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ORIGINAL ARTICLE

Investigating the Influence of Minimum Segment Width in Volumetric-modulated Arc Planning of Prostate Cancer

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OBJECTIVE

This study aims to investigate the impact of the minimum segment width on the planning outcomes of volumetric-modulated arc therapy (VMAT) in patients with prostate cancer and find the optimum value(s) for this parameter.

METHODS

A retrospective analysis was conducted on 12 patients with prostate cancer who underwent VMAT treatment. For every patient, four treatment plans were created using different values of MSW (0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm). Other optimization parameters and objective constraints were kept the same across every case. Several dosimetric parameters were evaluated, including target coverage (D_{mean} - Mean dose to the planning target volumes [PTV], D_{max} - Maximum dose to the PTV, conformity index, homogeneity index) and dose to the organ at risk. In addition, delivery efficiency metrics such as the number of control points, monitor units, and treatment time were assessed. Statistical analyses were performed using Wilcoxon signed-rank test.

RESULTS

Narrower segments (MSW0.5) yielded improved PTV coverage and conformity, while wider segments (MSW2.0) led to faster treatment delivery but compromised dosimetric parameters. There was no statistically significant difference between MSW0.5 and MSW1.0 ($p>0.05$) while the other MSW values showed statistically significant differences ($p<0.05$).

CONCLUSION

Based on the analysis of the plan quality and delivery efficiency, an MSW value of 1.0 cm exhibits optimal features in prostate cancer treatment plans. Further investigation with a larger number of patients and assessment of clinical outcomes is necessary to validate this conclusion.

Keywords: Minimum segment width; MSW; prostate cancer; VMAT; volumetric-modulated arc planning.

INTRODUCTION

Prostate cancer is one of the most prevalent cancers among men, with a significant impact on their health and quality of life.[1] The treatment of prostate cancer often involves radiation therapy, which plays a crucial role in eradicating cancer cells and reducing the risk of recurrence.[2] In recent years, advancements in radiation therapy techniques have greatly improved treatment outcomes, allowing for more precise targeting of

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tumor volumes while minimizing radiation exposure to healthy surrounding tissues.[3]

One such technique that has gained considerable attention is volumetric-modulated arc therapy (VMAT). VMAT is an advanced form of intensity-modulated radiation therapy that delivers radiation through a continuous arc of motion around the patient. This technique utilizes dynamic modulation of multileaf collimators and gantry rotation to shape the radiation beam precisely, conforming to the tumor's three-dimensional shape. VMAT offers several advantages over conventional radiation therapy techniques, including shorter treatment times, improved dose conformity, and reduced radiation exposure to healthy tissues.[4,5]

The planning process in VMAT involves the optimization of various parameters to achieve the desired treatment goals. One critical parameter in VMAT planning is the minimum segment width (MSW), which determines the width of the individual radiation beam segments used during treatment delivery. The MSW directly influences the treatment plan's quality and efficiency by impacting factors such as dose distribution, target coverage, organ sparing, and treatment delivery time.[6] VMAT plan with a higher value of MSW has fewer monitoring units (MU), less delivery time (PDT), and more delivery efficiency than VMAT plan with a lower MSW.[6–11]

Some studies have demonstrated the superiority of the VMAT plan with lower MSW over the plan with higher MSW.[12,13] Several studies have suggested using an MSW of 1.0 cm for the VMAT plan as compared to an MSW of 0.5 cm.[7–9] Therefore, this study aims to investigate the influence of the MSW on the planning outcomes of VMAT in prostate cancer patients. By systematically varying the MSW value, we will evaluate its impact on various dosimetric parameters, including target coverage, dose conformity, organ at-risk sparing, and treatment delivery efficiency metrics. The findings from this study will contribute to a better understanding of the role of MSW in VMAT planning for prostate cancer and help identify the optimal MSW value(s) that can maximize treatment efficacy while minimizing treatment time and potential side effects.

MATERIALS AND METHODS

Patient Selection

The study included twelve patients (aged between 55 and 68 years) who were diagnosed with prostate cancer and received VMAT treatment at our hospital from January 2022 to November 2022. To ensure accurate treatment, all patients were positioned in the supine position and immobilized using a 4-clamp thermoplastic pelvis mask. A Siemens computed tomography (CT) simulator was used to perform scans, with a slice thickness of 3 mm.

The CT images obtained from the scans were then reconstructed and imported into the Monaco planning system version 5.51.10. The planning target volume (PTVP) encompassed the prostate tumor and seminal vesicles, with a 5-mm margin on all sides except for a 3 mm margin posteriorly. The delineation of PTVLN, which included the pelvic lymph nodes, was performed by experienced oncologists following the institute protocol.

In addition, several organs at risk (OAR) structures were delineated, including the bladder, rectum, femoral heads, cauda equina, sigmoid colon, and bowel bags. These structures were outlined to ensure their protection during the treatment planning process.

Treatment planning

VMAT plans were designed for all patients using the Monte Carlo (MC) algorithm in the Monaco Treatment Planning System (TPS). The Elekta Synergy Linear Accelerator with a 6MV X-ray photon beam was utilized to deliver the plans. A dual arc of 360° rotation was employed for each case, clockwise from 181° to 179°. During gantry rotation, the collimator angle was set to 0° based on the patient's anatomy. The MC algorithm had a statistical uncertainty of 3% per control point, and the final dose calculation used a 3 mm resolution for the calculation grid. Each plan consisted of a maximum of 180 control points (CP).

Four VMAT plans were generated, namely MSW0.5, MSW1.0, MSW1.5, and MSW2.0. These plans had corresponding MSWs of 0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm, respectively. The remaining parameters and cost functions were kept constant. The prescription dose for PTVP was 68Gy delivered in 25 fractions, while for PTVLN, it was 45Gy in 25 fractions. Table 1 displays the cost functions.

Plan Evaluation

The dosimetric indices used to compare the different MSW prostate plans included the homogeneity index (HI), conformity index (CI), maximum dose of the target volume, MUs, CP, and the dose volume histogram (DVH) parameters concerning OARs. The CI and HI were calculated as follows:

$$CI = (TV_{PI})^2/(TVxV_{PI})$$

$$HI = (D_{5\%})/D_{95\%}$$

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Table 1 The optimization cost functions of VMAT plans for prostate cancer

Structure	Cost Function	Parameters	Isoconstraint
PTV P	Target EUD	0.5	68Gy
	Target penalty	95%	68Gy
	Quadratic overdose	69	1Gy
PTV LN	Target EUD	0.5	45Gy
	Target penalty	95%	45Gy
	Quadratic overdose	47 Gy	1Gy
Bladder	Parallel	40 Gy, k=3, Shrink= 0mm	45%
	Parallel	56 Gy, k=3, Shrink =0.2mm	12%
Rectum	Parallel	40 Gy, k=3, Shrink = 0mm	35%
	Parallel	56Gy, k=3, Shrink =0.2mm	15%
Left Femoral Head	Parallel	35 Gy, k=3, Shrink = 0mm	10%
Right Femoral Head	Parallel	35 Gy, k=3, Shrink =0mm	10%
Body	Quadratic overdose	68 Gy, Shrink = 0mm	0.1Gy
	Quadratic overdose	33.56 Gy, Shrink = 1.5cm	0.5Gy
	Conformity		0.70
	Maximum dose		72.7Gy

VMAT: Volumetric-modulated arc therapy; PTV P: Primary planning target volume; EUD: Equivalent uniform dose; PTV LN: Lymph node planning target volume

In the above equations, TVPI represents the target volume receiving the prescription dose, TV represents the total target volume, and VPI represents the volume receiving the prescription dose. Ideally, the CI should be close to 1. The D5% refers to the minimum dose received by 5% of the planning target volume (PTV) according to the DVH, indicating the maximum dose. Conversely, the D95% represents the minimum dose received by 95% of the PTV, indicating the minimum dose. A lower HI indicates better homogeneity.

Plan Verification

The MatriXX Universal Detector Array, manufactured by IBA in Germany, was utilized to compare the plan quality of all the plans in this study. The evaluation of plan quality involved calculating the gamma index and the gamma pass rate (GPR) by comparing the dose fluence generated by the TPS with the measurements obtained from the MatriXX detector.

The GPR was determined by dividing the number of measurement points that met the pre-defined criteria by the total number of measurement points within the specified threshold. To eliminate low-dose signals, a lower limit of 10% was set during the gamma calculation. The analysis of measurements was conducted using a 3% dose difference (DD) and a 3-mm distance to agreement (DTA).

In this study, the global gamma indices were considered clinically acceptable if the GPR for the 3%/3 mm criteria was equal to or greater than 95%. To facilitate the measurements, the immatrix detector was inserted into the miniphantom and positioned on the treatment couch. The iso-plane was set at the depth of the effective point of measurement on the side of MatriXX using the corresponding markers. MatriXX was calibrated at the used photon energy and all plan intended by calibration factors.

Statistical Analysis

To compare dosimetric parameters and measurement results between different groups, the Wilcoxon signed-rank test was employed. The statistical analysis was performed using SPSS 22.0 software. A $p<0.05$ was considered statistically significant, indicating a notable difference between the groups.

RESULTS

Target Doses

Figure 1 shows the DVH graph of VMAT plans with different MSW parameters for a typical patient. In MSW2.0 cases, PTV (primary) and PTV (LN) from the DVH failed to meet the clinical requirement, i.e., for PTV primary D95% = 90%, and for PTV lymph nodes, D95% = 91.2% (<95%).

Table 2 shows the comparison of the mean dose, maximum dose, HI, and CI of the target PTVs. The dosimetric parameters of PTVs' mean dose and maximum dose were comparable among four MSWs plans, but conformity and homogeneity

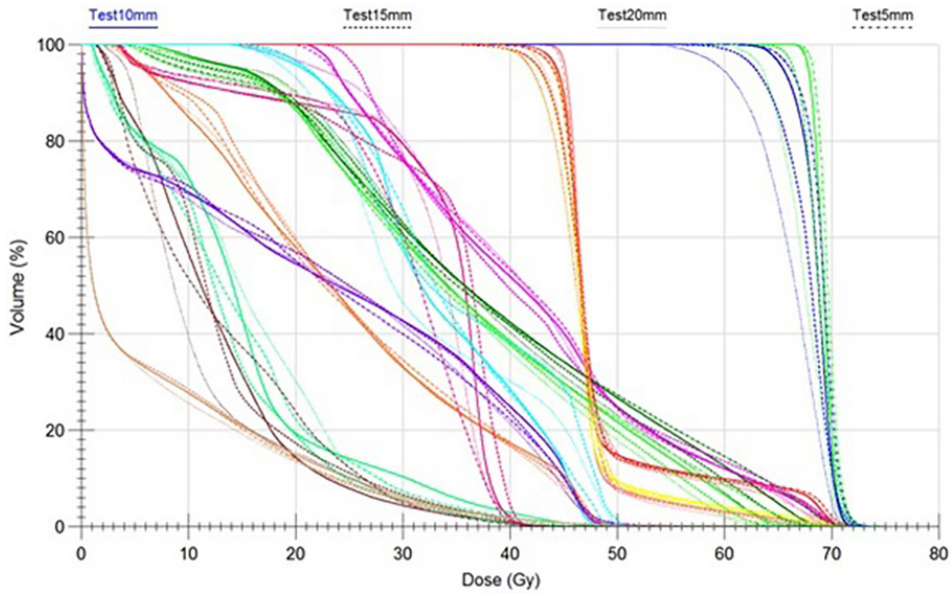

Fig. 1. The dose volume histograms of four different VMAT plan with different MSW's for a typical prostate cancer.
VMAT: Volumetric-modulated arc therapy; MSW: Minimum segment width.

were poor as MSWs value increased from 0.5 to 2.0. Therefore, all MSWs group plans were not comparable in terms of HI and CI. On average, a 15% decrement was found in conformity with MSW2.0 plans as compared to MSW0.5.

As shown in Figure 2, VMAT plans with MSW of 0.5 cm and 1.0 cm were similar for all dosimetric parameters of PTVP and PTVLN ($p>0.05$) except for maximum dose to PTVP. Except for maximum doses to both targets, VMAT plans with MSW of 0.5cm were better as compared to VMAT plans with MSW of 1.5 cm and 2.0 cm ($p<0.05$). However, the maximum dose to the PTV (Primary) in the MSW0.5 plan was 0.9Gy higher than in the MSW1.0 ($p=0.005$).

OAR Doses

Figure 3 compares V58Gy(%), V54Gy(%), V50Gy(%), and V41Gy(%) doses to the bladder, rectum, and V35Gy(%) of the femoral heads among the four MSW groups. As MSW's value increased, OAR doses decreased. There were no statistical differences in the OAR doses between the MSW1.0 and MSW0.5 plans ($p>0.05$). For OAR, there was no significant statistical difference in the OAR doses between the MSW1.5 and MSW0.5 plans except V58Gy for rectum and V41Gy for bladder as shown in Table 3. Except for bladder doses in higher MSW plans, there were no significant differences in doses between the four types of VMAT plans in terms of other remaining OAR.

Table 2 Dosimetric results of PTVs for prostate VMAT plans with different MSWs (n=12)

Structure	Parameter	MSW0.5	MSW1	MSW1.5	MSW2.0	p1	p2	p3
PTVP	Mean dose (Gy)	68.5±0.41	68.3±0.6	67.2±1.2	66.7±1.04	0.182	0.002	0.002
	Maximum dose (Gy)	74.1±0.56	73.3±0.5	73.6±1.74	73.3±1.3	0.005	0.272	0.117
	HI	1.09±0.02	1.09±0.01	1.12±0.01	1.15±0.02	0.937	0.006	0.002
	CI	0.81±0.04	0.79±0.05	0.72±0.08	0.69±0.08	0.209	0.002	0.003
PTVLN	Mean dose (Gy)	47.8±0.99	47.87±0.96	47.35±0.87	46.98±0.86	0.937	0.004	0.002
	Maximum dose (Gy)	73.52±0.65	73.1±0.55	72.78±1.26	72.47±1.06	0.117	0.099	0.023
	HI	1.39±0.13	1.38±0.13	1.42±0.14	1.44±0.14	0.754	0.008	0.002
	CI	0.54±0.05	0.56±0.05	0.52±0.05	0.51±0.07	0.117	0.019	0.034

MSW: Minimum segment width; P1: P value of comparison between the MSW0.5 and MSW1 groups; P2: P value of comparison between the MSW0.5 and MSW1.5 groups; P3: P value of comparison between the MSW0.5 and MSW2.0 groups; HI: Homogeneity index; CI: Conformity Index

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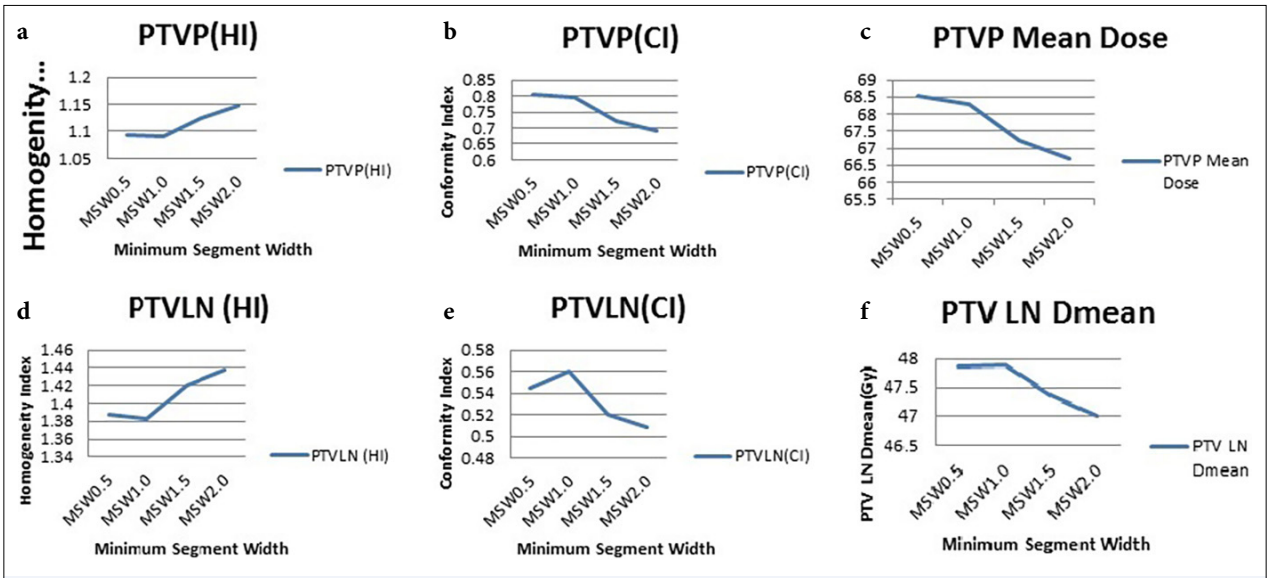

Fig. 2. Graphical Representation of homogeneity index, conformity index, and mean dose with different MSW's for both PTV's for n=12.
PTV P: Primary planning target volume; PTV LN: Lymph node planning target volume.

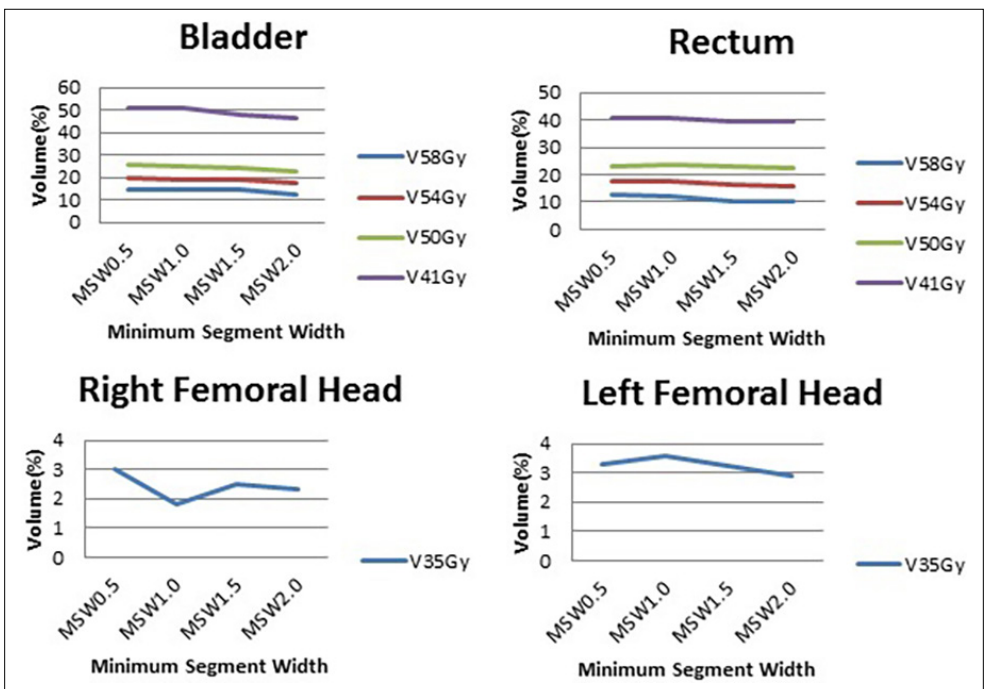

Fig. 3. Graphical Representation of OAR's doses with different MSW's for n=12.
OARs: Organ at risks.

MU and CP

As the MSW value increased, CP in the prostate cancer of the VMAT plan decreased; the mean number of CP for the plans with MSWs of 0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm was 274, 248, 204, and 188, respectively (Fig. 4). Moreover, the MUs of the VMAT plan decreased as the MSW increased (Fig. 4). The mean MUs for the plans with MSWs of 0.5, 1.0, 1.5, and 2.0 cm were 1503.7±80.4, 1102.4±76.7, 914.8±64.2, and 900.9±81.6, respectively.

Table 3 Dosimetric results of OARs for prostate VMAT plans with different MSWs (n=12)

Structure	Parameter	MSW0.5	MSW1	MSW1.5	MSW2.0	p1	p2	p3
Bladder	V58 Gy (%)	14.8±4.91	14.91±5.23	14.56±5.3	12.61±3.58	0.433	0.894	0.023
	V54 Gy (%)	19.64±6.93	19.38±6.9	18.96±6.93	17.42±5.38	0.638	0.814	0.034
	V50 Gy (%)	25.78±9.1	24.87±8.42	24.14±8.44	23.06±7.25	0.937	0.071	0.028
	V41 Gy (%)	50.96±5.95	50.52±5.93	47.87±6.83	46.64±7.1	0.754	0.003	0.003
Rectum	V58 Gy (%)	12.38±5.69	11.77±5.1	10.15±4.73	10.08±4.83	0.347	0.034	0.015
	V54 Gy (%)	17.58±7.15	17.4±6.25	16.49±6.05	15.99±6.17	0.783	0.347	0.06
	V50 Gy (%)	23.26±8.68	23.58±7.76	22.86±7.63	22.19±7.64	0.638	0.583	0.117
	V41 Gy (%)	40.59±11.1	40.68±10.52	39.46±9.96	39.27±9.73	0.754	0.272	0.308
Rt Femoral Head	V35 Gy (%)	3.03±1.72	1.81±0.99	2.52±1.41	2.35±1.3	0.05	0.583	0.209
Lt Femoral Head	V35 Gy(%)	3.28±1.69	3.57±2.06	3.22±2.23	2.87±2.17	0.875	0.347	0.48

OARs: Organ at risks; Rt: Right; Lt: Left

Dosimetric Verification and Plan Delivery Time

The evaluation involved a comparison between the measured planar dose and the dose calculated by the TPS, employing the gamma passing criteria with a 3% DD and a 3 mm DTA. Table 4 illustrates the GPRs for plans characterized by MSW of 0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm. The GPR was most pronounced in the plan using 1.5 cm MSW, while it was least pronounced in the plan using 0.5 cm MSW. In addition, Table 4 shows the PDT for the 12 patients from the time the beam is turned on to the time it is turned off. CP and MUs of the VMAT plan decreased as MSW increased, as did plan delivery time.

DISCUSSION

The process of designing VMAT plans to treat prostate cancer results in a significant number of long, small,

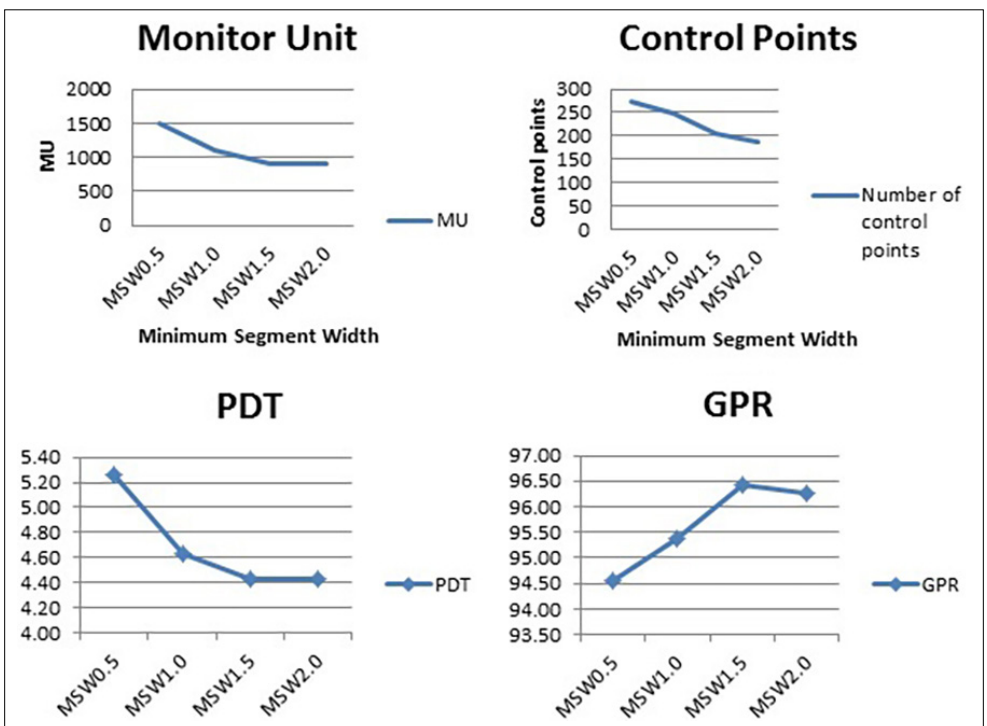

Fig. 4. Graphical representation monitor unit, control points, GPR, and PDT with VMAT plan of different MSW's for n=12.
PDT: Plan delivery time; GPR: Gamma passing rate.

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Table 4 Statistical Results MU, Control Points, PDT, and GPR of VMAT plans with different MSW values (n=12)

Structure	MSW0.5	MSW1	MSW1.5	MSW2.0	p1	p2	p3
MU	1503.68±85.35	1102.47±76.75	914.78±64.18	900.9±81.61	0.002	0.002	0.002
Control points	274±22.02	248.83±23.97	204±13.87	188±15.79	0.028	0.002	0.002
GPR	94.55±1.32	95.37±1.29	96.43±1.52	96.28±1.59	0.008	0.004	0.016
PDT	5.26±0.62	4.63±0.38	4.43±0.34	4.43±0.45	0.007	0.003	0.005

MU: Monitor unit; PDT: Plan delivery time; GPR: Gamma passing rate

and irregular segments.[14,15] The MSW plays a crucial role in optimizing the formation of these apertures. Unfortunately, these segments can sometimes lead to challenges during clinical delivery, causing low verification rates and even interruptions in the VMAT plan delivery.[9,16] To address the issue of plan complexity, we investigated the impact of varying MSW values on the quality of prostate cancer VMAT plans. We compared four different optimization schemes, each based on a different MSW value. The evaluation of plan quality involved assessing several parameters, including the HI, CI, maximum, and mean doses to the planning target volume (PTV), as well as the dose-volume indices of organ at risk, MUs, and CP. Our findings revealed that VMAT plans generated with an MSW of 1.0 cm exhibited similar dose distributions to plans with MSWs of 0.5 cm (Fig. 2). However, we observed that plans with MSWs of 1.5 cm and 2.0 cm displayed slightly inferior quality, failing to meet the clinical requirements adequately (Table 2).

In addition, the number of CP and MUs decreased as the MSWs increased (Table 4). When compared to the plan using an MSW of 0.5 cm, the mean MU reductions in the plans using MSWs of 1.0, 1.5 cm, and 2.0 cm were 26.68%, 39.16%, and 40.0%, respectively, while the total CP was decreased by 9.2%, 25.5%, and 31.3%, respectively. Previous studies showed that decreasing the MUs for treatment delivery reduces the constraint factor of the leaves' trajectories, the complexity of intensity-modulated radiation therapy plans, and treatment time[17–19] Hence, as the MSW increases and VMAT plan complexity decreases, the therapeutic efficiency may improve as well. The average delivery times of the plans using MSWs of 1.0, 1.5, and 2.0 cm were decreased by 37.8, 49.8, and 49.8 s, respectively (a drop of approximately 12%, 15.8%, and 15.8%, respectively), compared to the plan with an MSW of 0.5 cm.

The measured and computed doses were assessed through a matrix detector, and all treatment plans demonstrated favorable GPRs. The average GPR >94% with a 3% DD and 3-mm DTA threshold indicates strong congruence between measured and calculated doses.[20] Enhanced agreement between measured and TPS-calculated doses was observed with a higher MSW. This outcome was anticipated due to the decrease in the number of small fields as MSW increased, facilitating dosimetric verification.

CONCLUSION

We concluded that VMAT plans for prostate cancer generated with an MSW of 1.0 cm demonstrated comparable dose distributions to plans with MSWs of 0.5 cm. However, plans with larger MSWs showed a decline in quality, raising concerns about their clinical suitability.

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