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Influence of Segment Shape Optimization Parameter in Radiotherapy Volumetric Modulated Arc Therapy Planning of Cervical Cancer

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ABSTRACT

Introduction: The aim of this study is to find out the influence of different Segment shape optimization (SSO) parameters in radiotherapy Volumetric Modulated Arc therapy (VMAT) planning of Cervical Cancer and to find out the optimized value for cervical cancer patients.

Material and Methods: It was a retrospective study of 20 Ca cervix patients. Every patient had six plans named SL1, SL5, SL10, SL15, SL20, and NSL. In each case, the value of the shaping loop will be changed during the VMAT plan, while the other optimization parameters and constraint functions will remain the same in each case. All Dosimetric parameters have been measured and analysed for Planning Target Volume (PTV) and Organ at risk (OAR) dose, Monitor Unit (MU), memory, Plan Delivery Time (PDT), and Gamma Passing Rate (GPR) for comparison purposes.

Results: In NSL cases, the PTV dose derived from the DVH did not meet the clinical standards D95% = 86.8% (<95%) with a poorer homogeneity index (HI = 0.2). As the SL value increases, plan quality increases, monitor units increase slightly and plan delivery time decreases while there is a parallel increase in memory consumption. There is no statistical difference in target dose and OAR dose between the SL5 and SL1 plans (P > 0.05) compared with the other groups. SL5 has the least plan memory compared to other SL values.

Conclusion: Based on the plan quality, the dose accuracy, and the efficiency of delivery, SL1 and SL5 have similar characteristics in cervical cancer cases. Both SL1 and SL5 values should recommend for cervical cancer VMAT planning.

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Introduction

Cervical cancer has most often diagnosed in women between the ages of 35 and 44, posing a serious threat to women's life and health. More than 20% of cervical cancer cases have been found in women over the age of 65[1,2]. Furthermore, about 85% of the total incidence cases and mortality occur in countries with a low Human Development Index (HDI)[3,4]. The standard treatment for cervical cancer is considered to be external beam radiotherapy (EBRT) with chemotherapy and intra-cavity brachytherapy. Different stages of cervical cancer are treated through surgery and radiotherapy [1,2]. Recently, In radiotherapy, there has been a trend towards increased use of Volumetric Modulated Arc Therapy (VMAT) and Intensity Modulated Arc Therapy (IMRT) in cervical cancer treatment due to their advantages.

The Introduction of VMAT happened in 2007. The constant changes in VMAT are three parameters, i.e., gantry speed, multileaf collimator (MLC) shape, and speed and dose rate in the treatment plan. There are potential benefits of VMAT in comparison to IMRT. VMAT technique has a higher probability of tumor control and reduces normal structure toxicity compared to IMRT [5,6,7]. The quality of VMAT planning depends on a few parameters, such as the algorithms used for optimization and the physical and biological parameters used in the treatment planning system (TPS) [8,9,10]. Many authors have studied machine parameters such as the increase of gantry angle and the total number of arcs in Monaco VMAT planning and compared the plan quality. A.Chen et al.[11] and Nithya et al.[12] investigated whether gantry angle increment affected VMAT plan quality in cervical and oesophageal cancers. A. Chen et al.[11] observed that the gamma passing rates were 99.1%, 99.6%, and 99.4% for different values of IG respectively. They recommended IG30 for cervical cancer VMAT planning.

The VMAT planning optimization process divides into two steps: first, the optimization algorithm optimizes and computes the ideal fluence maps;

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Second, these fluence maps are converted into arc delivery maps according to the arc sequencer algorithm, while the MLC optimizes the shape sequence into serial segments (control points).In the Monaco treatment planning system (TPS), Monte Carlo Algorithm is commonly used for photon calculation [9,13]. Monaco TPS tries to approach the most suitable shape of the sub-fields for the plan through segment shape optimization (SSO), and Monaco TPS applies segment shape optimization loops after the initial sequencing of segments [14]. Segment Shape Optimization allows for areas of high and low modulation to better meet the IMRT constraints. Each SSO loop includes smoothing, sequencing (clustering), and optimization of beam weights and shapes. The Presence of SSO will increase the plan quality, increase optimization time, decrease delivery time, decrease the number of segments, and can increase the number of Monitor Units (MU) [15].In our study, the Monaco planning system was used to analyse the effect of different SSO loop Values.

The impact of other VMAT plan sequencing parameters like minimum segment width (MSW), control point spacing, and small monitor unit (MU) per segment dose rate, on plan quality, have been studied using the Elekta Synergy/Varian trilogy linear accelerator by other researchers [16,17,18]. In a study conducted by Wang et al.[16] on 19 patients with cervical cancer, he concluded that 1.0 cm MSW is suitable for cervical cancer treatment. Young Min Moon et al.[19] discussed the effect of MSW on gamma passing rate considering MLC position error for VMAT plan in prostate cancer. They concluded that higher MSWs were less affected by MLC leaf position errors. In another study using DVH analysis, Mohamed Yoosuf et al[20] concluded that minimum MSWs showed better plan quality and deliverability. Yang et al[18] have studied smart arc planning parameters such as dynamic leaf gap, leaf speed, number of arcs, maximum delivery time, control point spacing, and continuous Vs binned dose rate for VMAT planning. They included multiple site patients and certified the efficiency of the smart arc planning algorithm in generating appropriate plans. H. Xialong et al[14] studied the influence of SSO parameters on VMAT plans in nasopharyngeal carcinoma. In terms of major organs at risk (OAR) and target coverage, the SSO7 and SSO10 were superior to the SSO3 and SSO5. He concluded that SSO7 was also recommended for nasopharyngeal carcinoma. However, there has been no sufficient study on SSO shaping loop change parameters in cervical cancer in terms of VMAT plan quality, delivery, accuracy, and efficiency.

According to the literature, the sequencing parameter impacted the VMAT planning. We were to conduct this study to measure the influence of SSO parameters in cervical cancer and which SSO value will be better in cervical cases and how it would affect the target coverage and OAR doses.

This study seeks to investigate the impact of segment shape optimization parameters on VMAT treatment planning for cervical cancer and to determine the optimal value for the segment shape optimization loop.

Materials and Methods

Patient Selection and Simulation

Twenty patients with postoperative cervical cancer aged (30–68) years were selected in this study. Squamous cell carcinoma was diagnosed in 15 patients, while the remaining five had adenocarcinoma cases.

At the time of simulation, all 20 patients lay in supine position with hands on chest level. Thermoplastic masks were placed on the pelvis region of all patients. The contrast-enhanced computed tomography image was taken for all 20 patients with 3mm slice thickness, and the pitch of the machine parameter was 1 for every scan. Rectal marker and introitus marker was placed in every patient at the scanning time for better visualization of the rectum and exterior OS of the cervix. Images were exported to the Monaco treatment planning system through the DICOM network, and delineation of tumor and normal structures was done by the radiation oncologists.

Contouring

The gross tumor volume comprised the cervical tumor along with any lymph nodes that tested positive. In accordance with the RTOG guidelines, the clinical target volume includes the gross tumor volume as well as the uterine cervix, uterine corpus, parametrium, vagina, and ovaries. The planning target volume (PTV) is defined as a 5mm uniform expansion of the clinical target volume in all three dimensions.

Normal Structure

Normal structure encompassed bladder, Rectum, femoral heads, sigmoid colon, bowel bag, cauda equina, and patient body contour – all remaining volume was considered as normal tissue.

Dose Prescription

All plans had a prescription of 50.4Gy in 28 fractions (1.8Gy per fraction) with 5 fractions per week schedule. The primary goal of treatment planning was 95% of PTV should cover 95% of the prescribed dose of 50.4Gy and restrict the plan not more than 107% of the prescribed dose,i.e., 53.88Gy.

Table1. The optimization cost function of VMAT plans for cervical Cancer.

Structure	Cost Function	Parameters	Isoconstraint
PTV	Target EUD	0.5	50.4Gy
	Quadratic Overdose	52.4	1Gy
Bladder	Parallel	40Gy, k=3, Shrink= 0mm	45%
Rectum	Parallel	40Gy, k=3, Shrink = 0mm	35%
Left Femoral Head	Parallel	35Gy,k=3,Shrink = 0mm	10%
Right Femoral Head	Parallel	35Gy,k=3,Shrink =0mm	10%
Body	Quadratic Overdose	50.4Gy,Shrink = 0mm	0.1Gy
	Quadratic Overdose	33.56Gy,Shrink = 1.5cm	0.5Gy
	Conformity		0.70
	Maximum Dose		53.9Gy

EUD, equivalent uniform dose; PTV, planning target volume

As per RTOG (Radiation Therapy Oncology Group), The dose constraints for the OARs were as follows: 60% of the Rectum should not receive more than 30Gy (V30 < 60%); 30% of the bladder should not receive a dose more than 45Gy (V45 < 30%); The femoral head volume receiving a 35Gy was maintained at <15%; the maximum dose was < 45Gy for the cauda equina; and the 195cc volume of Bowel bag should receive <45Gy.

VMAT Planning

All twenty patients were planned in the Monaco planning system (Version 5.51.10) with 6MV photon energy. A dual arc in the counterclockwise direction from -180° to 180° was applied for all VMAT plans. The Monte Carlo algorithm was used in all plans with 1% statistical uncertainty. The Grid spacing was 3mm. The dose calculation was done in the actual medium. No calculation was done in the water medium for all plans. Each plan utilizes a maximum of 2 arcs, with up to 180 control points per arc. The collimator angle for each patient was set at 0° during gantry rotation.

This is six hand study. Five VMAT plans were optimized for each patient using the different number of shaping loops (SL) of 1, 5, 10, 15, and 20, and the SSO parameter was off in one hand of the study. Corresponds VMAT plans were named SL1, SL5, SL10, SL15, SL20, and NSL respectively. Other Optimization parameters and Constraint functions remained the same in all the plans to compare the impact of Shaping loop (SL) on plan quality and delivery efficiency in the optimization process. Table 1 shows the cost functions.

Plan Evaluation

The different SL cervical plans were compared in terms of dosimetric parameters such as Conformity Index (CI), homogeneity index (HI), Dose to 95% of volume (D95%), Volume receiving 95% of the prescribed dose (V95%) of the target volume, MUs, memory, OAR doses. Based on report no. 83 of ICRU, The HI and CI were calculated as follows:

$HI = (D_{2\%} - D_{98\%})/D_{50\%}$

$CI = (TV_{RI})^2/(TV \times V_{RI})$

Where $D_{50\%}$, $D_{98\%}$, and $D_{2\%}$, are the doses received by 50%, 98%, and 2% of the PTV, respectively. Target doses are more uniform when the HI value is smaller. TV_{RI} represents the target volume covered by 95% of the prescription dose; TV represents the total volume of the target PTV, and VRI is the total volume contained in the 95% prescribed isodose line. CI value should be closer to 1 to better conformity with the target volume.

Plan Verification

For all the plans, I'MatriXX (IBA, Germany), Universal Detector Array, was used to compare the plan quality in this study. The Gamma Index and gamma pass rate (GPR) of the plan were calculated by comparing the Dose fluence created by the TPS and I'MatriXX detector.

$$GPR = \frac{No.of\ measurement\ points\ passing\ the\ criteria}{total\ measurement\ points\ within\ the\ threshold}$$

I'MatriXX was inserted in the mini Phantom and positioned on the couch. For the elimination of low-dose signals, the lower limit was set at 10% in gamma calculation. Analysis of measurement was done using a 3mm distance to agreement and a 3% dose difference. Clinically acceptable gamma indices were determined by the GPR (3mm/3%), which was considered to be ≥95%.

Statistical Analysis

DVH parameter and Gamma results of SL5 were used as the reference study, and the result of SL1, SL10, SL15, SL20, and NSL was compared with that of SL5. The paired t-test was applied for intergroup comparison using SPSS software. P value <0.05 were considered statistically significant.

Results

Target Dose and OAR Dose

Figure 1 shows the Dose volume Histogram (DVH) graph of VMAT plans with different SL parameters for a typical patient. In NSL cases, PTV doses from the DVH failed to meet the clinical requirement D95% = 86.8% (<95%), and OAR was spared more in the NSL group than in the other groups.

Table 2 shows the comparison of the D2%, D98%, D50%, HI, and CI of the target PTV. It compares V40, V30, and mean doses to the bladder, rectum, and femoral

heads among the six SL groups. There were no statistical differences in the target doses and OAR doses between the SL5 and SL1 plans (P>0.05). However, the right femoral head mean dose in the SL5 plan was 0.5Gy higher than in the SL1 (P = 0.02).

In other groups, there were significant statistical differences in target doses. Figure 2 shows an averaged Homogeneity index (HI) and conformity Index (CI) of PTV with different SL values. SL20 plans have better target coverage, lower value of homogeneity index, and equivalent CI value compared to other SL value plans. The homogeneity of the target dose was very poor in NSL plans.

There have no significant differences in OAR doses between SL5, SL10, SL15, and SL20 plans shown in Table 2 (P>0.05).

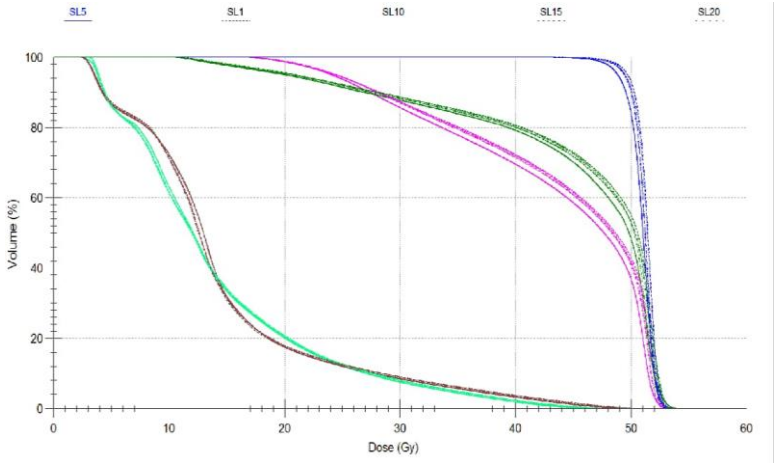

Figure1. VMAT plan Dose-volume histogram for a typical cervical carcinoma patient with different SL parameters.

Table 2. Dosimetric results of PTV and OARs for VMAT plans with different SL value (n=20)

Structure	Parameter	SL1	SL5	SL10	SL15	SL20	NSL	P1	P2	P3	P4	P5
PTV	D95(Gy)	48.28±1.43	48.6±0.67	49.21±0.66	49.39±0.51	49.50±0.59	43.79±1.21	0.43	0.00	0.00	0.00	0.00
	V95(%)	93.75±6.81	96.98±1.89	98.19±1.45	98.57±0.96	98.67±1.09	55.96±12.92	0.07	0.00	0.00	0.00	0.00
	D2%(Gy)	52.46±0.34	52.59±040	52.65±0.37	52.7±0.35	52.75±0.36	51.79±0.34	0.14	0.49	0.14	0.03	0.00
	D50%(Gy)	50.79±0.78	51.05±0.42	51.33±0.31	51.39±0.27	51.46±0.28	48.17±0.74	0.22	0.00	0.00	0.00	0.00
	D98%(Gy)	47.22±1.47	47.54±0.83	48.19±0.85	48.39±0.68	48.54±0.75	42.49±1.37	0.45	0.00	0.00	0.00	0.00
	HI	0.10±0.03	0.10±0.01	0.09±0.01	0.08±0.01	0.08±0.01	0.19±0.03	0.55	0.00	0.00	0.00	0.00
	CI	0.81±0.05	0.84±0.04	0.83±0.04	0.83±0.05	0.82±0.04	0.52±0.13	0.00	0.04	0.19	0.01	0.00
Bladder	V45(%)	61.85±12.92	62.76±12.94	62.73±13.12	63.56±12.77	63.95±12.68	46.34±13.67	0.38	0.94	0.19	0.09	0.00
Rectum	V30(%)	86.72±5.85	87.02±5.55	87.03±5.35	87.04±5.38	87.04±5.4	84.75±7.53	0.49	0.97	0.94	0.95	0.04
Rt Femur	Mean	15.79±2.52	16.13±2.84	15.85±2.5	15.91±2.53	15.95±2.58	15.26±2.28	0.02	0.14	0.18	0.25	0.00
LT Femur	Mean	16.71±3.14	16.53±3.29	16.64±3.29	16.71±3.26	16.75±3.27	16.04±3.17	0.34	0.46	0.19	0.08	0.05

P1,P value of comparison among the SL5 and SL1 groups;P2,P value of comparison among the SL5 and SL10 groups;P3,P value of comparison among the SL5 and SL15 groups;P4,P value of comparison among the SL5 and SL20 groups;P5,P value of comparison among the SL5 and NSL groups

HI, homogeneity index; CI, Conformity Index; SL, Shaping loops

Table 3. Statistical results of MU, Memory, PDT and GPR of VMAT plans with different SL value (n=20).

Parameter	SL1	SL5	SL10	SL15	SL20	NSL	P1	P2	P3	P4	P5
MU	961.8±104.8	969.5±98.4	965.9±107.2	968.9±107.9	970.1±107.1	928.7±96.9	0.43	0.67	0.95	0.94	0.00
Memory	16.4±4.3	15.67±4.4	16.5±4.4	16.8±4.4	17.0±4.4	16.9±4.2	0.06	0.00	0.00	2E-05	0.00
PDT	4.8±0.6	5.1±0.5	5.2±0.5	5.1±0.5	5.1±0.5	4.9±0.6	0.00	0.29	1.00	0.97	0.11
GPR	98.7±0.7	98.8±0.6	98.8±0.7	98.8±0.6	98.7±0.8	98.8±0.6	0.64	0.29	0.32	0.73	0.31

MU, monitor unit; PDT, plan delivery time; GPR, Gamma Passing Rate

P1,P value of comparison among the SL5 and SL1 groups;P2,P value of comparison among the SL5 and SL10 groups;P3,P value of comparison among the SL5 and SL15 groups;P4,P value of comparison among the SL5 and SL20 groups;P5,P value of comparison among the SL5 and NSL groups

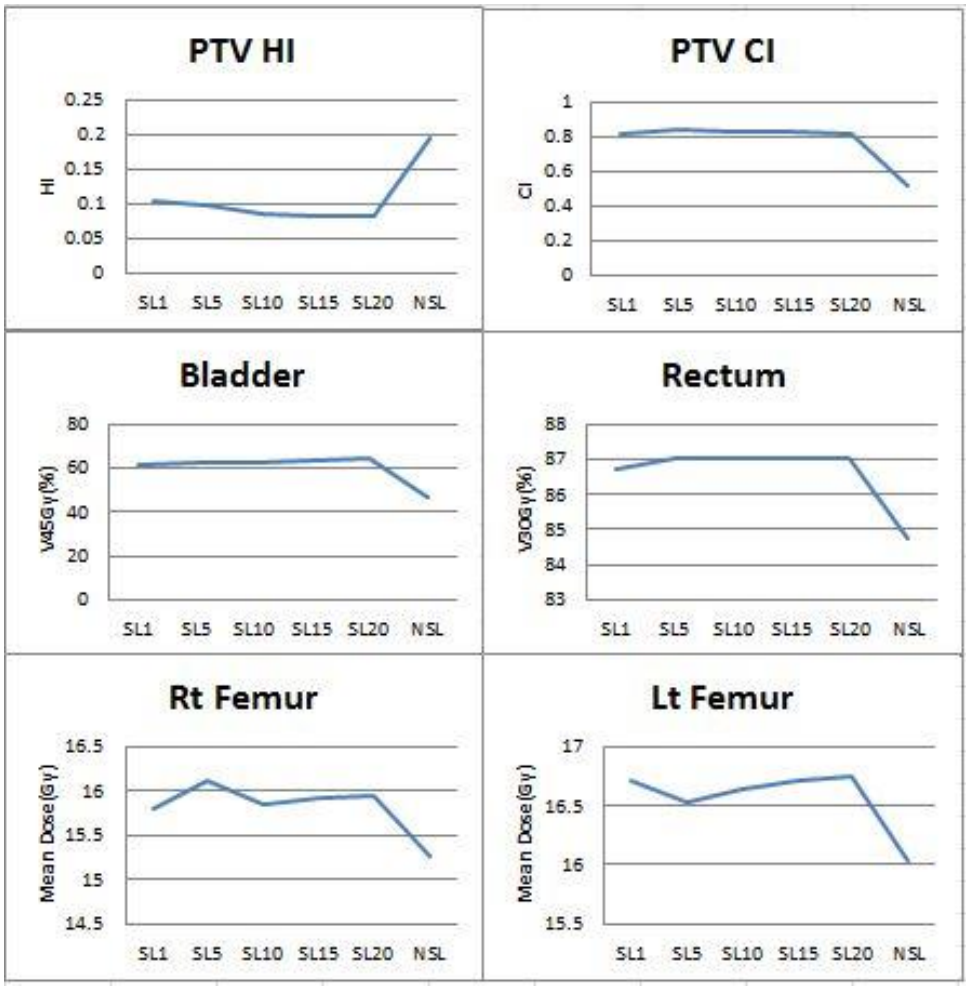

Figure 2. Line graph of target doses and OAR doses of VMAT plans using different SL parameters for 20 patients.

MU and Memory

As shown in Figure 3 and Table 3, SL5 has the lowest value of plan memory in comparison to other SL values. And as the SL value increases, memory taken by the system is increased. Moreover, the MUs of the VMAT plan do not vary significantly, the SL value increases shown in Figure 4, and MU calculated in the NSL plan was lower than other groups by 40MU.

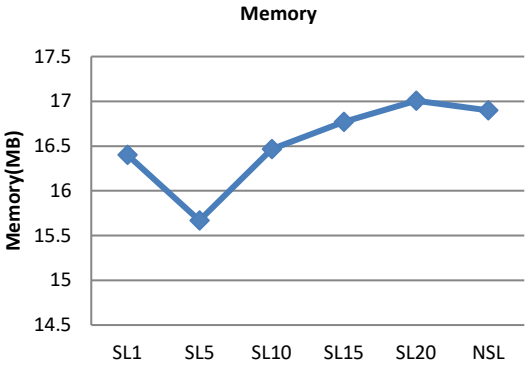

Figure 3. Line graph for Memory consumed by VMAT plans using different SL parameters for 20patients.

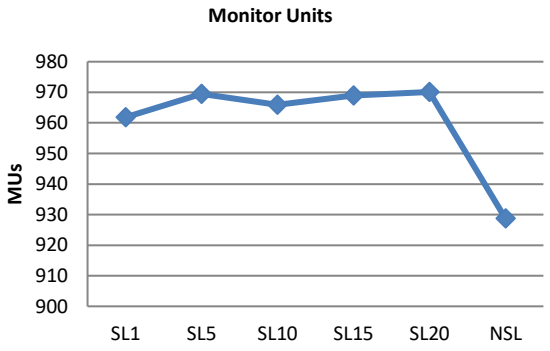

Figure 4. Line Graph between number of MUs generated and SL value for n=20 patients

Plan Delivery Time and Dosimetric Verification

Using the gamma passing criteria of at least 3% dose difference (DD) and 3mm distance to agreement (DTA), a comparison was made between the measured planer dose and TPS-calculated dose. Figure 5 shows the GPRs value for the SL1, SL5, SL10, SL15, SL20, and NSL cases. As the SL value increased, there was no significant difference

in GPR values (P>0.05). Moreover, The GPR was highest in the SL10 plan and lowest in the SL1. Table 3 also shows the Plan delivery time from beam turn-on to the turn-off for all 20 patients. Figure 6 shows that the plan delivery time was lowest in SL1. The P value also showed that there is no significant difference between the SL values of the other groups except SL1.

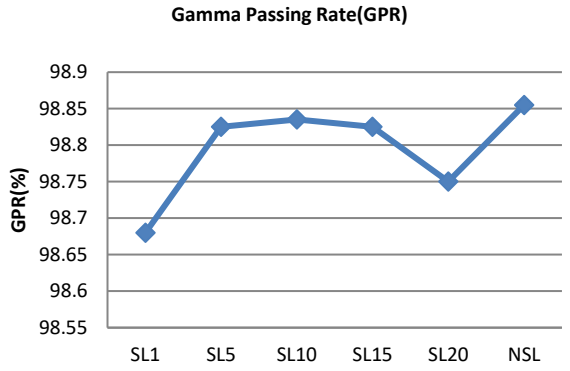

Figure 5. Line Graph between Gamma Passing Rate (GPR) in percentage with different SL parameter

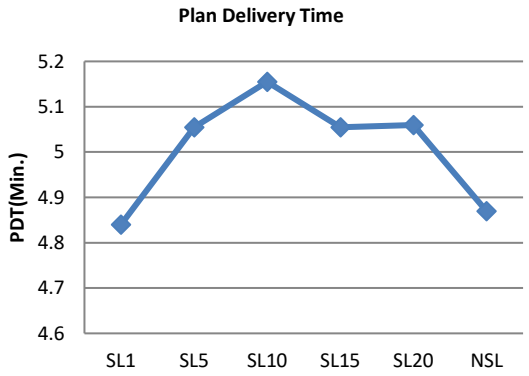

Figure 6. Line Graph between plan Delivery time in minutes using different SL parameter

Discussion

Cervical cancer ranks as the fourth most common malignant tumor globally [21,3,4]. Radiotherapy is a crucial treatment method for this disease [22,23,24]. Therefore, optimizing radiotherapy plans to enhance the effectiveness of cervical cancer treatment is a significant concern for radiation oncologists. The segment shape optimization (SSO) parameter is essential in determining the shape and size of segments created by multileaf collimators (MLC) in VMAT plans. However, its impact on treatment plans remains unclear. Generally, increasing the SSO value might result in more iterations to find the optimal MLC segment shape for the planning field. As a result, the higher SSO value will have better treatment plan quality. However, dose calculation time increases, and memory consumed by a plan will also increase in case of a higher SSO value [15]. Previous studies on optimization focused on the minimum segment width sequencing parameter. So far, we have found only one study on the influence of SSO parameters on nasopharyngeal carcinoma by H. Xialong [14].

No comprehensive research on cervical cancer in this context has been identified. Therefore, we designed this study to thoroughly investigate the impact of five different SSO values on the quality and efficiency of VMAT plans for cervical cancer.

The results of the present study are supported by H. Xialong et al and Monaco User Guide 5.51.10 who reported that higher SSO values led to better treatment plan quality but required better hardware support for Monaco services, especially memory [14,15].

Furthermore, similar to H. Xialong's research on SSO value in nasopharyngeal carcinoma plans[14], We found that the homogeneity index and conformity index of PTV decreased along with the increase in SL value. As the number of shaping loops (SL) increases, the quality of the plan increases. As shown in Table 2 and Figure 2, the SL20 VMAT plan has better target coverage, a lower homogeneity index, and a comparable conformity index than the plan in the other group. Table 3 also shows that SL20 has higher memory consumption, higher monitor units, and similar plan delivery times compared to the other clusters. Our results satisfy the statement given in the Monaco User Guide 5.51.10 and H. Xialong's research [14,15].

In Table 2 and Table 3, we observed that the SL1 and SL5 plans have a significantly similar VMAT plan quality for cervical cancer cases ($P > 0.05$) compared to the other groups. This study concluded that the SL1 group plans behave similarly to the SL5 group plan in all measurement parameters except memory and PDT. We observe that the SL5 group has the lowest memory consumption, and the SL1 VMAT plan has the least plan delivery time.

The dose fluence, both measured and computed, was analyzed using an Immatrix detector. All treatment plans exhibited excellent GPR values, with a mean GPR of over 98% under the 3% DD and 3mm DTA criteria [25]. This demonstrates strong consistency between the measured and calculated doses.

In addition, our study also showed that the absence of shaping loops (NSL group) led to worst planning and unable to meet the clinical requirement. It indicates that the segment size optimization parameter shows a vital role in the VMAT plan. An Increase in SL value did not impact monitor units shown in Table 3.Average plan delivery time (PDT) in SL1, SL5, SL10,SL15 and SL20 plans are 4.84min., 5.055min., 5.155min., 5.055min. and 5.06min. Respectively (Table 3). The average delivery times of the plans using SL of 5,10,15, and 20 were increased by 12.9,18.9,12.9 and 13.2s, respectively (an increment of 4.25%, 6.11%, 4.25%, and 4.35%, respectively), compared to the plan with SSO value 1. Therefore, the smaller SL value (SL1) has the lowest PDT. These trends also appeared in H. Xialong's research [14]. It is because the treatment volume in cervical cancer is large, and the optimizer uses up to five SSO loops, meaning that the optimizer allows a

maximum of +/- 5 mm from the original position. All the above results agreed with the hypothesis that a large SL value enhances the plan quality of the VMAT plan but also increases memory consumption.

Conclusion

Finally, VMAT planning with increasing SSO parameters can lead to better target coverage, HI/CI values, and reduced delivery times, while smaller SSO parameters can reduce memory consumption and decrease the number of MUs. Our data indicated that cervical cancer VMAT planning with SL5 or SL1 shows a clear advantage in terms of a trade-off between plan delivery efficiency and its quality for cervical cancer and better meeting clinical needs.

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