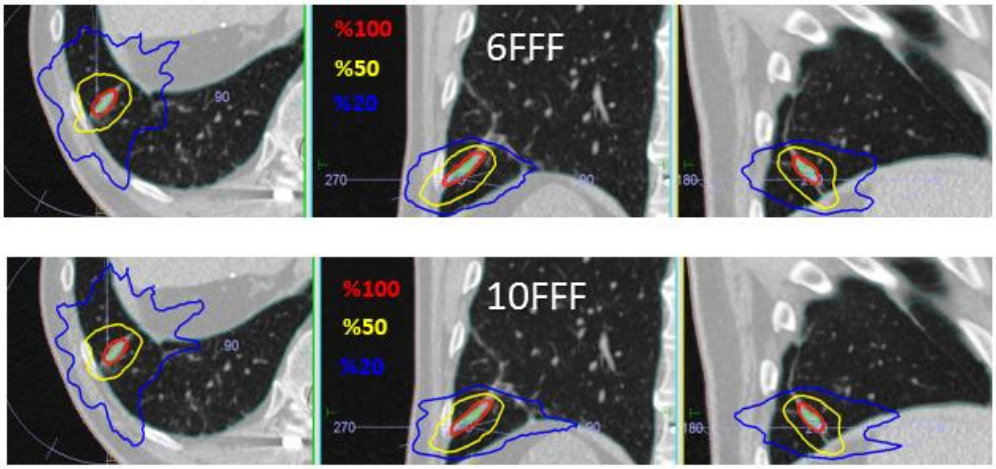
III. Results

Table 1. PTV doses and Plan quality values

	PTV							
	Mean(cGy)	**Min.(cGy)**	**Max. (cGy)**	**HI**	**HI_{ICRU}**	**CI**	**GI**	**MU**
6FFF	5161±1069	4025±885	5467±1797	1.23±0.05	0.167±0.07	0.975±0.04	5.63±1.9	6643±2740
95% CI	4637-5685	3591-4458	5204-6412	1.21-1.26	0.129-0.205	0.952-0.999	4.66-6.59	5300-7986
10FFF	5193±1083	3957±934	5857±1272	1.24±0.05	0.174±0.07	0.958±0.04	5.81±2	6344±2181
95% CI	4662-5724	3499-4416	5233-6481	1.21-1.27	0.135-0.212	0.935-0.982	4.80-6.83	5276-7413
p	0.017	0.044	0.053	0.02	0,313	0.002	0.007	0.327

While higher CI and lower GI values were obtained in plans prepared with 6 MVFFF energy, lower MU values were obtained in plans prepared with 10 MV FFF energy. However, it was not statistically significant. HI, HI_{ICRU}, $PTV_{maximum}$, PTV_{mean}, and $PTV_{minimum}$ values were similar for plans with both energies [Table 1].

Figure 1. Dose distributions of plans made with 6MV-FFF and 10MV-FFF



The maximum doses of critical organs have also been detected similar. However, for ipsilateral lung and body, 5 Gy volume, 10 Gy volume, and 20 Gy volume have been lower with 6 MVFFF, as presented in Table 2.

Table 2. Critical organ doses

	Heart	Spinal Cord	Ipsilateral-Lung			Body			
	Max.(cGy)	**Max. (cGy)**	**V5(%)**	**V10(%)**	**V20(%)**	**Mean(cGy)**	**V5(%)**	**V10(%)**	**V20(%)**
6FFF	844±1047	703±359	22.5±15	14±12	6.57±7.3	480±355	3.89±2	1.44±1.1	0.34±0.3
95% CI	331-1357	526-879	14.7-30.2	8.1-19.8	2.9-10.1	306-654	2.87-4.90	0.88-2	0.16-0.51
10FFF	883±1041	697±375	23.2±15	14.8±12	6.83±7,6	504±357	4.0±2	1.83±1.6	0.4±0.3
95% CI	373-1394	514-882	15.5-30.9	8.7-20.9	3.1-10.5	329-679	2.99-5.01	1.03-2.62	0.21-0.59
p	0.041	0.74	0.015	0.001	0.006	0.001	0.03	0.21	0.15

As for HDS% evaluation for 16 patients, all plans for 6 MVFFF and 10 MVFFF energies were observed to be < 15% of the PTV. The HDS% values, which define the high‑dose area other than PTV, were detected better for the 6 MVFFF energy plans [Table 3]. An average of 9% lower HDS% values were obtained with 6 MV FFF energy plan. But when compared with 10 MV FFF energy plan, these differences were not statistically significant (p = 0.856). Upper and lower limits of 95% CI were determined between 1.73 and 5.72 for the 6 MVFFF energy plan and between 1.79 and 5.76 for the 10 MVFFF energy plan.

Table 3. High Dose Spillage values for 16 lung SBRT patients

		High Dose Spillage	
Patient	**Volume(cc)**	**6FFF(%)**	**10FFF(%)**
1	0.61	8.66	6.80
2	2.02	13.20	15.10
3	2.94	0.98	1.01
4	3.54	2.74	4.71
5	6.35	1.27	3.36
6	8.13	4.32	3.44
7	11.15	11.70	10.36
8	11.46	1.97	1.81
9	17.59	0.17	0.13
10	18.62	5.17	4.77
11	18.71	1.23	1.53
12	28.66	4.06	3.78
13	45.66	0.05	0.57
14	60.41	0.99	0.99
15	64.76	0.60	0.47
16	155.29	2.55	1.65
Av.	28.49	3.85±4.2	4.25±4

Intermediate‑dose spillage values are compared for plans made with 6 MVFFF and 10 MVFFF pursuant to the RTOG Protocols. Although similar results were acquired with the two energies in the lower‑dose regions, in general, the $R_{50\%}$ values were observed to be significantly lower with 6 MVFFF energy plan (P: 0.423 for D_{2cm} and P: 0.012 for $R_{50\%}$) [Table 4]. Upper and lower limits of D_{2cm} 95% CI were determined between 51.5 and 66.8 for 6 MVFFF energy plan and between 51.6 and 65.6 for 10 MVFFF energy plan. Upper and lower limits of $R_{50\%}$, 95% CI were determined between 4.93 and 7.41 for 6 MVFFF energy plan and between 5.11 and 7.82 for 10 MVFFF energy plan. Table 4 shows intermediate dose spillage values (D_{2cm} and $R_{50\%}$).

Table 4. Intermediate Dose Spillage values for 16 lung SBRT patients

		RTOG D2cm		RTOG Deviation	RTOG R50%		RTOG Deviation
Patient	**Volume(cc)**	**6FFF(%)**	**10FFF(%)**	**None/Minor**	**6FFF(%)**	**10FFF(%)**	**None/Minor**
1	0.61	41.0	40.5	<50/<57	12.9	13.70	<5.9/<7.5
2	2.02	34.8	37.1	<50/<57	10.1	9.56	<5.9/<7.5
3	2.94	56.9	61.8	<50/<57	7.35	7.84	<5.9/<7.5
4	3.54	42.8	44.2	<50/<57	7.42	8.47	<5.9/<7.5
5	6.35	65.2	61.4	<50/<58	8.40	10.07	<5.1/<6.0
6	8.13	42.5	41.0	<50/<58	5.35	5.49	<5.1/<6.0
7	11.15	54.4	51.6	<50/<58	4.77	4.97	<5.1/<6.0
8	11.46	64.6	66.9	<50/<58	5.97	6.26	<5.1/<6.0
9	17.59	67.1	66.3	<50/<58	6.10	6.28	<4.7/<5.8
10	18.62	64.1	62.6	<50/<58	4.23	4.13	<4.7/<5.8
11	18.71	52.2	51.3	<50/<58	4.19	4.39	<4.7/<5.8
12	28.66	82.1	76.3	<54/<63	4.85	4.79	<4.7/<5.8
13	45.66	68.9	68.1	<58/<68	4.38	4.58	<4.3/<5.3
14	60.41	75.5	74.1	<62/<77	4.91	5.01	<4.0/<5.0
15	64.76	60.1	63.4	<62/<77	3.88	3.99	<3.5/<4.8
16	155.29	50.1	50.2	<73/<91	4.01	3.94	<3.1/<4.0
Av.	28.49	57.6	57.3		6.17	6.46	

Fluence from lung SBRT patient plans and fluence from measurements have been assessed using the IBA® myQA Software and the gamma index method. Results were evaluated by suppressing 5% and 10% in terms of the criteria of 2% DD-2 mm DTA, 3% DD-3 mm DTA, 4% DD-4 mm DTA, and 5% DD-5 mm DTA [Table 5]. Average gamma values were compared as well. An average gamma value provides mean information about accurate plan verification, and a score of <0.6 is expected for the average gamma value. If the average gamma value is <0.4, it means the plan is better.

Table 5. Patient QA Analysis

	5% Supress						**10% Supress**					
	γindex			*γaverage*			*γindex*			*γaverage*		
	6MV-FFF	**10MV-FFF**	***p***	**6MV-FFF**	**10MV-FFF**	***p***	**6MV-FFF**	**10MV-FFF**	***p***	**6MV-FFF**	**10MV-FFF**	***p***
2%-2mm	70.7±9.2	73.8±11.1	0.03	0.77±0.1	0.73±0.1	0.02	72±9.3	72.2±12.3	0.29	0.76±0.1	0.74±0.2	0.05
95% CI	65.7-75.1	67.8-79		0.69-0.83	0.63-0.80		66-76.1	65.4-78.9		0.68-0.84	0.63-0.84	
3%-3mm	89.3±4.9	90±7.8	0.05	0.51±0.1	0.48±0.1	0.02	88±5.9	87.8±9.7	0.08	0.51±0.1	0.49±0.1	0.19
95% CI	87-91.5	86.4-93.6		0.47-0.55	0.43-0.53		84.3-90.8	82.5-93.1		0.45-0.56	0.42-0.57	
4%-4mm	96.2±3.3	95.4±5.4	0.75	0.38±0.1	0.36±0.1	0.03	95.4±4.1	94.2±6.8	0.67	0.38±0.1	0,37±0.1	0.14
95% CI	94.4-97.8	92.4-97.8		0.34-0.41	0.32-0.4		93.1-97.7	90.5-98		0.34-0.42	0.31-0.42	
5%-5mm	100±0	100±0		0.3±0.1	0.29±0.1	0.02	100±0	100±0		0.3±0.06	0.29±0.1	0.11
95% CI	100	100		0.27-0.33	0.25-0.32		100	100		0.27-0.33	0.25-0.34	

The results suggest that average gamma and gamma index values were determined to be better with 6 MVFFF energy plans than their 10 MVFFF counterparts. Results have not been good enough, especially

regarding the 2% DD-2 mm DTA critera because of high‑dose gradient around target in SBRT plans. In addition, the resolution problem of MatriXX evolution has had an influence on our results. The evaluation of the criteria of 3% DD-3 mm DTA, 4% DD-4 mm DTA, and 5% DD-5 mm DTA for both energies has shown that quality assurances (QAs) of all plans are appropriate.

IV. Discussion

Chung *et al*. evaluated 20 localized prostate patients with VMAT‑SBRT plan for FFF and FF energies. In that study, in order to verify treatment delivery, pretreatment QA had been performed using the I'mRTMatriXX system and radiochromic EBT3 film, and gamma analysis had been employed to quantify the agreement between calculations and measurements. The QA results were 97% for 3% DD-3 mm DTA and 90% for 2% DD-2 mm DTA criteria. The mean MUs realized at 1701 MU for 6 MV flattened beam (FB), at 1870 MU for 6 MVFFF, at 1471 MU for 10 MVFB, and at 1619 MU for 10 MVFFF. MU and QA results are comparable with the results of our study regarding FFF beams.[22]

In another study, Hrbacek*et al*. compared 11 lung patients' VMAT‑SBRT treatment plans with 6 MVFB, 6 MVFFF, and 10 MVFFF energies. They observed less delivery time and high‑dose gradient with FFF beams. They also found out that lung V20 Gy and V12.5 Gy were 5.5% and 4.5% lower with 10 MVFFF and 6 MVFFF beams.[23]Tas*et al*. suggested that an average gamma index of patient QA is an important criterion for the plan quality. They determined an average gamma index <0.5 for prostate VMAT delivery. [24] The average gamma index value is comparable with our study.The plan verification for 20 pre-treatment cancer patients (seven lung, six spine, and seven prostate cancers) were tested by Chung *et al*. using three QA systems (EBT3 film, I'mRTMatriXX array, and MapCHECK). The plans of 20 SBRT patients were prepared using FFF energy. Regarding QA results, the gamma index values for 6 MVFFF according to 2% DD - 2 mm DTA critera were observed at 90.9% for EBT3 film, at 93.8% for MatriXX, and at 95.1% for MapCHECK. For 10 MVFFF, they found a rate of 92.2% for EBT3 film, 93.4% for MatriXX, and 95% for MapCHECK. The QA results were better with 10 MVFFF and they are compatible with our findings.[25]Using FFF energies in lung SBRT treatment has significant advantages. A rapid dose gradient and better critical organ protection are provided through 6 MVFFF energy. However, higher MU values have been observed with 6 MVFFF energy, while better QA results have been obtained with 10 MVFFF energy.In inhomogeneous media such as lungs, the absorption decreases, the lateral range increases, the penumbra expands, and the loss of charged particle equilibrium and rebuild‑up effect occurs. In case of SBRT, these effects are multiplied since it uses small fields. In addition, inhomogeneity effects become greater with 10 MVFFF.[26,27]

In our study, gradient index values have been determined to be better with 6 MV FFF. As the energy increases, the gradient index values also increase. On the other hand, the QA results are found to be better with 10 MVFFF energy plan since sudden dose change has been slower. Sudden dose reduction along with rapid dose gradient, which forms the basis of the SRS/SRT/SBRT, is crucial for critical organ protection. As a conclusion, our findings suggest that 6 MVFFF energy is more suitable for SBRT.

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