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RESEARCH ARTICLE

Effect of Minimum Segment Width on SRT/SBRT Volumetric Arc Therapy Plans for Flattening Filter Free Beams

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Abstract

Background: Volumetric arc therapy (VMAT) based stereotactic radiotherapy (SRT) or stereotactic body radiation therapy (SBRT) is a highly advanced radiation therapy technique that uses intensity-modulated radiation beams delivered in multiple arcs. After optimization, different segments of small sizes and shapes are created in an arc that will influence the indices like homogeneity index (HI), conformity index (CI), gradient index (GI), number of segments (NOS) which in turn will increase or decrease the total treatment time in terms of monitor units (MUs). The dose calculation algorithm faces difficulty in predicting the accurate dose for these small segments because of the lack of charged particle equilibrium (CPE) and requires precise modeling of lateral electron scatter. The segmentation parameter minimum segment width (MSW) can control the generation of these small-sized segments. It can also affect the quality and deliverability of a VMAT plan. **Methods:** This retrospective study includes 33 patients with lung, liver, and brain tumors (11 patients for each site) treated with the SRT/SBRT technique using a 6 MV flattening filter-free (FFF) beam. Four different plans with MSW 0.5 cm, 1 cm, 1.5 cm, and 2 cm were created by medical physicist using the Monaco treatment planning system (TPS) version 5.11.03. **Results:** A statistically significant reduction in MU (P= 0.01 for brain, P= 0.005 for lung) and NOS (P=0.034 for brain, P=0.011 for lung) was observed for brain and lung cases in plans with MSW 1 cm. For liver cases, along with MU and NOS (P= 0.029 & 0.013 respectively), the paired t-test shows a statistically significant difference (P= 0,046, 0.019 & 0.009) in the GI for intergroup comparison between two plans at different MSW. Improved GI in the case of plans with narrower segments (MSW 0.5 cm and 1 cm) corresponding to sharp dose fall-off compared to plans with broader segments (MSW 1.5 cm and 2 cm). There is no statistical difference in other parameters including global maximum dose and target coverage for plans at different MSW for all cases. **Conclusion:** VMAT plans for SRT/SBRT generated with an MSW of 1.0 cm demonstrated comparable dose distributions to plans with MSWs of 0.5 cm with fewer MUs for brain, liver, and lung cases treated with 6 MV FFF beams.

Keywords: Minimum segment width- Stereotactic radiation therapy- Volumetric arc therapy

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Introduction

In recent years, there has been significant progress in understanding cancer's growth and its treatment. However, as cancer becomes more common, managing it still remains a major challenge. Over the past century, advancements in radiation therapy and a better understanding of how cancer cells respond to radiation have helped to improve survival rates and reduce the side effects for patients [1].

Stereotactic body radiotherapy, or SBRT is a procedure used to treat extracranial tumors by delivering very high doses per fraction (ranging from 6 to 30 Gy) in a hypo fractionated schedule of five or fewer fractions. It is most commonly used for tumors in the spine, lung,

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liver, pancreas, kidney, and prostate. The precise tumor localization and accurate dose delivery required in SBRT are achieved through careful treatment planning, effective patient immobilization, respiratory motion management, and advanced image-guidance techniques for target positioning and geometric verification [2].

FFF beams offer a variety of advantages, including faster treatments, reduced risk of patient movement, and better suited for high-precision treatments. However, the choice between FF and FFF beams depends on the specific clinical need and the kind of treatment being administered [3].

In addition to the higher dose rate, other key benefits of FFF beams are reduced scatter radiation, lower leaf transmission, and less treatment head leakage. It has also been observed that the reduced variation in scatter factors and beam quality across the field simplifies dose calculations. Also, higher dose rate of FFF beams is especially advantageous for stereotactic body radiotherapy (SBRT), where respiration-controlled delivery is limited by the extended treatment times caused by large fractional doses [4].

The lack of charged particle equilibrium makes it difficult for the dose calculation algorithm to predict the dosage for these short distances and requires correct lateral electron scatter modeling. As opposed to conventional radiation, even a little error in the dose estimate for the thin, uneven, and small segments will have a substantial effect on the accuracy of delivering the required high dose per fraction. Thus, theoretical fluence can be divided into deliverable MLC segments, and sequencing parameters can be used to govern the production of these smaller segments. For creating segments of different sizes and shapes, the minimum segment width parameter in the segmentation process is essential [5].

Various authors had evaluated the influence of segment width on plans with FF beams including volumetric modulated arc-based stereotactic body radiotherapy. Literature was found on treatment plans of different site including cervical, oesophageal and rectal cancer that assessed the impact of minimum segment width on the quality, delivery accuracy, and efficiency of the VMAT plan made with MSWs of 0.5, 1.0, and 1.5 cm while maintaining constant other planning parameters [6-10].

All the above-mentioned studies have examined the effect of MSW on standard 6 MV photon beams, limited research exists regarding its impact on 6 MV FFF beam based SRT/SBRT plans. This study investigates the plan delivery and quality with different penalties on segment width in VMAT delivery for SRT/SBRT cases with FFF beams.

Materials and Methods

For this retrospective study, a total of 33 patients already undergone treatment with the 6 MV FFF beam from Elekta Versa HD LINAC with the clinically accepted VMAT plans made at an MSW of 0.5 cm were chosen from the institutional database. Versa HD is equipped with an Agility MLC System consisting of 80 leaf pairs with a projected width of 0.5 cm at the isocenter. Out of these 33 patients, 11 patients were of each site from the brain (10 Female and 1Male) with average volume 15cc, lung (4 Female & 7 Male) with average volume 60cc, and liver (4 Female & 7 Male) with average volume 216cc. All the plans were with a single target volume, so planned with a single isocentre only. The plans were generated using the Monaco Treatment Planning System (version 5.11.03). The VMAT plans generated at various MSW were evaluated in terms of target coverage, gradient index (GI), conformity index (CI), global maximum dose, monitor units (MUs), and number of segments (NOS). Other plan optimization parameters like Constraints, Beam arrangement, Prescription dose, Grid spacing, Statistical uncertainty, Maximum number of control points, layering order of target, and OARs were kept fixed for all the plans of an individual patient. For the plan evaluation, the following indices were individually evaluated.

Coverage

It is defined as the percentage of target volume covered by the prescription isodose radiation.

$$C=TV_{ref,p}/TV_p$$

Where, $TV_{ref,p}$ is the target volume, TV_p is the volume covered by the reference isodose curve [9].

Conformity Index (CI)

CI_p [11] is defined as the ratio of the square of TV_p covered by prescription isodose volume (PIV_p) to the product of TV_p and PIV_p

$$CI_p=(TV_{ref,p})^2/(TV_p \times PIV_p)$$

Gradient Index (GI)

The GI [12] is the ratio of the volume of half the prescription isodose to the volume of the prescription isodose. The index can be used for any prescription isodose. For a plan normalized to the 100% isodose line, it is the ratio of the 50% isodose volume ($PIV_{50\%}$) to the 100% isodose volume ($PIV_{100\%}$). This index shows the sharpness of dose fall-off outside the target.

$$GI = PIV_{50\%}/ PIV_{100\%}$$

Homogeneity Index (HI)

Dose homogeneity characterizes the uniformity of the absorbed dose distribution within the target volume. According to ICRU 83, HI [6] is defined as

$$HI =(D_2-D_{98})/D_{50}$$

Where D_2 represents the dose received by 2% of TV,

D_{98} represents the dose received by 98% of TV,

D_{50} represents the dose received by 50% of PTV volume.

Statistical Analysis

Analysis of the normal distribution of the data was done

using the student t-test of MS Office v16.0. A one-way analysis of variance (ANOVA) test was used to evaluate the effect of MSW on four different plans. ANOVA is an effective statistical method for simultaneously comparing the means of three or more groups, providing a more efficient and accurate alternative to perform multiple t-tests. Conducting multiple t-tests increases the risk of Type I errors (false positives) as each individual test carries its own error rate. In contrast, ANOVA allows for a single test that evaluates the overall differences between groups while controlling for the cumulative error risk.

To find the difference among the datasets, the paired t-test was used as a method for determining the null hypothesis i.e. the two datasets are homogeneous, is accepted or rejected. A paired t-test is generally used for the situations depending on the parametric or non-parametric data distributions of measured data sets respectively. If the $P \leq 0.05$, we can conclude that the two paired samples are significantly different. For the plotting of various graphs, MS Office v16.0 was used. The notation $T_{0.5,1}$ will represent the t-test comparison between the data set for MSW 0.5 cm and 1.0 cm. $T_{0.5,1.5}$ will represent the t-test comparison between the data set for MSW 0.5 cm and 1.5 cm; $T_{1,1.5}$ will represent the t-test comparison between the data set for MSW 1.0 cm and 1.5 cm; $T_{1.5,2}$ will represent the t-test comparison between the data set for MSW 1.5 cm and 2.0 cm.

Results

Brain Cases

Except for the difference in MU and NOS, there were no statistically significant differences between the other dosimetric parameters in the planning target volumes including HI, GI, CI, global maximum dose (Dmax), and target coverage (C). Figures 1 and 2 show the histogram plots of MUs and NOS for all 11 patients with different MSW values of 0.5 cm, 1 cm, 1.5 cm, and 2 cm respectively for brain cases. It has been observed that with an increase in MSW, there is a decrease in MUs. But at MSW 2 cm there is again an increase in MUs. For NOS, with increase in MSW causes an increase in NOS.

The difference in NOS is statistically significant according to the ANOVA test ($P < 0.0347$). With the increase in MSW, there is a reduction in NOS.

According to a paired t-test, there is a significant increase in MUs with MSW 0.5 cm as compared to MSW 1 cm ($P= 0.001$). Similarly, the plan with 1.5 cm of MSW resulted in more no. of MUs than the plan with MSW 1 cm ($P= 0.043$). On the other hand, there is no significant difference in no. of MU for the plans with MSW 0.5 cm and 1 cm ($P = 0.196$).

Table 1 shows the p values for intergroup comparison between two plans ($T_{0.5,1}$; $T_{0.5,1.5}$; $T_{1,1.5}$; $T_{0.5,2}$), which show the statistical difference in the parameters for two plans at two different MSWs according to a paired t-test for brain cases.

Liver Cases

For the liver cases, the ANOVA test shows that plan evaluation parameters like HI, CI, global maximum dose, and target coverage are statistically insignificant, but NOS and MU show statistically significant differences ($P < 0.05$, P-value: 0.0288 and 0.0131, respectively).

Also, the paired t-test shows a statistically significant difference ($p < 0.05$) in the GI for intergroup comparison between two plans ($T_{0.5,1.5}$; $T_{1,1.5}$; $T_{0.5,2}$) at different MSW with the P-value 0.0455, 0.0194, 0.0087 respectively shown in Table 2. GI was best achieved with MSW of 0.5 cm and 1 cm.

Lung Cases

The statistical analysis of plan evaluation parameters shows no significant difference in GI, global maximum dose, and target coverage. However, the difference in NOS is statistically significant according to the ANOVA test with a p-value of 0.0111. The paired t-test shows a statistically significant difference in NOS for intergroup comparison between two plans ($T_{0.5,1}$; $T_{0.5,1.5}$; $T_{1,1.5}$; $T_{0.5,2}$) at different MSW with the value 0.0094, 0.0008, 0.0002 and 0 respectively shown in Table 3. Although a better CI is achieved with a narrowed segment width of 0.5 cm.

In all three cases, VMAT-based SRS/SBRT plans show that MSW of 1 cm is statistically and dosimetrically better when compared with MSW of 0.5 cm, 1.5 cm, and 2 cm.

Table 1. Results of ANOVA and Student's paired t-test Statistical Analysis of Plan Evaluation Parameters for Brain Cases

Plan evaluation parameter	ANOVA test (P value)	$T_{0.5,1}$ (P value)	$T_{0.5,1.5}$ (P value)	$T_{1,1.5}$ (P value)	$T_{0.5,2}$ (P value)
Monitor units (MUs)	0.2138	0.0012	0.1961	0.0433	0.1013
No. segments (NOS)	0.0347	0.006	0.0034	0.0057	0.009

Table 2. Results of ANOVA and Student's paired T-test Statistical Analysis of Plan Evaluation Parameters for Liver Cases

Plan evaluation parameter	ANOVA Test (P value)	$T_{0.5,1}$ (P value)	$T_{0.5,1.5}$ (P value)	$T_{1,1.5}$ (P value)	$T_{0.5,2}$ (P value)
Monitor units (MUs)	0.0131	0.0008	0.0008	0.0921	0.0671
No. segments (NOS)	0.0288	0.0016	0.0007	0.0086	0.0001
Gradient Index (GI)	0.7975	0.1388	0.0455	0.0194	0.0087

Table 3. Results of ANOVA and Student's paired T-test Statistical Analysis of Plan Evaluation Parameters for Lung Cases

Plan evaluation parameter	ANOVA Test (P value)	$T_{0.5,1}$ (P value)	$T_{0.5,1.5}$ (P value)	$T_{1,1.5}$ (P value)	$T_{0.5,2}$ (P value)
Monitor units (MUs)	0.0131	0.0008	0.0008	0.0921	0.0671
No. segments (NOS)	0.0288	0.0016	0.0007	0.0086	0.0001

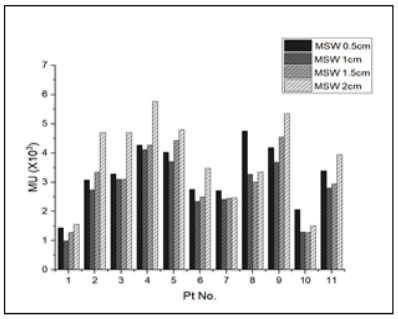

Figure 1. Histogram Plot of MUs for MSW 0.5 cm, 1 cm, 1.5 cm, and 2 cm against patient I.D. for all 11 Patients for Brain Cases.

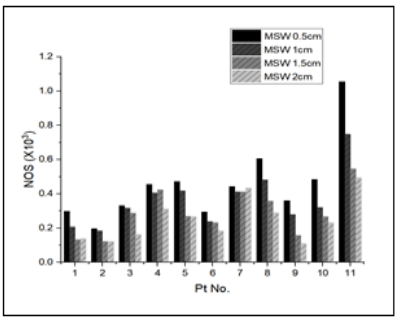

Figure 2. Histogram Plot of NOS for MSW 0.5 cm, 1 cm, 1.5 cm, and 2 cm Against Patient I.D. for all 11 Patients for Brain Cases.

Discussion

To accomplish the intended treatment goals, several parameters must be optimized during the VMAT planning phase. To find the least leaf separation between two opposing leaves inside the segmented field of any given segment, the sequencing method employed the parameter minimum segment width (MSW). To produce a sequence with a limited number of narrow segments, the MSW parameter was developed. By affecting variables including target coverage, HI, CI, GI, and treatment delivery time, the MSW has a direct impact on the effectiveness and quality of the treatment plan. Compared to VMAT plans with lower MSW, those with higher MSW have lower MU and more efficient delivery [13].

Number of segments reduced with increasing MSW as during Monaco optimization, when the minimum segment width is increased, smaller segments that would have been created for finer dose control are no longer allowed. The optimizer merges or removes these small segments, leading to fewer, larger segments overall. Thus, increasing the minimum segment width forces the optimization algorithm to use broader segments, reducing the complexity of the plan. This means fewer distinct segments are required to achieve the same overall dose distribution. So, there is reduction in NOS with increase in the MSW.

The increment in MU observed at a segment width of 2 cm for FFF beams can be attributed to the beam profile characteristics of FFF beams. When broader segments are created at this MSW (2 cm), a significant portion of the dose might be delivered by the less intense tapered regions of the beam. This implies that the dose delivered per unit of MU decreases because the beam is less efficient in these areas. To compensate for the reduced dose contribution from the tapered portions of the beam, more MUs are required to achieve the desired dose.

So, it is very important to wisely choose the MSW for treatment plan optimization. Moreover, no literature has been found for the selection of MSW for the FFF beam.

Limitations

This study is mainly applicable or limited to Monaco TPS as Eclipse TPS does not allow to change of the MSW. Also, it was small sample sized and is site-specific study, which may limit the generalizability of the findings to larger populations or other clinical settings.

In conclusion, we concluded that VMAT plans for SRT/SBRT generated with an MSW of 1.0 cm demonstrated comparable dose distributions to plans with MSWs of 0.5 cm with less MUs for brain, liver, and lung cases treated with 6 MV FFF beams. However, plans with larger MSWs showed a decline in quality, raising concerns about their clinical suitability. The present includes only 3 sites mainly, brain, liver and lung but in the future, we would imply this study on the other SRS/SBRT sites as well with large sample size.

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The authors have nothing to disclose.

Author contributions

Conception and design: Satinder Pal Kaur and Arun Oinam.

Data collection

Satinder Pal Kaur and Shivanjli

Data analysis and interpretation

Satinder Pal Kaur, Shivanjli, and Arun Oinam

Final approval of manuscript

Arun Oinam, J S Shahi, GY Srinivasa, Sushmita Ghoshal

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