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Dosimetric evaluation of volumetric modulated arc therapy with simultaneous integrated boost hypofractionated radiation based on two types of multileaf collimators for prostate cancer

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ABSTRACT

For localized prostatic adenocarcinoma, hypofractionated radiation has been shown to minimize treatment times while producing results that are similar to those of conventionally fractionated radiotherapy; therefore, volumetric modulated arc therapy (VMAT) plans face a real challenge in achieving the dosimetric parameters for planning target volumes (PTVs) and organs at risk (OARs).The aim of this study is to compare the plan quality and dosimetric effects of two types of multi-leaf collimators (MLCs) on simultaneous integrated boost (SIB) hypofractionated prostate cancer treatment using VMAT. Using the VMAT procedure, ten patients with prostate cancer were re-planned with two separate MLCs. For each patient, two treatment plans were carried out.

The dose volume histogram (DVH) for PTVs and OARs, as well as the conformity index (CI) and homogeneity index (HI) with 5mm vs. 10mm MLC width, were used to examine the dosimetric parameters. The prescribed doses for the prostate gland (PTV_p) and the pelvic nodes (PTV_n) are 60 Gy/20fractions and 44 Gy/20fractions, respectively. In treatment plans for Agility to MLCi2, HI and CI were improved. For Agility MLC, the p-values for HI and CI were 0.017 and 0.008, respectively. When compared to MLCi2, the dose distribution for PTVs was improved with Agility MLC. When compared to MLCi2, the delivery time with Agility MLC was reduced by 31%. With Agility MLC, the smallest leaf width results in a dosimetric benefit for PTV.

INTRODUCTION

External-beam radiotherapy (RT) is a therapeutic alternative for patients who need cancer treatment [1]. In a significant proportion of them, RT is thought to be the mainstay of care. The aim of RT preparation was to provide a higher radiation dose to the targeted tumor while avoiding the healthy organs in the surrounding area [2]. Prostate cancer has recently become one of the most common forms of tumors among men all over the world [1]. Volumetric modulated arc therapy (VMAT) has become a common technique for prostate care because it reduces the treatment time and allows less machine units (MUs) [3-4].VMAT became one of the high-accuracy treatments with image guidance in modern RT techniques, allowing for less excessive dose around the organs at risk (OARs) surrounding the target volume as well as a better patient and target positioning [5-6]. For cancer patients, hypo fractionated radiotherapy has the advantage of minimizing treatment times while achieving outcomes that are equivalent to conventionally fractionated radiotherapy [4]. The VMAT system incorporates gantry rotation speed, multileaf collimator (MLC) continuous motion, and dose rate modulation into a single unit. Due to the complex volume target shapes and the multiple dose dosage levels, VMAT treatment can necessitate more than two arcs to improve dosimetric distribution [7,8]. The most suitable method for beam forming is the MLC, which is built with a tongue-and-groove shape on the side of each leaf to reduce interleaf

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radiation leakage and to distinguish each design of head linear accelerator [2,9,10]. However, since radiation transmission through the leaves is not uniform, MLC rotation in the VMAT will help to reduce interleaf radiation leakage [4, 9]. The width of MLC can be reduced to render an accurate irradiated area [2]. The MLCs in most linear accelerators have been redesigned as the value of the leaf width has increased [11].Each type of MLC has its own leaf distance, maximum leaf speed, and minimum gap between opposing leaves, as well as inter-digitation abilities [11].Over the previous two decades, MLC hardware and controller software had been gradually improving. The American Association of Physicists in Medicine Report No.72 [12] outlined the various operating limits, physical characteristics, and types of MLC architecture. The aim of this study is to compare the dosimetric effects of MLCs agility (10mm) versusMLCi2(5 mm) for prostate cancer treatment using the VMAT technique.

2. PATIENTS AND METHODS

2.1. Patient and Treatment planning:

Ten patients with high risk prostate cancer (pelvic node involvement) were selected for this planning study. Patients were asked to evacuate the rectum and let the bladder comfortably full before undergoing computed tomography (CT) simulation. Three reference markers are added to the skin of the participants. Serial CT cuts were rendered with a 2.5 mm slice width. The images were then transferred to the focal contouring station, where the objective target (Clinical target volume CTV and Planning target volume PTV) and OARs were delineated. The proximal 10 mm of the seminal vesicles were included in the prostate gland, which was described as CTV 60Gy.The PTV 60Gy was designed to expand 7 mm in all directions except 4 mm posteriorly. CTV 44 Gy, which includes the distal typical iliac, external and internal iliac, and obturator vessels, was used to characterize the pelvic lymph node. PTV 44Gy was built with a thickness of 7 mm in all directions. Both plans utilized a hypofractionated dose with simultaneous integrated boost (SIB). plans were created by VMAT on Monaco planning system, with energy 6MV. The dose to the prostate (PTV_p) 60Gy/20fractions and pelvic nodes (PTV_n) 44Gy/20 fractions was prescribed to minimize radiation complexity[13-14].

2.2. Dosimetric analysis

Both agility MLC (5mm width, Agility Elekta AB, Stockholm, Sweden) and MLC i2(10 mm width, Elekta synergy platform) plans were normalized by making 95% of the PTV receive 95% of the prescribed dose to conduct the dosimetric study of MLC leaf width and evaluation.PTV and OARs were calculated and evaluated using dose-volume histograms (DVH). The same constraints were applied to both plans for this study. For the two MLC plans, meeting OARs constraints took precedence over target coverage. The treatment plan's efficiency was measured using monitor units (MUs), time delivery, and dosimetric indices such as conformity index (CI), homogeneity index (HI), and normalized dose contrast (NDC) [4,11]. According to the report(ICRU) 62 published by the International Commission on Radiation Units and Measurements , the volume percentage of the target volume irradiated by at least 95 % of the prescription dose was calculated ($V_{95\ \%}$). The doses distribution of prostate gland and lymph nodes for both MLC types is shown in Figure (2). Homogeneity index (HI) was defined as:

$$HI = \frac{(\mathbf{D2\% - D98\%})}{\mathbf{Prescribed\ dose}} \qquad \textbf{(1)}$$

Where, $D_{2\%}$ is the dose received by 2% of PTV, $D_{98\%}$ is the dose received by 98% of PTV (HI= 0).

The conformity index (CI) was defined as:

$$CI = \frac{\mathbf{V100\%\ prescribed\ dose\ for\ PTV}}{\mathbf{Volume\ PTV}} \qquad \textbf{(2)}$$

Where, $V_{100\%}$ prescribed dose is the volume of the PTV receiving the dose prescriptions (CI =1). The normalized dose contrast (NDC), was used to compare the dose gradient for SIB plans (NDC =1).

$$NDC = \frac{\mathbf{ActualDC}}{\mathbf{IdealDC}} \qquad \textbf{(3)}$$

Actual DC was equal to the mean dose of (PTV_p) divided by the mean dose of (PTV_n), while, the ideal DC was calculated from the ratio between the prescribed dose of (PTV_p) to the prescribed dose of (PTV_n). Mean dose, maximum dose, V_{60}Gy, V_{56}Gy, V_{52}Gy, and V_{48}Gy of the rectum, as well as V_{60}Gy, V_{56}Gy, and V_{52}Gy of the bladder, were calculated for OAR. The average dose for the penile bulb did not exceed 42 Gy. The maximum dose was calculated for each femoral head. V_{45}Gy and D_5 mL for the small bowel bag [15].

2.3. MLC properties

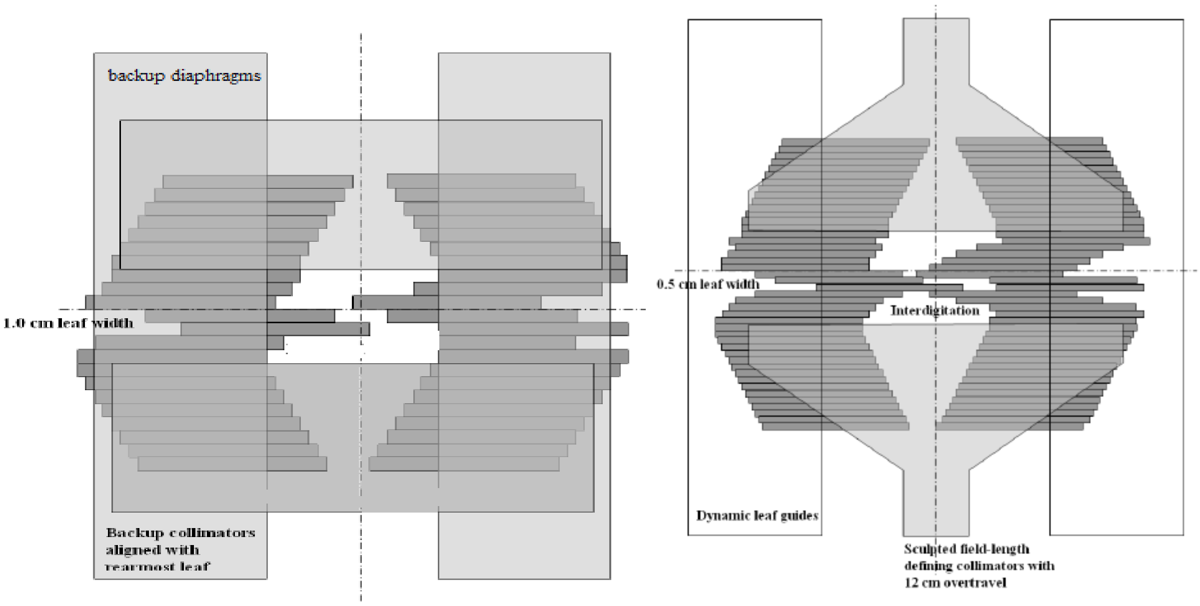
In this research, the differences in leaf width between two linear accelerator head designs of MLC parts were investigated. MLCi2 parts (Elekta Synergy) are found in one, while Agility MLC parts are found in the other (Elekta Versa HD). The Agility MLC is made up of 80 leaf pairs with a maximum field size of 40 cm x 40 cm, each 5-mm wide, projected at the iso-center, giving the leaves the ability to travel up to 15 cm over the central axis of the beam at a leaf speed of 6.5 cm/s and a minimum distance of 3 mm between opposite leaves joined with a dynamic leaf index [11]. There are no backup collimators moving in the leaf motion direction, and Inter-digitation will help [16,17]. The isocenter of the MLCi2 head, on the other hand, has 40 pairs of leaves with a leaf width of 10 mm. The overall field size was 40 cm x 40 cm, with a leaf pace of 2 cm/s and a 5 mm distance between leaves. To mitigate interleaf leakage, leaves have auto tracking backup diaphragms beyond them, but these do not affect leaf speed like the dynamic leaf guides in the agility head. MLCi2 has a maximum space between leaves of 32.5 cm on the same leaf directory, leaves can move up to 12.5 cm along the central axis, and leaves support inter-digitization [11]. Table1 and Figure 1(A and B), summarize the difference between two types of MLCs.

Statistical methods

The data were analyzed using the Statistical Package of Social Science (SPSS) (version 26). Data were presented as mean ± standard deviation. The normality of the data was tested using the Shapiro-Wilk’s test. The data were not normally distributed, so a comparison of paired data was conducted using Wilcoxon Signed Ranks test. A p-value < 0.05 was considered significant.

Table (1): Differences between MLC agility and MLCi2

MLC parameters	MLCi2	MLC Agility
Leaf width	10 mm	5mm
Leaf speed	2cm/s	6.5cm/s
Minimum leaf gap	5mm	3mm
Inter-digitation	-/+	+
Backup jaws	Yes	no



(A) **(B)**

Fig. (1): (A and B) shows the simple design to Agility MLC and MLCi2 [17]

3. RESULTS

Both VMAT plans with MLC agility and MLC i2 met the acceptance criteria for the dose prescriptions. The dose-volumetric parameters of both agility MLC and MLCi2 plans for the PTVs are shown in Table (2). The dose volume histogram (DVH) for PTV60 and PTV44 is shown in Figures (3 and 4). MLC agility had a higher target volume coverage than MLCi2 however, OARs sparing met the criteria for both MLC types. For PTV60, agility MLC shows a better target coverage than MLCi2. D_{98}%, $D_{95\%}$, $D_{50\%}$, D_{min} and D_{mean} for agility was significantly higher than MLCi2(p=0.007,0.008,0.014,0.037 and 0.034 respectively). The homogeneity, conformity indices and the normalized dose contrast (NDC) showed a significantly better plan quality for agility MLC than MLCi2 (p=0.017, 0.008 and 0.011) respectively. Agility MLC plans were delivered significantly faster than MLCi2 plans (P=0.007). However, it requires a higher monitor units (MUs) than MLCi2. For PTV44, the mean dose is nearly similar for both MLC types. There were no significance differences for comparing the agility MLC and MLCi2 in terms of $D_{2\%}$, $D_{98\%}$, $D_{95\%}$, D_{max}, $D_{mean.}$, homogeneity and conformity index. The only significant value was seen in Dmin for agility MLC (P= 0.022). The actual delivery time was shorter with agility MLC by 31% than MLCi2.

Table (2): Dose volume parameters comparison and treatment efficiency used in both MLC types

PTV60Gy	Agility mean ±SD	MLCi2 mean ±SD	P-value
$D_{2\%}$ (Gy)	63.8 ± 0.7	63.3 ± 0.55	0.021
$D_{98\%}$ (Gy)	58.3 ± 1.2	56.9 ± 1.05	0.007
$D_{95\%}$ (Gy)	59.3 ± 0.71	58.2 ± 0.71	0.008
$D_{50\%}$ (Gy)	61.7 ± 0.51	61.1 ± 0.4	0.014
D_{max} (Gy)	66 ±0.98	65.6±0.87	0.085
D_{min} (Gy)	51.3 ± 5	47.6 ±6	0.037
D_{mean} (Gy)	61.5 ±0.53	61±0.4	0.034
Homogeneity index	0.09 ±0.02	0.11 ±0.02	0.017
Conformity index	0.89±0.054	0.78±0.1	0.008
PTV44Gy			
$D_{2\%}$ (Gy)	56.5 ±0.91	56.2 ±0.78	0.092
$D_{98\%}$ (Gy)	42.8 ±0.5	42.4 ±0.7	0.093
$D_{95\%}$ (Gy)	43.6 ±0.4	43.2 ±0.6	0.086
$D_{50\%}$ (Gy)	46.2 ±0.3	45.97 ±0.2	0.046
D_{max} (Gy)	63 ±1.1	63 ±1.83	0.919
D_{min} (Gy)	37.1 ±2.99	35.5 ±1.9	0.022
D_{mean} (Gy)	46.7 ±0.2	46.5 ±0.31	0.065
Homogeneity index	0.29 ±0.01	0.31±0.02	0.067
Conformity index	0.92 ±0.02	0.89 ±0.05	0.083
Monitor units (MUs)	1528.6 ±267.2	1398 ±230.3	0.093
Time delivery (Sec)	318.5 ±21.1	461.1 ±90.65	0.007
NDC	0.97 ±0.001	0.96 ±0.001	0.011

Data were presented as mean ±Standard Deviation (SD), Where D_{min}: Dose minimum, D_{max}: Dose maximum, Gy: Gray, D2%: dose at 2% volume and NDC: normalized dose contrast. Sec: seconds

Table (3) shows a detailed summary of the OARs results. The constraints for the maximal and mean dose to the rectum, bladder, V56 andV52 were achieved with both MLC types. MLCi2 showed a significantly lower maximum dose in the bladder (p=0.028) and the V60 for bladder and rectum(p=0.028 and 0.013). MLCi2 was significantly lower in D45 Gy and D_5ml, for bowel bag (p= 0.013 and 0.037) than agility MLC but the differences were not significant in both femoral head and penile bulb.

Table (3): Dosimetric comparison of OARs between agility MLC and MLC i2

OARs Parameters	Agility mean ±SD	MLCi2 mean ±SD	P-value
Bladder			
V_{60}Gy<25%	9.6 ±6.2	7.2 ±7.7	0.028
V_{56}Gy<35%	16.7 ±9.3	15.6 ±10.9	0.066
V_{52}Gy<50%	22 ±12.3	21.6 ±13.3	0.678
mean dose	36.7 ±5.8	37.7 ±6.2	0.407
maximum dose	65.3 ±0	64.2 ±1.3	0.028
Rectum			
V_{60}Gy <15%	4.2 ±3.3	3 ±3.13	0.013
V_{56}Gy<25%	9.6 ±4.2	9.1 ±5.4	0.333
V_{52}Gy<35%	14.6 ±4.9	14.8 ±6.6	0.594
mean dose	37.1 ±3	37.2 ±3.50	0.185
maximum dose	63.8 ±1.5	63.1 ±1.2	0.066
Femoral head max. dose <45Gy			
Right	39.3 ±2.6	39.2 ±3.1	0.440
Left	39 ±2.1	39.8 ±2.8	0.514
Bowel bag			
V_{45}Gy<200ml	76.2 ±53.1	57.9 ±46.8	0.013
D_5ml <60Gy	48.4 ±1.2	47.7 ±1.3	0.037
Penile bulb			
D_{mean}<45Gy	23.3 ±10	24.7 ±8.3	0.610

Data were presented as mean ±Standard Deviation (SD), V: Volume, D: Dose, Gy: Gray

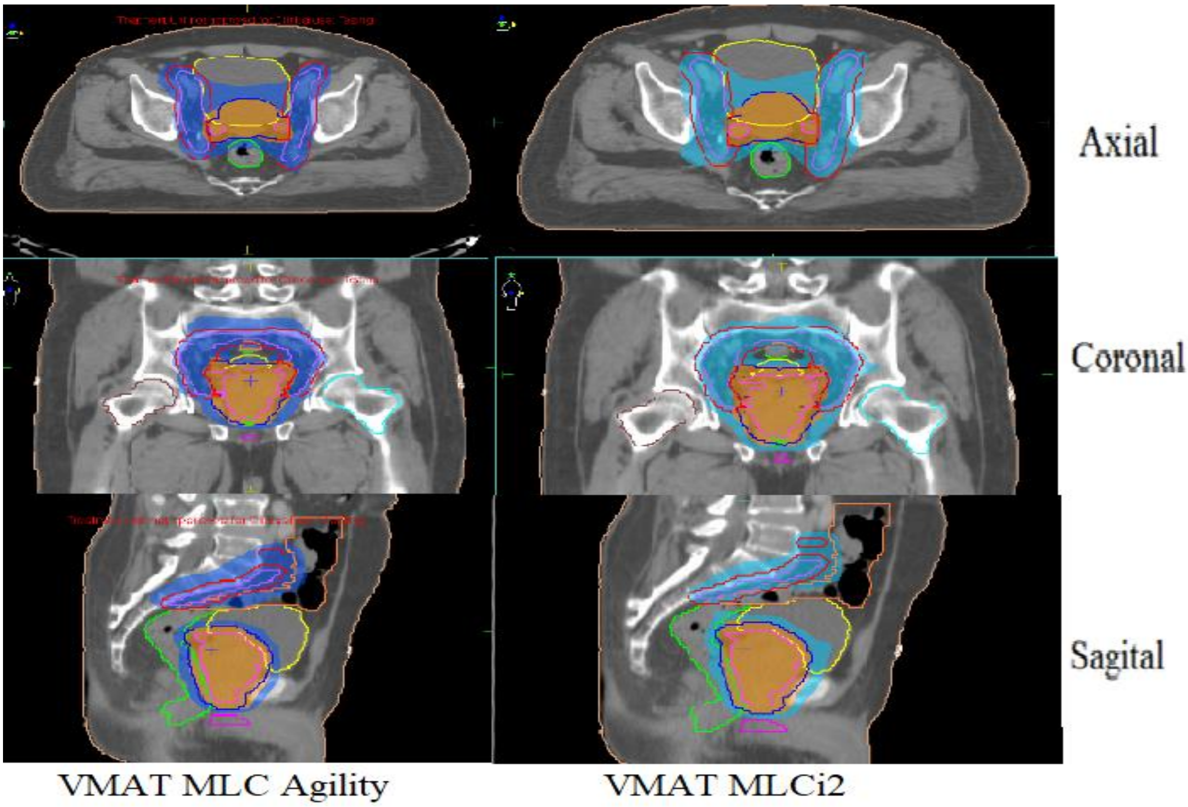


Fig. (2): The doses distribution of prostate gland and lymph nodes using VMAT plans for both MLC types

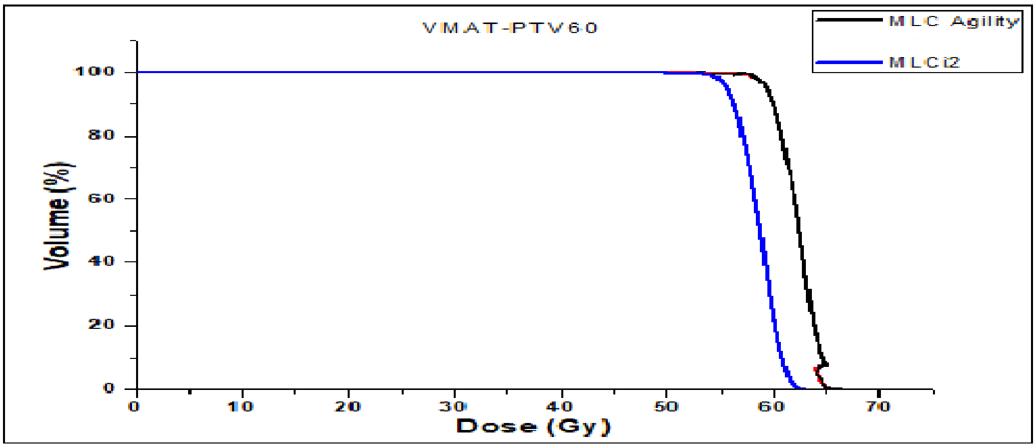


Fig. (3): Dose-volume histograms of both types MLC plans for PTV 60.

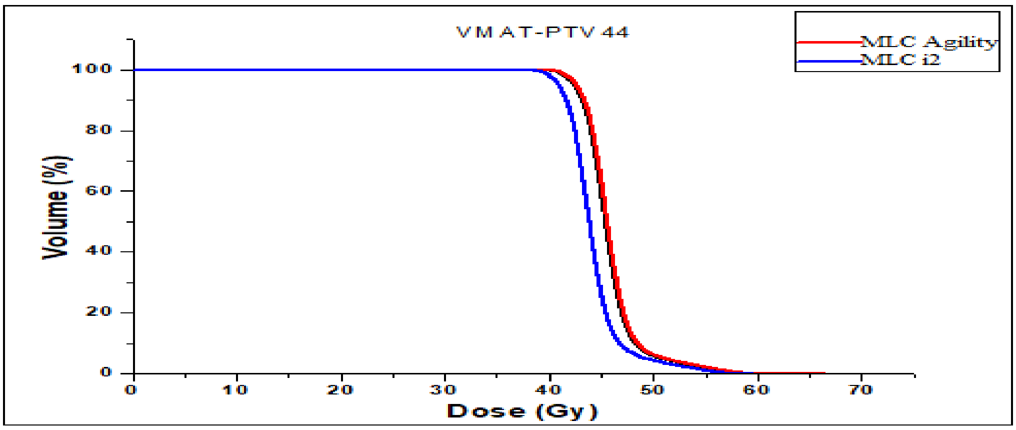


Fig. (4): Dose-volume histograms of both types MLC plans for PTV 44

4. DISCUSSION

The design of MLC in a linear accelerator is one of the factors that helped in the development of radiotherapy to be used in advanced treatment which needs to deliver a higher dose to the target and avoids the normal tissues at the same time. As a result, a smaller leaf width is expected to result in better beam shaping, resulting in an increased dose around the target and lower doses to normal tissues [19]. In addition, the leaf width of MLCs is significant in the planning framework because it allows the plan to be completed with fewer segments, monitoring units, and time [11]. Several studies have looked into the impact of MLC leaf width on various tumor sites. Chase et al. [20] investigated the impact of MLC leaf widths between 2.5 and 5 mm on target coverage and gradient index while using VMAT techniques for spine lesion care. They found that the smaller MLC leaf 2.5-mm MLC increased target coverage and gradient index. Wu et al. [21] compared the impact of MLCs on a prostate case between 4 mm MLC and 10 mm MLC. With 4 mm MLC, the results were improved to achieve a more conformal dose distribution with no difference in the target DVH. Kubo et al. [22] investigated the effects of various MLCs on prostate cancer. The small leaf width was found to be more effective in rectum and bladder dose sparing. The dosimetric effect of 2.5, 5, and 10-mmMLCs in dynamic IMRT for prostate and head and neck cancer was studied by Jacob et al. [23]. Small variations in target coverage were discovered in the results. Blümer and colleagues used VMAT technique to investigate the impact of leaf width on two forms of MLCs (5mm and 10mm). When compared to 10-mm MLCs in the target volume, the plan's HI and CI were improved with 5-mm MLCs. Jin et al. and Dvorak et al. [25,26] used the IMRT technique to demonstrate MLC leaf width between 10mm and 3mm. The use of 3-mm wide MLC increased the CI and target volume coverage (TVC) significantly. In the present study, it was found that PTV with Agility MLC has strong dosimetric advantages over MLCi2 in the treatment of prostate cancer patients. The results of the present study showed that the smaller leaf of MLC improved the dosimetric parameters in PTV 60 significantly. In addition, Agility MLC had the maximum V 95 %for PTVs as compared to MLCi2. As a result, with the smallest leaf width, the dose distribution in the PTV was increased. In two VMAT plans, the mean values for homogeneity and conformity in PTV 60 with Agility MLC (0.09 and 0.89, respectively) were increased as compared to (0.11 and 0.78) MLCi2. Except for some DVH parameters with large values with MLCi2, such as bowel pocket, the results for DVH of OARs with different types of MLCs were relatively similar. However, DVH for OARs revealed the same findings as other MLCs: smaller leaves (agility) were able to escape OARs as as the larger leaves, but coverage for PTV increased as leaf width decreased. Although MLCi2 achieved constraints around OARs, PTVs coverage was lacked. SIB-plan efficiency was assessed using the NDC factor for plan parameters. The NDC value at Agility MLC was higher than that at MLCi2. Furthermore, the leaf distance, transportation, and maximum leaf speed may all have an effect on the quality of VMAT plans [10]. When compared to MLCi2, the Agility MLC has a faster leaf travel speed, which helps with the treatment delivery. When compared to MLCi2, the most notable benefit of Agility MLC is the reduction in delivery time by 31%. During radiation delivery, the patient becomes more relaxed and the intra-fraction motion of organs is reduced, as predicted. The VMAT technique aided in reducing the treatment time and delivering several doses in a single fraction to different locations.

5. CONCLUSION

The efficiency of VMAT plans can be influenced by MLC widths. Accordingly, MLC with a 5-mm width demonstrated superior dosimetric properties, including improved dose conformity, homogeneity to the target, and OARs sparing. In addition, by using VMAT, agility MLC can provide patient with care substantially faster than MLCi2.

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