STUDY ON MONITORING UNIT EFFICIENCY OF FLATTENING-FILTER FREE PHOTON BEAM IN ASSOCIATION WITH TUMOR SIZE AND LOCATION

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To investigate monitoring unit (MU) efficiency and plan quality of volumetric modulated arc therapy (VMAT) using flattening-filter free (FFF) photon beam in association with target size and location. A virtual patient was generated in Eclipse^{TM} (ver. A10, Varian Medical Systems, Palo Alto, USA) treatment planning system. The length of major and minor axis in axial view was 50 cm and 30 cm, respectively. Cylindrical-shaped targets were generated inside that patient at the center (symmetric target) and in the periphery (asymmetric target, 7.5 cm away from the center of the patient to the right direction) of the virtual patient. The longitudinal length was 10 cm and the diameters were 2, 5, 10 and 15 cm. Total 8 targets were generated. RapidArc^{TM} plans using TrueBeam STx^{TM} were generated for each target. Two full arcs were used and the axis of rotation of the gantry was set to be at the center of the virtual patient. Total MU, homogeneity index (HI), target mean dose, the value of gradient measure and body mean dose were calculated. In the case of symmetric targets, averaged total MU of FFF plan was 23% and 19% higher than that of flattening filter (FF) plan when using 6 MV and 10 MV photons, respectively. The difference of HI, target mean dose, gradient measure and body mean dose between FF and FFF was less than 0.04, 2.6%, 0.1 cm and 2.2%, respectively. For the asymmetric targets, total MU of FFF plan was 21% and 32% was higher than that of FF when using 6 MV and 10 MV photons, respectively. The homogeneity of the target was always worse when using FFF than using FF. The maximum difference of HI was 0.22. The target mean dose of FFF was 3.2% and 4.1% higher than that of FF for the 6 MV and 10 MV, respectively. The difference of gradient measure was less than 0.1 cm. The body mean dose was higher when using FFF than FF about 4.2% and 2.8% for the 6 MV and 10 MV, respectively. No significant differences between VMAT plans of FFF beam and FF beam were observed in terms of quality of treatment plan. The HI was higher when using FFF 10 MV photons for the asymmetric targets. The MU was increased noticeably when using FFF photon beams.

Keywords: Flattening-filter free photon beam, Monitoring unit efficiency, Volumetric modulated arc therapy

1. INTRODUCTION

Volumetric modulated arc therapy (VMAT) is state-of-the-art radiation treatment technique enabling to deliver prescription dose enough for tumor control while minimizing unnecessary irradiation to normal tissue [1]. It could deliver similar or better quality of dose distributions compared to intensity modulated radiation therapy (IMRT) in a very short treatment time [2]. VMAT is generally believed as a suitable technique for stereotactic body radiation therapy (SBRT) which needs to deliver large amount of dose to a small target volume, *i.e.* generally having a diameter less than 5 cm, within few fractions necessitating short treatment time [3, 4]. On the other hand, flattening-filter free (FFF) technique has been suggested in order to reduce treatment time for SBRT [5]. Since FFF technique increases dose rate by removal of flattening filter (FF) in a gantry head, high dose rate could be acquired due to minimal loss of photon beam while sacrificing flatness of a profile. However, the un-flatness of FFF is no more a problem by virtue of the ability of intensity modulation with IMRT or VMAT. Furthermore, even in FFF beam, the profile is almost flat at the field size less than 7 cm [6]. Therefore, un-flatness of FFF tech-

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nique is not problematic for SBRT since the target size of SBRT is generally less than 5 cm as mentioned above [7].

TrueBeam STx (Varian Medical Systems, Palo Alto, CA, USA) is a linac specialized for SBRT possible to perform VMAT in FFF mode. It is possible to deliver dose to a patient with high dose rate up to 2400 MU/min during FFF mode. However, this high dose rate is only valid along the central axis (CAX) even in FFF mode. Since the shape of FFF beam profile is pointed at center region, the dose rate decreases as the off-axis distance increases. Therefore, the advantage of FFF is only valid for small target located at CAX as in the case of SBRT. Even though the advantage of FFF mode for SBRT is obvious, it is uncertain that FFF mode is beneficial for a large target volume or a target volume located in the periphery of a patient.

To the best of our knowledge, no study has been yet performed to analyze monitoring unit (MU) efficiency in association with target size and location during VMAT in FFF mode. If the target is located in the periphery of the patient body or target size is large, in order to deliver uniform dose to the target volume, high dose along CAX in FFF mode should be adjusted by multi-leaf collimator (MLC) during IMRT or VMAT delivery. This potentially might increase MU significantly causing inefficient treatment compared to use of FF beam. In this study, MU efficiency in connection with the size of target volume and location was investigated. The dose-volumetric indicators were evaluated for each plan with various target volumes and their locations.

2. MATERIALS AND METHODS

1. Generation of a virtual patient and target volumes

A virtual patient was generated in Eclipse^{TM} (ver. A10, Varian Medical Systems, Palo Alto, USA) treatment planning system for this study. The virtual patient was illustrated in Fig. 1. The virtual patient was cylindrical-shaped and the cross-section was oval-shaped. The length of major and minor axis in axial view was 50 cm and 30 cm, respectively, to simulate the abdomen or pelvis region of an adult. The Hounsfield unit (HU) was set to be zero same as water since the effect of inhomogeneity was out of scope of this study. Cylindrical-shaped targets were generated inside that patient at the center named as symmetric target (Fig. 2) and in the periphery named as asymmetric target (Fig. 3). For the asymmetric target, the center of the target circle in axial view was set to be located at 7.5 cm away to the right direction from the center of

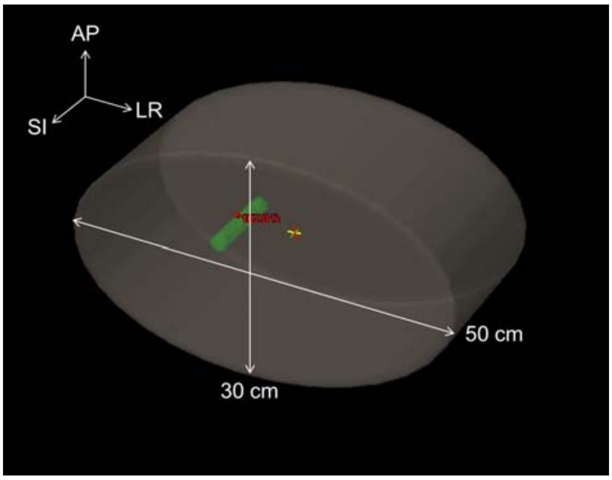

Fig. 1. A virtual patient generated by treatment planning system. The shape of the virtual patient was cylindrical-shaped and the cross-section was oval-shaped. The length of major and minor axis in axial view was 50 cm and 30 cm, respectively, to simulate the abdomen or pelvis region of an adult. The Hounsfield unit was set to be zero.

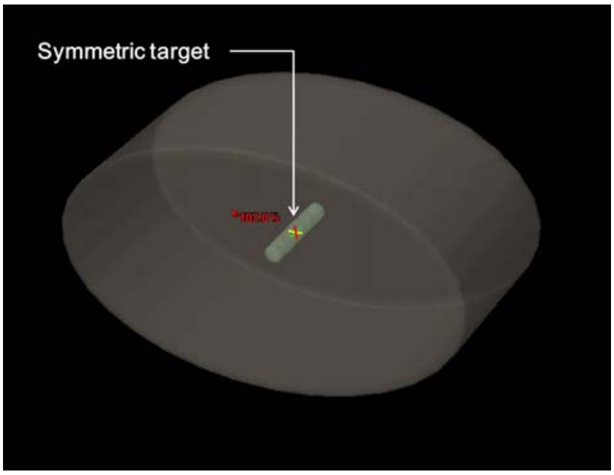

Fig. 2. Symmetric target located at the center of a virtual patient.

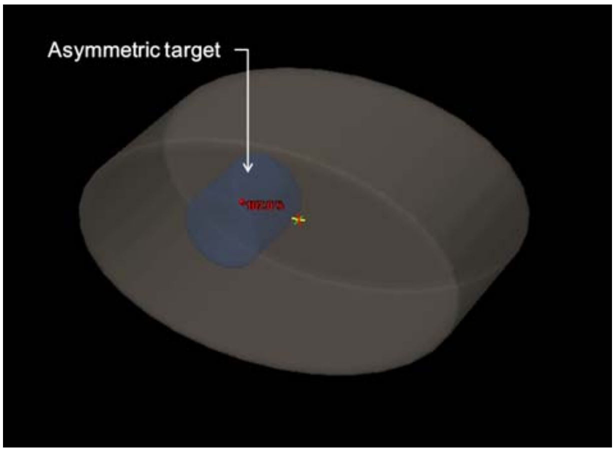

Fig. 3. Asymmetric target located in the periphery of a virtual patient. The center of the axial circle of target set to be located at 7.5 cm away from the center to the right direction of the virtual patient.

the virtual patient. Both symmetric and asymmetric target have longitudinal lengths in superior to inferior (SI) direction of 10 cm and the diameters were 2, 5, 10 and 15 cm. Therefore, total 8 targets were generated for this study.

2. Treatment planning

RapidArc^{TM} plans using TrueBeam STx^{TM} were generated for each target. Two full arcs were used and the axis of rotation of a gantry was set to be at the center of the virtual patient. For the target located in the periphery, the axis of the rotation of gantry is generally set to be the center of the target in the clinic. However, due to the clearance problem of the gantry rotation, the axis is not sometimes possible to be set at the target center. In order to simulate this situation and investigate the dosimetric effect at this situation, the gantry rotation axis even for the target in the periphery was set to be the center of the virtual patient in this study. The optimization algorithm and calculation algorithm used in this study was progressive resolution optimizer 3 (PRO3, ver. A10, Varian Medical Systems, Palo Alto, CA, USA) and anisotropic analytic algorithm (AAA, ver. A10, Varian Medical Systems, Palo Alto, CA, USA), respectively. Every plan was optimized for 98% of target volume to be covered by 98% of prescribed dose which was set to be 100 cGy. The calculation grid was set to be 0.25 cm. For each target, VMAT plans with 6 MV FF, 6 MV FFF, 10 MV FF and 10 MV FFF photon beams were generated. Therefore, total 4 VMAT plans per target were generated. During optimization, every dose-volume constraints were maintained same for fair comparison between FF and FFF plans. Besides dose-volume constraints, every parameter in VMAT plans was also set to be same.

3. Data analysis

Dose-volumetric indicators and MUs of each VMAT plan were collected and analyzed. In order to evaluate the dose-volumetric quality of target volume, *homogeneity index (HI)*, $D_{95\%}$ of target. $D_{5\%}$ of target and target mean dose were calculated and analyzed. The *HI* was calculated as follows [8].

$$\textit{Homogeneity index (HI)} = D_{5\%}/D_{95\%} \qquad (1)$$

To assess the delivered dose to normal tissue, the values of *gradient measure (GM)* and body mean doses were calculated and analyzed. The value of *GM* was calculated as follows [9].

Gradient measure (GM) = the radius of equivalent sphere of 50% prescription isodose line – the radius of equivalent sphere of prescription isodose line (2)

After that, MU in association with target size and location were compared.

3. RESULTS AND DISCUSSION

1. Results of symmetric target

Since 98% of target volume was set to be covered by 98% of prescribed dose in every target, the con-

Table 1. $D_{95\%}$ and $D_{5\%}$ of Flattening-filter free and Flattening-filtered Plan for Symmetric Target.

Target diameter (cm)	$D_{95\%}$*				$D_{5\%}$			
	6 MV photon beam		10 MV photon beam		6 MV photon beam		10 MV photon beam	
	FF† (%)	FFF‡ (%)	FF (%)	FFF (%)	FF (%)	FFF (%)	FF (%)	FFF (%)
2	98.6	98.7	98.8	98.7	104.2	104.6	106.4	103.9
5	98.8	98.7	101.6	99.3	103.3	104.5	106.4	104.6
10	98.8	98.9	98.9	99.1	103.4	103.7	103.6	104.7
15	98.9	99.1	99.1	99.4	103.8	105.5	104.3	108.6

*$D_{n\%}$ = dose received by n% volume of target volume, †FF = flattening filtered, ‡FFF = flattening-filter free

Table 2. Homogeneity Index of Flattening-filter Free and Flattening-filtered Plan for Symmetric Target.

Target diameter (cm)	6 MV photon beam		10 MV photon beam	
	FF*	FFF†	FF	FFF
2	1.06	1.06	1.08	1.05
5	1.05	1.06	1.05	1.05
10	1.05	1.05	1.05	1.06
15	1.05	1.06	1.05	1.09

*FF = flattening filtered, †FFF = flattening-filter free

Table 3. Target Mean Dose of Flattening-filter Free and Flattening-filtered Plan for Symmetric Target.

Target diameter (cm)	6 MV photon beam		10 MV photon beam	
	FF* (%)	FFF† (%)	FF (%)	FFF (%)
2	101.6	101.7	103.5	101.9
5	101.0	101.6	104.5	102.7
10	101.3	101.3	101.9	102.4
15	101.7	102.6	102.3	105.0

*FF = flattening filtered, †FFF = flattening-filter free

Table 4. The Value of Gradient Measure of Flattening-filter Free and Flattening-filtered Plan for Symmetric Target.

Target diameter (cm)	6 MV photon beam		10 MV photon beam	
	FF* (cm)	FFF† (cm)	FF (cm)	FFF (cm)
2	1.4	1.3	1.3	1.3
5	2.1	2.1	1.8	1.9
10	3.2	3.3	2.8	2.8
15	3.9	4.0	3.5	3.6

*FF = flattening filtered, †FFF = flattening-filter free

Table 5. Body Mean Dose of Flattening-filter Free and Flattening-filtered Plan for Symmetric Target.

Target diameter (cm)	6 MV photon beam		10 MV photon beam	
	*FF (%)	†FFF (%)	FF (%)	FFF (%)
2	7.2	7.1	6.4	6.5
5	14.1	14.3	13.5	13.2
10	26.1	26.1	24.5	24.4
15	36.4	37.1	35.2	35.9

*FF = flattening filtered, †FFF = flattening-filter free

Table 6. Monitoring Unit of Flattening-filter Free and Flattening-filtered Plan for Symmetric Target.

Target diameter (cm)	6 MV photon beam		10 MV photon beam	
	FF*	FFF†	FF	FFF
2	354	374	266	298
5	284	336	238	270
10	264	318	214	274
15	250	302	208	270

*FF = flattening filtered, †FFF = flattening-filter free

formity was identical in every plan. The value of $D_{95\%}$ and $D_{5\%}$ was shown in Table 1. To compare the $D_{95\%}$ between FF and FFF, no noticeable differences were observed in both 6 MV and 10 MV photon beam. Similar results were observed in $D_{5\%}$. The *HI* shown in Table 2 was not changed significantly according to the size of target and no noticeable differences were observed between FF and FFF. Target mean dose was shown in Table 3. In the case of 6 MV results, no differences in target mean dose were observed between FF and FFF. However, in the case of 10 MV results, as increasing the size of target volume, target mean dose was increased in FFF mode.

The values of *GM* listed in Table 4 showed no significant differences between FF and FFF showing that the maximum difference was 1 mm. The *GMs* of 10 MV were smaller than those of 6 MV. In the case of body mean shown in Table 5, there were no noticeable differences between FF and FFF. To compare 6 MV and 10 MV, body mean doses by 10 MV were smaller than those of 6 MV.

Table 6 and Fig. 4 show the total MU required for each plan. To compare 6 MV and 10 MV, plans with 6 MV required more MU than those with 10 MV. Treatment plans with 6 MV needed 56 MU more on average than 10 MV. Treatment plans in FFF mode required 46 MU more than those in FF more on average. The averaged total MU of FFF plans was 15% and 19% higher than that of FF plans when using 6 MV and 10 MV photons, respectively. As increasing the target size, the required MUs were generally decreased. The treatment times in FFF mode and FF

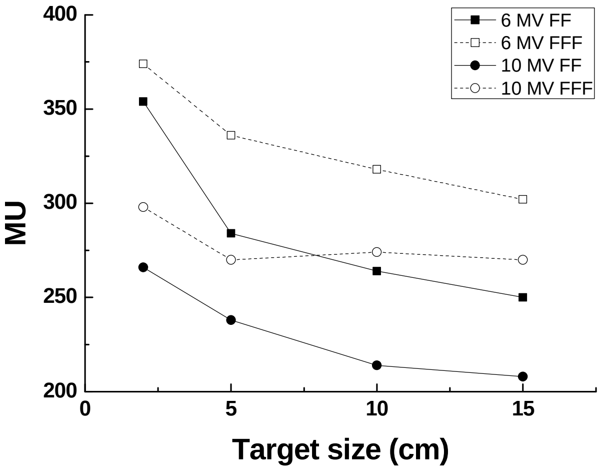

Fig. 4. Required monitoring units (MU) to achieve same conformity of target and target coverage with various photon energies are shown for each symmetric target. As increasing the target size, required MU generally decreased. Plans with flattening filter free (FFF) beams required more MU than those with flattening filter (FF) beams.

mode were both 118 sec showing same values. The differences in the treatment time between FFF mode and FF mode was not observed since the treatment plans were generated using two full arcs to deliver prescription dose of 100 cGy which was much smaller than those of SBRT. The conventional dose rate of 600 MU/min in the FF mode was enough to deliver the prescription dose of 100 cGy by the VMAT technique of two full arcs with maximum speed of gantry rotation. The treatment time of 118 sec was the time of the two full gantry rotations with maximum speed in both FFF plans and FF plans in this study.

2. Results of asymmetric target

Same as the results of symmetric targets, the conformity for asymmetric target was identical in every plan since 98% of target volume was set to be covered by 98% of prescribed dose in every target. The value of $D_{95\%}$ and $D_{5\%}$ was shown in Table 7. To compare $D_{95\%}$ between FF and FFF, no noticeable differences were observed in both 6 MV and 10 MV photon beam. Similar results were observed in $D_{5\%}$. The *HI* shown in Table 8 demonstrated no significant changes in FF mode according target size. However, as increasing target size, the value of *HI* became worse in FFF mode. In the case of target mean dose listed in Table

Table 7. $D_{95\%}$ and $D_{5\%}$ of Flattening-filter Free and Flattening-filtered Plan for Asymmetric Target.

Target diameter (cm)	$D_{95\%}$*				$D_{5\%}$			
	6 MV photon beam		10 MV photon beam		6 MV photon beam		10 MV photon beam	
	FF† (%)	FFF‡ (%)	FF (%)	FFF (%)	FF (%)	FFF (%)	FF (%)	FFF (%)
2	98.9	99.3	98.9	98.9	104.1	107.1	103.9	104.9
5	99.2	99.2	99.2	99.2	104.4	105.7	104.3	104.7
10	99.2	99.7	99.5	99.8	105.0	112.6	105.4	118.9
15	98.7	100.8	99.2	100.3	103.8	116.1	105.7	128.6

*$D_{n\%}$ = dose received by n% volume of target volume, †FF = flattening filtered, ‡FFF = flattening-filter free

Table 8. Homogeneity Index of Flattening-filter Free and Flattening-filtered Plan for Asymmetric Target.

Target diameter (cm)	6 MV photon beam		10 MV photon beam	
	FF*	FFF†	FF	FFF
2	1.05	1.08	1.05	1.06
5	1.05	1.07	1.05	1.06
10	1.06	1.13	1.06	1.19
15	1.05	1.15	1.07	1.28

*FF = flattening filtered, †FFF = flattening-filter free

Table 9. Target Mean Dose of Flattening-filter Free and Flattening-filtered Plan for Asymmetric Target.

Target diameter (cm)	6 MV photon beam		10 MV photon beam	
	FF* (%)	FFF† (%)	FF (%)	FFF (%)
2	102.3	103.8	102.1	102.8
5	102.3	102.8	102.4	102.6
10	102.5	106.8	103.1	109.6
15	101.5	108.7	102.7	112.7

*FF = flattening filtered, †FFF = flattening-filter free

Table 10. The Value of Gradient Measure of Flattening-filter Free and Flattening-filtered Plan for Asymmetric Target.

Target diameter (cm)	6 MV photon beam		10 MV photon beam	
	FF* (cm)	FFF† (cm)	FF (cm)	FFF (cm)
2	1.5	1.4	1.5	1.5
5	2.3	2.2	2.2	2.1
10	3.4	3.4	3.0	3.0
15	3.9	3.8	3.5	3.6

*FF = flattening filtered, †FFF = flattening-filter free

Table 11. Body Mean Dose of Flattening-filter Free and Flattening-filtered Plan for Asymmetric Target.

Target diameter (cm)	6 MV photon beam		10 MV photon beam	
	FF* (%)	FFF† (%)	FF (%)	FFF (%)
2	6.5	6.8	6.4	6.4
5	13.4	13.2	12.6	12.3
10	24.0	25.3	23.5	24.6
15	34.4	37.5	33.9	37.1

*FF = flattening filtered, †FFF = flattening-filter free

Table 12. Monitoring Unit of Flattening-filter Free and Flattening-filtered Plan for Asymmetric Target.

Target diameter (cm)	6 MV photon beam		10 MV photon beam	
	FF*	FFF†	FF	FFF
2	403	480	323	440
5	370	420	288	376
10	262	342	208	314
15	212	276	180	240

*FF = flattening filtered, †FFF = flattening-filter free

9, FF mode showed no differences in target mean dose as increasing the target size while it increased as increasing the size of target volume in FFF mode.

The values of *GM* were shown in Table 10. No significant differences were observed between FF and FFF mode showing the maximum difference of 1 mm. The *GMs* of 10 MV were generally smaller than those of 6 MV. Body mean dose listed in Table 11 was generally smaller in FF mode than FFF mode. To compare 6 MV and 10 MV, body mean doses by 10 MV were smaller than those of 6 MV.

Table 12 and Fig. 5 show the total MU required for each plan. To compare 6 MV and 10 MV, plans with 6 MV required more MU than those with 10 MV. Treatment plans with 6 MV needed 50 MU more on average than 10 MV. Treatment plans in FFF mode required 80 MU more than those in FF mode on average. Total MU of FFF plan was 21% and 32% was higher than that of FF when using 6 MV and 10 MV photons, respectively. As increasing the target size, the required MUs were generally decreased. The treatment times in FFF mode and FF mode were both 118 sec showing same values as the results of symmetric targets.

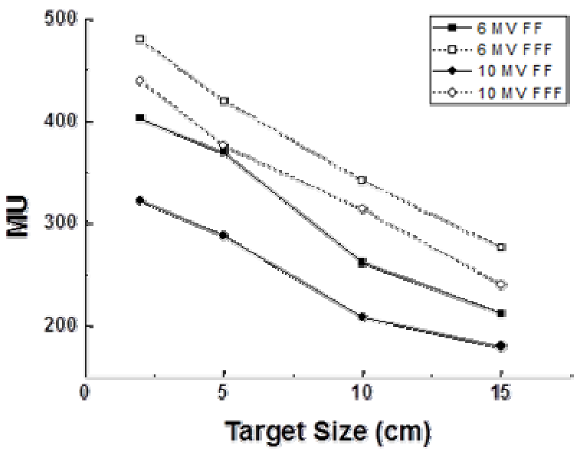

Fig. 5. Required monitoring units (MU) to achieve same conformity of target and target coverage with various photon energies are shown for each asymmetric target. As increasing the target size, required MU decreased. Plans with flattening filter free (FFF) beams required more MU than those with flattening filter (FF) beams.

4. DISCUSSION

In this study, the MU efficiency between FF and FFF photon beam has been investigated keeping the conformity of the target and target coverage maintaining same.

The target mean doses increased slightly in both symmetric and asymmetric target when using FFF beam. Since the target coverage was set to be $D_{98\%}$ should be 98% of prescription dose, increased target mean dose indicated the homogeneity in target became worse. In 6 MV FFF plans, the worsening of *HI* was not clearly observed while it was clearly observed when using 10 MV FFF beams which have profiles more pointed out. However, the amount of difference was not significant as shown in results. To analyze the *GM* and body mean dose, there were no noticeable differences between FF and FFF while clear differences were observed between 6 MV and 10 MV. This is quite reasonable since the energy of 10 MV photon beam is higher than that of 6 MV photon beam. Therefore, photon beams of 10 MV cause less tissue lateral effect than 6 MV beams resulting in less irradiation to normal tissue [10]. In conclusion, there were generally no significant differences in terms of plan quality with or without a flattening filter, similar with previous studies [11-14].

Noticeable differences in MU were observed between FF and FFF beams. At the same energy, FFF beams always required more MUs than FF beams, *i.e.* FFF beams needed more MUs to maintain similar plan quality. Generally, more MUs were needed for asymmetric target than symmetric target in FFF mode except at the very large target with a diameter of 15 cm. Since dose rate decreases as increase of off-axis distance in FFF mode, the MU was needed more for asymmetric target than symmetric target. However, since the center of asymmetric target was at 7.5 cm away from the patient center and the radius of large target was 7.5 cm, the effect of off-axis distance in FFF mode became weak for this large target. This might explain why the tendency was not observed for the target with diameter of 15 cm.

As increasing the target size, required MUs decreased. As the target size increases, the field size also increases. The patient scatter factor and head scatter factor increases as increasing field sizes, consequently, increase of target size needed less MU. This tendency was also observed in FF mode.

The reduction of the treatment time which is the main benefit of FFF mode was not observed in this study since the prescription dose was 100 cGy which was much smaller than those of SBRT. Therefore, unless the treatment plan requires large MU in a small rotation of gantry angle such as the highly-modulated plan, the high dose rate of the FFF mode seems to be no more beneficial for the fractionated radiation therapy.

The results shows that even symmetric targets with diameters less than 5 cm needed more MUs in FFF mode than FF mode. Even though the diameters were less than 5 cm, the longitudinal length was 10 cm in this study. Therefore, it is explainable the contradictory results in this study compared to previous studies about small target in FFF mode [15,16].

5. CONCLUSION

In this study, it has been demonstrated that VMAT plans with FFF beams for large targets were possible to yield similar qualities of plans with FF beams while spending more MU than FF VMAT plans. It is advisable that FF beam is more beneficial than FFF beam in terms of MU efficiency for large targets.

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