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Assessment of the impact of minimum segment width on volumetric modulated Arc therapy planning for head and neck cancer

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ABSTRACT

Background: The purpose is to identify the standard minimum segment width [MSW] in terms of planning outcomes of Volumetric modulated arc therapy [VMAT] in patients with Head and Neck Carcinoma [HNC]. ***Material and Methods:*** A retrospective analysis was conducted using planning computed tomography scans from 15 patients diagnosed with head and neck carcinoma. Four separate VMAT plans, utilizing MSW of 0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm, were created in the Monaco Treatment Planning system [TPS]version 5.11.03. Target volume and critical structures were optimized with the same criteria. The comparison focused on Conformity Index [CI], Homogeneity Index [HI], target volume coverage, dose to Organs at risk [OARs], and total Monitor units (MUs). Data analysis was performed using Jamovi software. At $p<0.05$, statistical significance was established. ***Results:*** MSW of 1.0 cm plans showed significantly enhanced planning target volume [PTV] coverage [p=0.021], fewer monitor units [p=0.03], and an optimal combination of Conformity [CI = 0.816±0.214] and Homogeneity [HI = 1.065±0.017]. Furthermore, the spinal cord received a substantially lower maximum dose in plans created with 0.5 cm and 1.0 cm MSWs compared to those with wider segment widths [p=0.017]. ***Conclusions:*** Among the configurations tested, the 1.0 cm MSW offered the most favorable balance between precise target coverage, organ-at-risk sparing, and overall treatment delivery efficiency for head and neck cancer using VMAT planning.

INTRODUCTION

Head and neck cancer is among the top seven most prevalent cancers in the worldwide. *Radiotherapy is known to be the standard treatment* [1]. In 2018, approximately 302,000 new cases of pharyngeal cancers [nasopharynx, oropharynx, and hypopharynx] were reported, with

hypopharyngeal cancers accounting for approximately 30% of these cases [2, 3]. IMRT and VMAT are superior to traditional radiation therapies in terms of precise dosage contouring, preservation of healthy tissues, and improvement of therapeutic outcomes. They are particularly helpful in the treatment of H&N cancers, where it is crucial to protect vital organs such the spinal cord, salivary glands, and ocular structures [4].

Volumetric modulated arc therapy [VMAT], an advanced radiotherapy technique derived from Intensity-modulated radiotherapy [IMRT], delivers radiation continuously as the gantry rotates around the patient. By modulating multi leaf collimators [MLCs] and gantry speed. VMAT precisely conforms the dose to the three-dimensional tumor shape Compared with the conventional technique such as three-dimensional conformal radiotherapy [3DCRT] is preferable [5, 6]. Intensity Modulated Radiation Therapy (IMRT) utilizes advanced beam modulation to achieve highly conformal dose delivery by varying radiation field shape and intensity. Consequently, IMRT generates more heterogeneous dose distributions than conventional three-dimensional (3D) conformal radiotherapy, as it relies on multiple fields with complex modulation patterns [7]. Modern radiotherapy uses multi-leaf collimators (MLCs) to better shape the radiation dose around the target. In techniques such as IMRT, the higher level of modulation usually requires more monitor units, leading to longer beam-on times and possible effects on dose accuracy, especially outside the treatment field [8].

In advanced radiation therapy techniques such as VMAT, even small inaccuracies in dose estimation for thin or irregular segments can affect the accurate

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delivery of high doses per fraction. To address this, the ideal fluence is divided into deliverable multileaf collimator (MLC) segments, which are governed by sequencing parameters [9, 10]. Among these parameters, the minimum segment width (MSW) defines the minimum distance between opposing MLC leaves and determines the size of the deliverable segments. In the Monaco treatment planning system, appropriate selection of MSW enables the generation of narrow, well-controlled segments while maintaining efficient dose delivery, with commonly reported values ranging from 0.5 cm to 2.0 cm [11, 12].

Although the influence of MSW has been investigated in several treatment sites, including prostate cancer, stereotactic body radiotherapy, and cervical cancer [9-11], these findings cannot be directly extrapolated to head and neck cancer because of its complex anatomy and the close proximity of critical organs at risk. Studies in esophageal cancer and high-precision SRT/SBRT have demonstrated that plan quality and delivery efficiency are sensitive to MSW selection [14], with similar observations reported in prostate VMAT planning [15]. Given the irregular target geometry and steep dose gradients in head and neck VMAT, small variations in MSW can markedly influence target conformity and organ-at-risk sparing. Therefore, this study evaluates the dosimetric impact and delivery efficiency associated with different MSW settings in head and neck cancer planning.

MATERIALS AND METHODS

Patient selection

Fifteen patients (aged 50-70 years) histologically confirmed hypopharyngeal carcinoma who received external beam radiotherapy at the Department of Radiation Oncology, Kasturba Hospital (June 2019 - January2022), were included, since this was a retrospective observational study, approval from the departmental research committee was obtained prior to its initiation.

Immobilization and simulation

Patients were immobilized in the supine position via a custom four-clamp thermoplastic head–neck mask [Orfit]. Computed Tomography [CT] scans [3 mm slice thickness] were acquired on a Philips Brilliance Big Bore 16-slice CT simulator, [Philips Healthcare, Netherlands]. Images were imported into the Monaco TPS [version 5.11.03] for target and OAR delineation. The gross tumor volume [GTV] represents the visible size and location of the tumor. The clinical target volume [CTV] is determined by adding a margin to the GTV and encompasses the cancer and any suspected areas that may contain cancerous tissue. The planning target volume [PTV] includes the CTV uniformly expanded by 1cm in all directions to ensure that, despite of movement prescribed dose adequately covers CTV. The organ at risk (OAR) brainstem, parotids, spinal cord, larynx, mandible, thyroid, larynx, oral cavity, and optic chiasma were delineated according to the Radiation Therapy Oncology Group [RTOG] Guidelines by the radiation oncologists.

Treatment planning

VMAT plans were generated using a full dual-arc setup, with an arc spanning a complete 360-degree rotation in a clockwise direction and using a 6 MV photon beam, and the isocenter was placed at the PTV center. Dose calculations employ the Monte Carlo algorithm. The prescribed dose to the PTV was 70 Gy in 35 fractions, with 2 Gy per fraction. For each patient, four plans were created with MSWs of 0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm in Monaco TPS from Elekta VERSA HD [AB, Sweden], which boasts 160 agility multileaf collimators with a spatial resolution of 5 mm at the isocenter. All treatment plans aimed to reduce OAR doses and increase PTV coverage (figure 1).

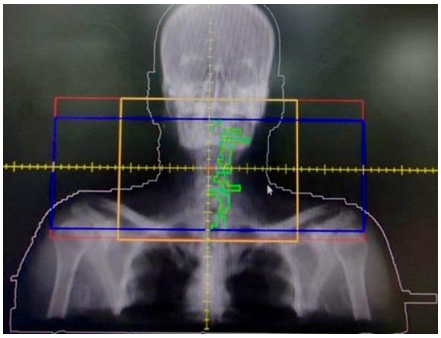


Figure 1. Multileaf collimator (MLC) aperture configuration corresponding to the planning target volume (PTV).

Plan evaluation

The dosimetric parameters analyzed included, target volume receiving 95% of the recommended dose, PTV mean and maximum dose, MU count, and the OAR doses.

Homogeneity Index (HI): The Homogeneity Index (HI)(9) describes the uniformity of dose distribution within the planning target volume (PTV). It is defined as the ratio of the dose received by 5% of the PTV (D_5%) to the dose received by 95% of the PTV (D_{95}%):

HI=D5%/D95%

Conformity Index (CI): The Conformity Index (CI), (10) as recommended by the Radiation Therapy Oncology Group (RTOG), evaluates how well the prescribed dose conforms to the target volume. It is calculated as the ratio of the volume receiving the reference isodose VRI to the target volume (TV):

CI=VRI/TV

Where; VRI is the volume enclosed by the reference isodose (i.e., prescribed dose).

TV is the target volume. A CI value of 1.0 is ideal, meaning the prescribed dose exactly covers the

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target. Values >1 suggest the dose extends beyond the target volume [15].

Other evaluated endpoints: MU count, PTV coverage, and OAR doses.

Statistical analysis

Statistical analysis for this study was conducted Jamovi [The Jamovi Project, Australia]. All dosimetric parameters, including target coverage, conformity index [CI], homogeneity index [HI], and Organ-at-risk [OAR] doses, were expressed as the mean ± standard deviations [$\bar{x}$ ± s]. To assess the impact of the minimum segment width [MSW] across the four study groups [0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm], one -way analysis of variance [ANOVA] was performed. A p value of < 0.05 was considered statistically significant for all tests. The choice of statistical methods ensured robustness in detecting differences in dosimetric outcomes among the MSW groups.

RESULTS

Dosimetric parameters of target volumes and Organs at risk [OAR]

Table 1 summarizes the dosimetric outcomes associated with varying minimum segment width [MSW] values in VMAT planning for head and neck cancer. Statistically significant differences were observed in both the target coverage and conformity index [CI] across the evaluated MSWs (figure 2). The highest mean target coverage was recorded with an MSW of 0.5 cm, with a progressive decline noted as the MSW increased. While the 1.0 cm MSW group presented the highest maximum target coverage among all the groups, no statistically significant differences were detected between the 0.5 cm and 1.0 cm MSW and there were no differences between the 1.5-cm and 2.0 -cm groups. The homogeneity index [HI] was optimal at 0.5 cm, reflecting more uniform dose distributions within the planning target volume [PTV] (figure 3). Figures 4 & 5 demonstrates the homogeneity and conformity index of various minimum segments. Analysis of conformity revealed that the CI exhibited improved standard deviation values at narrower MSWs, with the 0.5 cm group outperforming wider segment widths in achieving superior dose conformity. These findings suggest that decreasing MSW enhances plan conformity and homogeneity, albeit at the cost of increased plan complexity and potentially higher monitoring units [MUs].

Organ-at-risk (OAR) dosimetric evaluation

As presented in table 2, the dosimetric analysis of critical OARs indicated modest, nonsignificant trends in dose variation across different MSW. Specifically, incremental increases in the MSW from 0.5 cm to 2.0 cm were associated with higher mean doses [Dmean] to the thyroid and increased maximum doses [Dmax] to the brainstem. Conversely, a reduction in Dmean to the larynx and Dmax to the optic chiasm was observed with broader segment widths. However, none of these variations reached statistical significance, suggesting that the influence of MSW on OAR sparing is limited to within the evaluated range and may not have substantial clinical implications.

Monitor units [MUs] and treatment efficiency

The influence of MSW on plan efficiency was assessed by analyzing the total number of MUs required for treatment delivery. A reduction in MU was observed with MSW values of 1.0 cm and 1.5 cm, indicating enhanced delivery efficiency. However, an increase in MU was noted at 2.0 cm, likely attributable to broader segments interacting with beam profile characteristics, thereby reducing dose efficiency in certain regions. The overall variation in MUs across the tested MSWs ranged from 4% to 24%, although these differences were not statistically significant. Notably, the 1.0 cm MSW achieved the lowest mean MU and standard deviation, reflecting a favorable balance between plan quality and delivery efficiency.

Table 1. Dosimetric parameter analysis for the planning target volume (PTV) for all evaluated minimum segment width (MSW) settings. Parameters include D (95%), D (98%), mean, dose, homogeneity index (HI), and conformity index (CI).

Parameter	0.5 cm MSW	1 cm MSW	1.5 cm MSW	2 cm MSW	P-value
TC%	97.80± 2.06	97.82± 1.83	95.95± 4.89	87.25± 19.15	0.042
D_{mean}(cGy)	7066.2± 68.48	7055.3± 54.24	7039.6± 100.74	6939.9± 174.94	0.5166
D_{max}(cGy)	7606.8± 87.88	7510.8±8 8.52	7542.7±1 04.69	7568± 172.61	0.7187
D_5 (cGy)	7261.6± 54.71	7246.5±4 0.16	7226.8±1 35.51	7208.± 142.8	0.9498
D_{95} (cGy)	6798.9± 133.82	6799.6±1 14	6775.6±2 11.60	11671.8± 175	0.0259
CI	0.83713± 0.2381	0.8164± 0.2141	0.736± 0.292	0.526± 0.3107	0.0231
HI	1.068± 0.0176	1.065± 0.0165	1.0676± 0.04	1.009± 0.285	0.6985
MU	1034.694± 337.20	810± 144.52	872.9± 162.34	912.54± 175.6	0.09646

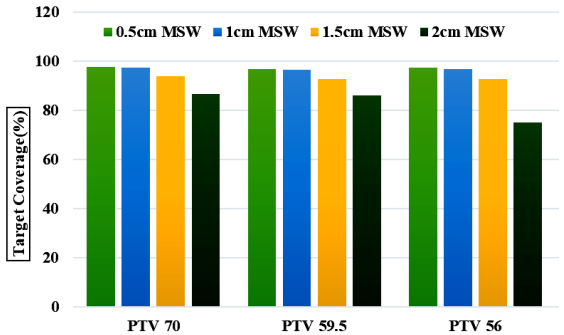


Figure 2. Target coverage (%) of the planning target volumes (PTVs) for all evaluated minimum segment width (MSW) settings. The figure compares PTV coverage achieved with MSW values of 0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm, highlighting the influence of MSW on dose coverage performance across the study.

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Table 2. Average mean and maximum dose values (cGy) for all evaluated organs at risk (OARs) across the different minimum segment width (MSW) settings. The table summarizes the dose variations received by each OAR to assess the impact of MSW on normal-tissue sparing.

OAR	PARAMETER (cGy)	0.5 cm	1.0 cm	1.5 cm	2 cm	p-value
Spinal cord	(D_{max})	4100±219.7	4059.7±166.8	4144.7± 151.78	4157± 204.53	0.539
Brainstem	(D_{max})	2826.9± 943.2	3085.2±1051.7	3247.67 ±1294	3341.1 ±1493.5	0.6828
Mandible	(D_{max})	6564.2± 566.9	6472.3 ±538.8	6405.3 ±529.172	6523.65± 555.0	0.9143
Left parotid	(D_{mean})	2541 ±309.86	2573.8± 357.6	2498.1 ±338.46	2468.4± 391.52	0.7938
Right parotid	(D_{mean})	2535.3 ±446.3	2529.8± 40129	2487.7 ±429.9	4119.1 6137.6	0.2962
Oral cavity	(D_{mean})	5906.1±386	3567.8 ±542.1	3871.3 ±560.5	3715.8 ±532.49	0.4974
Optic chiasm	(D_{max})	1238± 258.22	1176± 178.3	1013 ±133.3	1072 ±230.3	0.5637
Thyroid	(D_{mean})	5770.7 ±852.3	6132.7 ±287.5	6110.6± 323.57	6006.8 ±405	0.6156
Larynx	(D_{max})	7032.9 ±666.6	6879.6 ±699.6	6795.5± 759.5	6958.45 ±964.8	0.9902

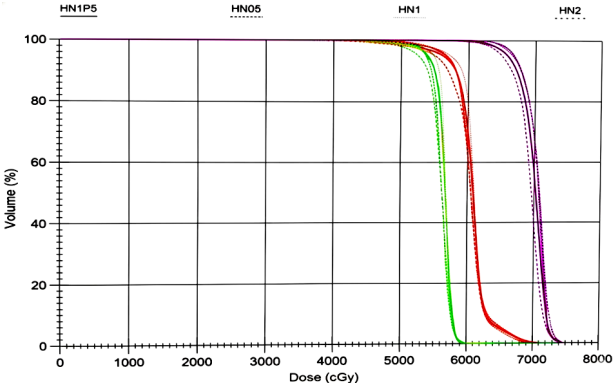


Figure 3. Showing DVH curves for the PTV in a patient with the minimum segment dose-volume histogram (DVH) curves for the PTV corresponding to minimum segment widths of 0.5 cm, 1.0 cm, 1.5 cm, and 2.0 cm in a representative patient. The DVH comparison illustrates the effect of MSW variation on dose within the target volume.

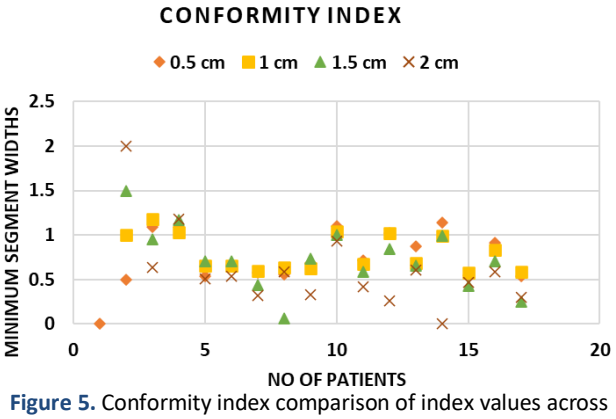


Figure 5. Conformity index comparison of index values across various segment width settings.

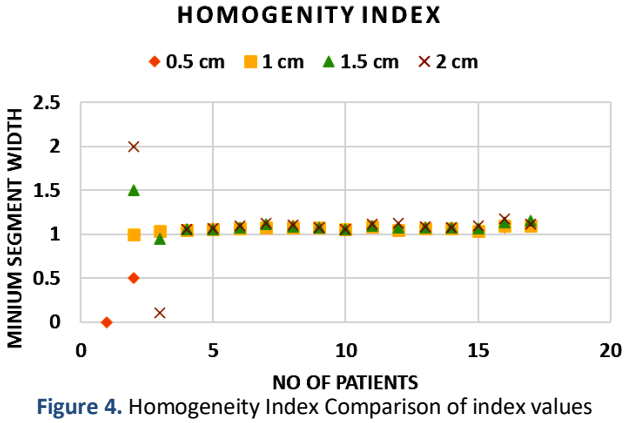


Figure 4. Homogeneity Index Comparison of index values across various segment width settings.

DISCUSSION

Minimum segment width (MSW) plays an important role in VMAT optimization by influencing modulation capability, plan complexity, and delivery efficiency. In this study, intermediate MSW values demonstrated favourable performance in head and neck VMAT planning, supporting the concept that excessive modulation is not always necessary to achieve clinically acceptable plans. While narrower MSWs increase the degree of modulation, they also introduce greater plan complexity, which may not translate into meaningful clinical benefit when compared with slightly wider segment widths.

The results obtained with a 1.0 cm MSW indicate that this setting provides adequate modulation to achieve good target conformity and dose homogeneity without compromising delivery efficiency. Earlier studies conducted in different anatomical sites have shown that although very narrow segment widths can enhance modulation, they often lead to higher monitor units and less efficient treatment delivery in prostate, SBRT, cervical cancer, and general VMAT planning [7-10]. By comparison, intermediate MSW values have consistently been reported to strike a reasonable balance between plan quality and deliverability in high-precision techniques such as SRT/SBRT and esophageal cancer treatments [11-13]. Comparable observations have also been noted in prostate VMAT studies, where moderate segment widths improved overall treatment efficiency [13, 14], and additional investigations combining minimum segment width with fluence smoothing have further supported the use of intermediate MSW settings to maintain dosimetric quality while improving delivery performance [16].

The limited influence of MSW on organ-at-risk (OAR) doses observed in this study indicates that MSW optimization primarily affects target modulation rather than OAR sparing. This is clinically relevant, as it suggests that MSW can be adjusted to improve planning efficiency without increasing the risk of excessive dose to surrounding normal tissues. Similar trends have been reported in previous VMAT

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and IMRT studies, which noted that OAR doses are more strongly driven by optimization objectives than by segmentation constraints alone.

From a clinical perspective, selecting an MSW that balances modulation and delivery efficiency is essential for routine practice, particularly in head and neck treatments where treatment time, plan robustness, and deliverability are important considerations. The findings of this study indicate that a 1.0 cm MSW meets these requirements and may be preferable to narrower settings that increase complexity without providing substantial dosimetric advantage. The study is limited by its retrospective design, small cohort, and use of a single treatment planning system. As MSW implementation is TPS-specific, further investigations involving larger patient populations, additional disease sites, and different planning systems are needed to confirm the general applicability of these results.

CONCLUSION

Although narrower MSW values provide greater modulation, the 1.0 cm MSW demonstrated the most practical performance in head and neck VMAT planning by maintaining plan quality while improving delivery efficiency. These findings suggest that a 1.0 cm MSW is a suitable choice for routine clinical use in head and neck VMAT. Future multi-institutional studies incorporating different treatment sites and planning systems are recommended to further validate these observations.

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Conflicts of interest: The authors declare no conflicts of interest.

Ethical consideration: study was based on retrospective observational and departmental research committee approval was taken prior to start the study.

Author Contributions: L.M. and Y.M.H., Data collection; J.N.,Manuscript drafting; S.S.N. and S.C., Study design and manuscript structure; S.L., A.S. and K.S., Manuscript review and critical revision. All authors reviewed and approved the final version of the manuscript.

Use of AI in manuscript preparation: AI tools, including ChatGPT (OpenAI), were used to assist in improving the language and clarity of the manuscript. All scientific content and data interpretation were conducted by the authors.

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