



ORIGINAL ARTICLE

Comparison of dosimetric characteristics between flattening filter-free and flattening filter mode volumetric-modulated arc therapy plans in rectal cancer

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Abstract

Objective: We aimed to compare the dosimetric characteristics of 6-MV flattening filter mode (FF) and flattening filter-free mode (FFF) volumetric-modulated arc therapy (VMAT) plans in preoperative radiotherapy for rectal cancer using an Edge linear accelerator.

Methods: Two-arc FF-VMAT and FFF-VMAT plans were generated for 15 patients with rectal cancer using the Philips Pinnacle treatment planning system (version 9.10). The homogeneity index, conformity index, planning target volume covered by 105% isodose lines, organ-at-risk dosimetry characteristics, and monitor units (MUs) were compared between the plans. The results were analyzed using paired *t*-tests.

Results: The conformity index of the FF-VMAT plan and FFF-VMAT plan were (0.93 ± 0.01) and (0.92 ± 0.02), and the homogeneity index of the two groups were (0.07 ± 0.03) and (0.08 ± 0.01), the differences were not statistically significant (both $P > 0.05$). The volume covered by 105% isodose lines of the FFF-VMAT plan was significantly higher than that of the FF-VMAT plan. The FFF-VMAT plan required a higher monitor unit ($t = 11.49$, $P = 0.002$) and shorter beam-on time ($t = 5.78$, $P = 0.001$) compared with the FF-VMAT plan. There were no significant differences in the absolute volume receiving 30 Gy and 40 Gy of the bladder between the plans. The absolute volume receiving 30 Gy and absolute volume receiving 40 Gy of the intestine and colon in the FFF-VMAT plan increased by 5.5% and 2.1% compared with those in the FF-VMAT plans that increased by 7.2% and 2.2%, respectively (both $P > 0.05$). The absolute volume receiving 20 Gy of the left and right femoral head in the FFF-VMAT plan decreased by 3.7% and 4.9% compared with those in the FF-VMAT plans ($P > 0.05$).

Conclusion: Both FF-VMAT and FFF-VMAT plans met the clinical requirements.

KEYWORDS

dosimetry, flattening filter free, rectal cancer radiotherapy, volumetric-modulated arc therapy

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1 | INTRODUCTION

Rectal cancer is one of the most common malignant tumors of the digestive system. The location of the rectum within the bony pelvis and its proximity to vital structures present significant therapeutic challenges.^{1,2} Preoperative radiotherapy can increase the radical resection rate and significantly reduce the local recurrence rate. The combination of preoperative radiotherapy and chemotherapy, named neoadjuvant therapy, has become the standard treatment for stage II/III rectal cancer.^{3,4} Currently, two main preoperative radiotherapy schemes are available for the treatment of rectal cancer⁵: (i) short-course neoadjuvant radiotherapy, with a prescribed dose of 25 Gy in five fractions; and (ii) long-course neoadjuvant radiotherapy, with a prescribed dose of 45–50 Gy in 25 fractions. The short-course neoadjuvant radiotherapy regimen is simple and does not significantly delay the operation time; however, tumor retraction is not obvious because of the short cycle. The long-course neoadjuvant radiotherapy regimen significantly decreases tumor stage and increases the pathological complete remission rate.^{6,7} However, there are no significant differences in terms of long-term side-effects, local recurrence rate, and survival time between the two radiotherapy regimens.⁸

Owing to the development of radiotherapy technology, intensity-modulated radiation therapy and volumetric-modulated arc therapy (VMAT) techniques have improved dose conformity, homogeneity, and normal tissue sparing. VMAT has become the primary technical scheme for preoperative radiotherapy in rectal cancer because of greater optimization angle, shorter treatment time, and better dose distribution, comparing to intensity-modulated radiation therapy. Although the flattening filter in the linear accelerator can make the dose distribution uniform at a specific media depth, the X-ray quality hardens and the scattering increases after the X-rays pass through the filter. With the development of intensity modulation technology, a uniform dose distribution can be achieved using a multi-leaf collimator (MLC).^{9–11} When the flattened filter is removed, the X-ray quality becomes softer and scattering is reduced. Wang et al. found that the use of 6-MV photon rays in the flattening filter-free mode (FFF) combined with the deep inspiratory breath-hold technique reduced the beam-on time (BOT) and improved treatment efficiency.¹² Studies have also shown that a non-uniform beam (FFF) can reduce the dose to normal tissue and the incidence of secondary cancer.¹³ However, when the field was less than $10 \times 10 \text{ cm}^2$, the incident dose was higher than that of the uniform beam, although the difference was not significant for larger fields.¹⁴ Currently, FFF is mostly used in stereotactic radiotherapy. In the present study, 15 patients with rectal cancer were selected to compare the dosimetry differences of VMAT between 6-MV flattening filter mode (FF) and heterogeneous integration mode (FFF) of the Varian Edge linear accelerator in preoperative radiotherapy for rectal cancer.

2 | METHODS

2.1 | Patient selection and contouring

The present study included 15 patients with a median age of 62 years. All patients were immobilized with a thermoplastic mask in the supine position. Computed tomography (CT) images with 5.0-mm slice thicknesses were acquired using a 16-slice CT scanner (GE Healthcare, Waukesha, WI, USA). The scanning range was from the upper edge of the lumbar 1 vertebral body to the inferior ischial tubercle (5.0 cm).

The clinical target volumes (CTVs) were delineated by an experienced radiation oncologist according to the Radiation Therapy Oncology Group guidelines.¹⁵ The CTV included the gross tumor volume, gross tumor lymph node, mesorectum, presacral area, obturator drainage area, and some bilateral iliac and internal and external lymphoid drainage areas. The planning target volume (PTV) was defined as a 0.5-cm expansion of the unified CTV. The organs at risk (OARs) included the bladder, intestine, colon, and bilateral femoral heads.

2.2 | Treatment planning

Two-arc FF-VMAT and FFF-VMAT plans were generated for each patient using the Philips Pinnacle (version 9.10) treatment planning system modeled for the Edge linear accelerator (Varian Medical Systems) equipped with high-definition MLCs. The first arc ranged from 181° to 179° , whereas the second arc ranged from 179° to 181° . The same optimization objectives, convolution optimization, and iterative optimization were used in the FF-VMAT and FFF-VMAT plans. The prescribed dose was 50 Gy in 25 fractions (2.0 Gy/fraction).

2.3 | Dosimetric evaluation

The dose coverage, homogeneity index, conformity index (CI), 105% dose coverage ($V_{105\%}$), monitor unit (MU), and BOT values were evaluated. The homogeneity index was defined as: where $D_{2\%}$ and $D_{98\%}$ are the doses received by 2% and 98% of the PTV, respectively, and D_p is the prescribed dose.

The CI was defined as: where $V_{t,ref}$ is the PTV covered by the reference isodose line, V_t is the PTV, and V_{ref} is the volume of the reference isodose (95%).

For the OARs, dose–volume histograms were evaluated. The absolute volume receiving 30 Gy (V_{30}) and 40 Gy (V_{40}) of the bladder, intestine, and colon, and the absolute volume receiving 20 Gy (V_{20}) of the bilateral femoral head were determined.

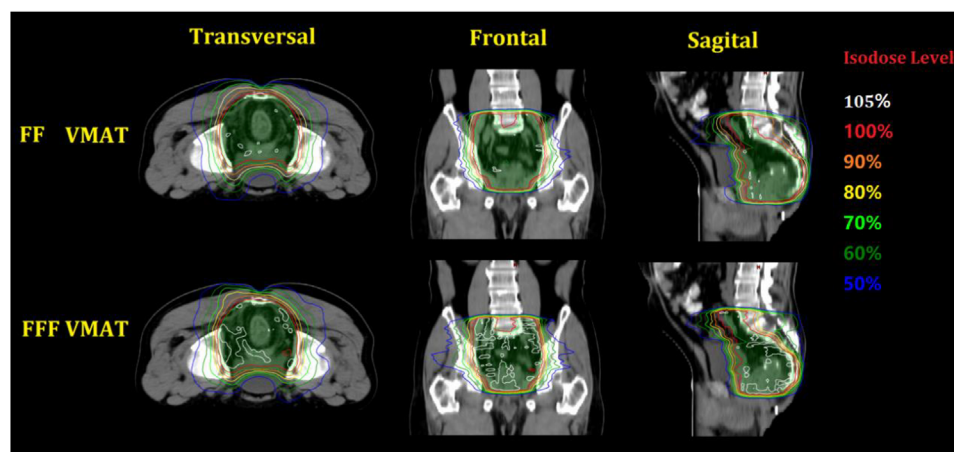


FIGURE 1 Isodose distribution in the transversal, frontal, and sagittal section. The green volume represents the planning target volume. The isodose levels are shown

2.4 | Dose delivery

The total MUs and BOT of the FF-VMAT and FFF-VMAT plans were analyzed.

2.5 | Statistical analysis

All statistical analyses were carried out using IBM SPSS Statistics for Windows, version 22.0 (IBM Corp., Armonk, NY, USA). The plan evaluation parameters for each structure and deviation from the dose constraints were calculated for each plan. Student's *t*-tests were used for data that obey normal distribution. Statistical significance was set at $P < 0.05$.

3 | RESULTS

3.1 | PTV dose distributions and evaluations

Both plans reached the clinical constraints, with similar dose coverages of the PTV (Figure 1). Table 1 lists the dosimetry parameters of the PTV. The FF-VMAT plan achieved better conformity, with higher CIs, than the FFF-VMAT plan (Table 1).

In addition, the FF-VMAT plan achieved better homogeneity, with a lower homogeneity index, than the FFF-VMAT plan. The $V_{105\%}$ signifi-

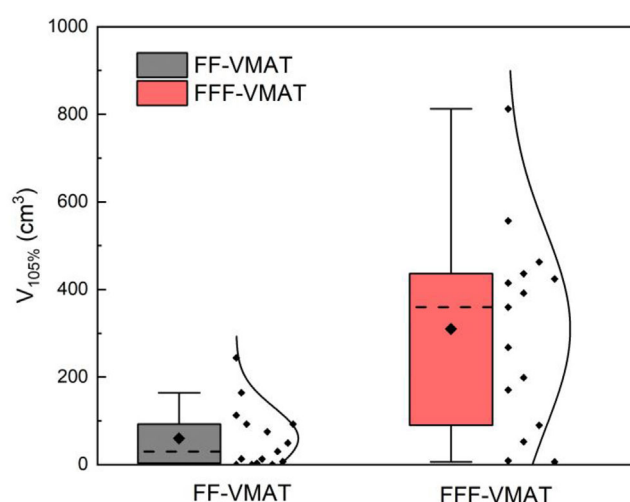


FIGURE 2 Box plot shows the volume of planning target volume covered by 105% isodose lines (cm^3) of flattening filter mode volumetric-modulated arc therapy (FF-VMAT) and flattening filter-free mode volumetric-modulated arc therapy (FFF-VMAT) plans for 15 patients

cantly increased in the FFF-VMAT plan than in the FF-VMAT plan (Figure 1). The $V_{105\%}$ of the FFF-VMAT plan was significantly higher than that of the FF-VMAT plan (Figure 2).

TABLE 1 Dosimetric comparisons for planning target volumes ($\bar{x} \pm s$)

Parameters	FF-VMAT	FFF-VMAT	P-value	t-value
Conformity index	0.93 ± 0.01	0.92 ± 0.02	0.003	3.59
Homogeneity index	0.07 ± 0.03	0.08 ± 0.01	0.100	1.75

Abbreviations: FF, flattening filter mode; FFF, flattening filter-free mode; VMAT, volumetric-modulated arc therapy.

3.2 | Dose sparing of the OARs

There was no significant difference in the V_{30} and V_{40} of the bladder between the FF-VMAT and FFF-VMAT plans (Figure 3). The V_{30} and V_{40} of the small intestine increased by 5.5% and 2.1% (Table 2), respectively, in the FFF-VMAT plan compared with those in the FF-VMAT plan. The V_{30} of the colon increased by 7.2% in the FFF-VMAT plan compared with that in the FF-VMAT plan (Table 2). There was no

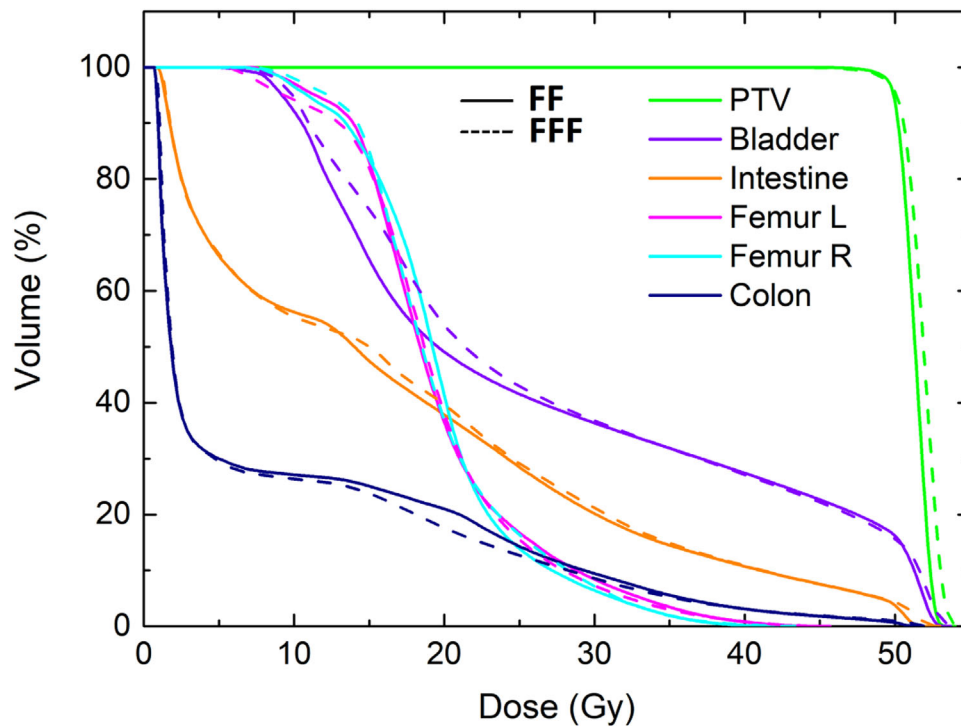


FIGURE 3 An example of the dose volume histogram of flattening filter (FF) mode volumetric-modulated arc therapy and flattening filter-free (FFF) mode volumetric-modulated arc therapy plans. PTV, planning target volume

TABLE 2 Dose–Volume histogram parameters of organs at risk ($\bar{x} \pm s$)

Parameters	FF-VMAT	FFF-VMAT	P-value	t-value
Bladder				
V ₃₀ (cc)	347.54 ± 115.36	345.36 ± 114.78	0.95	0.78
V ₄₀ (cc)	259.77 ± 83.14	257.09 ± 82.45	0.93	2.93
Intestine				
V ₃₀ (cc)	48.64 ± 36.64	51.30 ± 39.48	0.85	2.61
V ₄₀ (cc)	32.01 ± 29.66	31.26 ± 30.27	0.94	1.06
Colon				
V ₃₀ (cc)	43.66 ± 30.65	46.81 ± 33.27	0.78	2.91
V ₄₀ (cc)	26.31 ± 21.16	26.90 ± 21.53	0.94	1.20
Left femoral head				
V ₂₀ (cc)	32.31 ± 18.16	31.09 ± 18.12	0.85	0.98
Right femoral head				
V ₂₀ (cc)	32.68 ± 16.02	31.06 ± 16.34	0.78	1.47

Abbreviations: FF, flattening filter mode; FFF, flattening filter-free mode; V₂₀, absolute volume receiving 20 Gy; V₃₀, absolute volume receiving 30 Gy; V₄₀, absolute volume receiving 40 Gy; VMAT, volumetric-modulated arc therapy.

significant difference in the V₄₀ of the colon between the plans ($P > 0.05$). The V₂₀ of the bilateral femoral head decreased by 3.7% (femoral head left) and 4.9% (femoral head right) in FFF-VMAT plan compared with that in the FF-VMAT plan ($P > 0.05$).

3.3 | Beam delivery efficiency

The total MUs and BOT were collected and analyzed (Table 3). The FFF-VMAT plan required a higher MU ($t = 11.49$, $P = 0.002$) and shorter BOT ($t = 5.78$, $P = 0.001$) compared with the FF-VMAT plan.

TABLE 3 Total monitor units and beam-on time in the flattening filter mode volumetric-modulated arc therapy and flattening filter-free mode volumetric-modulated arc therapy plans ($\bar{x} \pm s$)

Plan	MU	BOT (s)
FF-VMAT	750 $\pm$ 157	133.1 $\pm$ 2.13
FFF-VMAT	1279 $\pm$ 212	130.9 $\pm$ 1.33
P-value	0.002	0.001
t-value	11.49	5.78

Abbreviations: BOT, beam-on time; FF, flattening filter mode; FFF, flattening filter-free mode; MU, monitor unit; VMAT, volumetric-modulated arc therapy.

4 | DISCUSSION

Both FF-VMAT and FFF-VMAT techniques provide improved dose conformity, homogeneity, and sparing of high-dose irradiation. VMAT technology reduces the therapeutic time and MUs, and is associated with an enhanced tumor gain ratio.¹²⁻¹⁴ Conventional VMAT uses the FF, which is associated with some disadvantages, including prolonged delivery time, reduced treatment dose rate, decreased photon intensity, and enhanced treatment dose scattering.^{16,17} Although the flattening filter in the linear accelerator can make the dose distribution uniform at a specific depth of the phantom, the X-ray quality hardens and scattering increases after the X-rays pass through the homogenizer.^{18,19} With the development of intensity modulation technology, a uniform dose distribution can be achieved using an MLC. When the flattening filter is removed, the X-ray quality becomes softer and scattering is reduced.²⁰ VMAT technology combined with the FFF has been widely used in stereotactic radiotherapy because of its good conformal degree and high efficiency.^{21,22}

To investigate whether the FFF-VMAT plan is applicable for rectal cancer, FF-VMAT and FFF-VMAT plans were generated for each patient using the Philips Pinnacle treatment planning system for the Edge linear accelerator equipped with high-definition MLCs.

Both the plans reached the clinical constraints, with similar dose coverages of the PTV. The FF-VMAT plan achieved better conformity and homogeneity, with higher CIs, than the FFF-VMAT plan. The $V_{105\%}$ of the FFF-VMAT plan was significantly higher than that of the FF-VMAT plan. The non-flattened beam has a greater number of low-energy photons than the flattened beam because of minimal beam hardening owing to the absence of the flattening filter. Thus, the non-flattened beam requires slightly more intensity than the flattened beam for the same dose.¹⁷ The rectum target was located deep within the bony pelvis. Thus, to meet the target dose in the deep volume, the cumulative dose was increased in the ray path. Furthermore, the accelerator also needed to output more machine hops to meet the dose in the deep target area, leading to a significantly higher $V_{105\%}$ and MU in the FFF-VMAT plan than in the FF-VMAT plan. The dose sparing of the OARs did not differ significantly between the FF-VMAT and FFF-VMAT plans. The FF-VMAT plan delivered approximately half of the MU of the FFF-VMAT plan. However, the BOT of the FFF-VMAT plan decreased slightly owing to its higher dose rate compared with the FF-VMAT plan.

In conclusion, the present study generated FF-VMAT and FFF-VMAT plans for 15 patients with rectal cancer using the Philips Pinnacle treatment planning system for the Edge linear accelerator equipped with high-definition MLCs. Both the plans met the clinical constraints. The FF-VMAT plan achieved better conformity and homogeneity than the FFF-VMAT plan. The FFF-VMAT plan showed no significant advantage in terms of dose sparing of the OARs compared with the FF-VMAT plan. The FFF did not significantly shorten the treatment time.

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CONFLICT OF INTEREST

The authors declare that they have read the article and there are no competing interests.

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