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Dosimetric and Treatment Delivery Analysis of Volumetric Modulated Arc Therapy systems for Pharyngeal Carcinoma

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ABSTRACT

Introduction: This study evaluated the dosimetric performance and delivery efficiency of three volumetric modulated arc therapy (VMAT) techniques using different multileaf collimator (MLC) systems: MLCi2, Agility and HDMLC for the treatment of pharyngeal cancer.

Material and Methods: A retrospective analysis of 21 pharyngeal cancer patients was performed. For each patient, three VMAT plans were generated using a simultaneous integrated boost (SIB) technique, delivering 66 Gy, 60 Gy and 54 Gy to PTV66, PTV60 and PTV54 respectively, over 30 fractions. Plans were created in Monaco treatment planning system (TPS) with MLCi2 (VMAT1) and Agility (VMAT2) and in Eclipse TPS with HDMLC (RapidArc). Plan quality was evaluated using conformity index (CI), homogeneity index (HI) and mean dose for target volumes. Organ-at-risk (OAR) doses were assessed according to RTOG criteria, while treatment efficiency was analyzed using monitor units (MUs) and beam-on time (BOT).

Results: All techniques produced clinically acceptable plans. RapidArc demonstrated superior conformity for PTV66 and significantly improved homogeneity for PTV60 and PTV54. It also achieved reduced maximum doses to the spinal cord and decreased low- and medium-dose spillage to normal tissue compared with VMAT1 and VMAT2. RapidArc required fewer MUs and achieved shorter BOT ($p < 0.05$), indicating enhanced delivery efficiency.

Conclusion: While all techniques met clinical requirements, RapidArc with HDMLC achieved superior conformity, better OAR sparing and improved delivery efficiency. These findings underscore the pivotal role of MLC design and configuration in optimizing VMAT plan quality and treatment performance for head and neck cancers.

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Introduction

Radiotherapy for head and neck malignancies remains technically demanding because of the intricate regional anatomy, where target volumes are frequently situated in close proximity to critical normal structures, thereby limiting the safely deliverable dose. Volumetric modulated arc therapy (VMAT), an advanced radiotherapy technique now routinely employed in the management of head and neck cancers, has demonstrated superior delivery efficiency compared with intensity-modulated radiation therapy (IMRT) while preserving and in some cases improving, overall plan quality [1]. VMAT enables the generation of highly conformal dose distributions with enhanced target coverage and improved sparing of adjacent normal tissues, in addition to reducing treatment delivery time and monitor unit (MU) requirements relative to conventional radiotherapy approaches [2–4].

In parallel, medical linear accelerator (Linac) manufacturers have continuously refined multi-leaf collimator (MLC) designs in response to growing evidence highlighting the clinical significance of parameters such as leaf width, inter-leaf transmission, maximum leaf speed and positional accuracy [5]. Reduced leaf width and sharper leaf penumbra are particularly advantageous for the treatment of small targets and anatomically complex volumes or organs at risk (OARs). Furthermore, the use of narrower MLC leaves has been associated with a reduction in dose to surrounding normal tissues of up to 5% within the 70% and 50% isodose regions [6–9].

This study aimed to compare three different MLC designs used with the VMAT technique for pharyngeal cancer, employing two different treatment planning systems (TPS). The dosimetric impact of different MLC design parameters, including target coverage, OAR

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doses, MUs and beam-on time (BOT) were analyzed for three systems: Elekta MLCi2, Elekta Agility and Varian HDMLC.

Materials and Methods

Patient selection

A retrospective planning study was conducted on 21 patients with pharyngeal carcinoma, including 13 hypopharyngeal and 8 oropharyngeal cases. The study cohort comprised 12 male patients and 9 female patients, with patient age of 57± 9 years. All patients received radical radiotherapy using the VMAT technique, delivering a total dose of 66 Gy in 30 fractions by the simultaneous integrated boost (SIB) technique. The patients were immobilized in the supine position with arms alongside the body, using five-clamp head and neck thermoplastic masks. Contrast-enhanced computed tomography (CECT) scans were acquired with 5 mm slice thickness using a 16-slice GE Discovery RT scanner (GE HealthCare, Chicago, USA).

Contouring

For each patient, CT images were transferred via the Digital Imaging and Communications in Medicine (DICOM) network to both Monaco and Eclipse TPS workstations for contouring. Target volumes and critical structures were delineated using radiotherapy oncology group (RTOG) contouring guidelines on the same CT dataset by an expert radiation oncologist and independently verified by a second expert to ensure consistency. The body volume extending 2 cm superior and inferior to the total target, excluding the target itself, was defined as normal tissue (NT).

MLC parameters

MLC parameters such as leaf width, leaf speed, interleaf gap, positional accuracy and transmission play a major role in modulating the dose to surrounding tissues. The leaf positioning uncertainties are an important consideration, especially under conditions where MLC leaves operate at their maximum speed or are subjected to highly modulated motion patterns [10–12]. The maximum permissible leaf speed has also been shown to affect VMAT plan quality, as demonstrated in investigations involving nasopharyngeal and rectal cancer treatments. Notable improvements in plan quality have been observed as the maximum MLC leaf speed increases from 1 to 3.5 cm/s, whereas additional gains beyond this threshold are relatively limited [13]. The principal characteristics of the three MLC systems analyzed in the present study are outlined in Table 1.

Elekta Linacs and Monaco TPS

The Elekta Synergy platform linac equipped with an MLCi2 assembly comprises 40 opposing leaf pairs, each projecting a width of 1 cm at isocenter. The Elekta Versa-HD linac with an Agility MLC head consists of 80 opposing leaf pairs, each projecting a width of 0.5 cm at isocenter. Monaco TPS version 6.01, employing the Monte Carlo dose calculation algorithm with a grid size 2.5mm, was used for both MLCi2 and Agility VMAT plans.

Table 1. Multi-leaf Collimator Parameters

Parameter	MLCi2	Agility	HDMLC
Leaf width	10 mm	5 mm	2.5 mm central & 5 mm outer leaves
Leaf Speed	20 mm/s	65 mm/s	25 mm/s
Min. Leaf Gap	5 mm	3 mm	0.4 mm
Backup Jaws	yes	no	yes
Leaf transmission	<2.5%	<0.4%	<2%

Varian Linac and Eclipse TPS

The Varian Novalis Tx linac is equipped with a 120-leaf HDMLC (32 central leaf pairs of 2.5 mm width, 28 outer pairs of 5 mm width, maximum MLC-defined field size of 22 cm × 32 cm, and leaf thickness of 6.9 cm). Eclipse TPS version 15.6.04 was used to generate the RapidArc plan. Final dose calculations were performed using the Analytical Anisotropic Algorithm (AAA) with a grid resolution of 2.5 mm.

Treatment planning and evaluation

For each patient, three SIB-VMAT plans were generated: two in Monaco TPS for the Elekta Synergy with MLCi2 (VMAT1) and Elekta Versa-HD with Agility (VMAT2) and one in Eclipse TPS for the Varian Novalis Tx with HDMLC (RapidArc). All plans were generated using a 6 MV photon beam with a maximum dose rate of 600 MU/min and treatment planning objectives according to RTOG guidelines. To ensure consistency, all cases were replanned by an experienced medical physicist. All plans employed two arcs (190°–170°) delivered in clockwise and counterclockwise directions, with the collimator and couch fixed at 0°. Couch structures were included in dose calculations to account for megavoltage beam attenuation. Each VMAT plan delivered 66 Gy to PTV66, 60 Gy to PTV60 and 54 Gy to PTV54 in 30 fractions using the SIB technique. The planning objective was to cover at least 95% of each PTV volume with 95% of the prescribed dose. According to institutional protocol, PTV66 was restricted to a maximum of 107% of the prescribed dose (70.62 Gy). The maximum point dose constraints were 45 Gy for the spinal cord and 54 Gy for the brainstem, while the mean dose to each parotid gland was limited to <26 Gy. Treatment planning objectives are summarized in Table 2.

Table 2: Treatment planning objectives

Structure	Parameter	Constraint
PTV66	D95%	> 95% of Prescribed Dose
	D2%	< 107% of Prescribed Dose
PTV60	D95%	> 95% of Prescribed Dose
PTV54	D95%	> 95% of Prescribed Dose
Brainstem	Dmax	< 54 Gy
Spinal Cord	Dmax	< 45 Gy
Parotids	Dmean	< 26 Gy

PTV: Planning Target Volume

Dosimetric evaluation metrics

The homogeneity index (HI), conformity index (CI_{95}) and mean dose were used to compare target volume coverage across the three plans. HI was calculated as $(D_{2\%} - D_{98\%}) / D_{50\%}$, where $D_{2\%}$, $D_{98\%}$ and $D_{50\%}$ represent the doses received by 2%, 98% and 50% of the PTV, respectively [17]. An HI value closer to zero reflects superior dose homogeneity within the target volume. The CI_{95} was defined as the ratio of the patient volume receiving at least 95% of the prescribed dose (V_{95}) to the volume of PTV (VT), expressed as $CI_{95} = V_{95} / VT$ [16]. A CI value of 1 represents perfect dose conformity. HI and mean dose were analyzed for all PTVs, while CI_{95} was specifically evaluated for PTV66. For OARs, dose analysis was performed using dose–volume histograms (DVHs). The spinal cord and brainstem were assessed by maximum dose (Dmax), while the mean dose was analyzed for both parotid glands. The volume of NT receiving ≥5, ≥10, ≥20, ≥30 and ≥40 Gy, as well as the mean NT dose, were recorded. Treatment efficiency was evaluated using the total number of MUs per plan and BOT.

Statistical analysis

Statistical analysis was performed using one-way ANOVA with post hoc testing, considering $p < 0.05$ as statistically significant.

Ethical Committee approval

The retrospective study was approved by the Basavatarakam Indo-American cancer hospital and research institute ethics committee (IEC/2025/AC/38). Informed consent was obtained from all participants included in the study.

Results

All three VMAT techniques produced clinically acceptable plans with adequate coverage for all PTVs. Table 3 represents the dose-volume histogram (DVH) statistics on target volumes and Table 4 details the doses to NT and critical structures as mean values ± standard deviation (SD). All three techniques consistently met institutional planning objectives and clinical acceptability criteria. However, statistically significant differences were identified among the techniques in selected dosimetric and treatment efficiency parameters, highlighting their distinct performance characteristics.

Table 3. Dose volume statistics of target volumes, monitor units, and beam-on time

		VMAT1 (MLCi2)			VMAT2 (Agility)			RapidArc (HDMLC)			p-value
		MEAN	SD	95%CI	MEAN	SD	95%CI	MEAN	SD	95%CI	
PTV66	MEAN	65.254	0.445	0.202	65.147	0.315	0.143	65.226	0.608	0.277	0.7465
	CI	1.496	0.187	0.09	1.496	0.198	0.09	1.161	0.105	0.05	<0.0001
	HI	0.081	0.018	0.01	0.079	0.018	0.01	0.073	0.019	0.01	0.34
PTV60	MEAN	61.463	0.71	0.323	61.418	0.561	0.255	60.566	0.866	0.394	0.00015
	HI	0.162	0.018	0.01	0.163	0.016	0.01	0.125	0.038	0.02	<0.0001
PTV54	MEAN	54.767	0.517	0.235	54.935	0.739	0.336	54.116	0.592	0.269	0.00016
	HI	0.167	0.047	0.02	0.173	0.042	0.02	0.114	0.047	0.02	<0.0001
MU		749	82	38	790	110	51	551	56	26	<0.0001
BOT (min)		3.94	0.39	0.18	2.69	0.21	0.1	2.27	0.09	0.04	<0.0001

SD: Standard deviation, 95%CI: 95% of confidence interval, PTV: Planning target volume, CI: Conformity index, HI: Homogeneity index, MU: Monitor units, BOT (min): Beam on time in minutes

Table 4. Dose volume statistics of organs at risk

OAR	VMAT1 (MLCi2)			VMAT2 (Agility)			RapidArc (HDMLC)			p-value
	MEAN	SD	95%CI	MEAN	SD	95%CI	MEAN	SD	95%CI	
Spinal Cord (Dmax)	38.73	1.56	0.73	38.80	1.61	0.97	35.07	1.08	0.50	<0.0001
Brain Stem (Dmax)	41.91	7.27	3.39	43.67	6.67	3.73	39.89	3.81	1.78	0.29
Lt Parotid (Mean)	25.92	6.94	3.24	24.71	7.42	3.46	22.05	5.72	2.67	0.18
Rt Parotid (Mean)	25.75	6.47	3.02	24.43	6.20	2.89	21.77	5.08	2.37	0.11
NT Mean	24.16	2.73	1.24	22.97	2.56	1.17	18.18	1.45	0.69	<0.0001
NT V5Gy (%)	84.34	3.99	1.86	82.38	4.17	1.94	78.39	4.20	1.96	<0.0001
NT V10Gy (%)	70.66	4.86	2.27	67.43	3.88	1.81	61.63	3.70	1.73	<0.0001
NT V20Gy (%)	50.35	5.69	2.65	45.64	5.27	2.46	37.48	4.45	2.08	<0.0001
NT V30Gy (%)	31.92	5.31	2.48	29.48	4.88	2.28	19.67	3.00	1.40	<0.0001
NT V40Gy (%)	21.89	4.83	2.25	20.81	4.74	2.21	10.29	2.05	0.96	<0.0001

SD: Standard deviation, 95%CI: 95% of Confidence interval, NT: Normal tissue, V5Gy: % volume receiving ≥5 Gy; V10Gy: % volume receiving ≥10 Gy; V20Gy: % volume receiving ≥20 Gy; V30 Gy: % volume receiving ≥30 Gy; V40 Gy: % volume receiving ≥40 Gy

Planning target volumes

Acceptable target dose coverage was achieved in all three plans. Doses to all the target volumes were comparable. The RapidArc plan gave statistically significant improvement in CI_{95} for PTV66 compared to both VMAT1 and VMAT2 [CI_{95} of PTV66 for RapidArc (1.161 ± 0.105); VMAT1 (1.496 ± 0.187) and VMAT2 (1.496 ± 0.198)]. The HI of PTV66 showed non-significant difference among all plans. RapidArc gave statistically significant improvement in HI for PTV60 and PTV54 compared to both VMAT1 and VMAT2 [HI of PTV60 for RapidArc (0.125 ± 0.038); VMAT1 (0.162 ± 0.018) and VMAT2 (0.163 ± 0.016) and of PTV54 for RapidArc (0.114 ± 0.047); VMAT1 (0.167 ± 0.047) and VMAT2 (0.173 ± 0.042)]. There was no significant difference in the mean dose of PTV66 among all the plans, whereas the mean doses of both PTV54 and PTV60 for the RapidArc plan showed significant differences compared to those of the VMAT1 and VMAT2 plans.

Spinal cord

The planning objectives were met in all the plans. The RapidArc plan showed a statistically significant difference in maximum dose (D_{max}) to the spinal cord compared to both VMAT1 and VMAT2 plans [D_{max} of SC for RapidArc (35.07 ± 1.08 Gy); VMAT1 (38.73 ± 1.56 Gy); and VMAT2 (38.80 ± 1.61 Gy), respectively; p <0.001].

Brainstem

The planning objective for the brainstem was easily met in all three plans. The D_{max} for the brainstem was lower in the RapidArc (39.89 ± 3.81 Gy) compared with VMAT1 (41.91 ± 7.27 Gy) and VMAT2 (43.67 ± 6.67 Gy). The D_{max} of the brainstem in the VMAT1 plan was less compared to the VMAT2 plan. The maximum dose to the brainstem in all the plans showed no significant statistical difference (p = 0.29).

Parotid glands

The planning objective of both the parotid glands [left (Lt) parotid and right (Rt) parotid] was not fulfilled. Target coverage was prioritized over parotid sparing. Hence, the objective of both the parotid glands was not fulfilled. The mean dose received by both the parotids in the Rapid Arc plan [Lt parotid (22.05 ± 5.72) Gy; Rt parotid (21.77 ± 5.08) Gy] was less than the VMAT1 [Lt parotid (25.92 ± 6.94) Gy; Rt parotid (25.75 ± 6.47) Gy] and VMAT2 [Lt parotid (24.71 ± 7.42) Gy; Rt parotid (24.43 ± 6.20) Gy] plans. The mean dose of both the parotids in all three plans showed no significant difference.

The statistical analysis of OARs (brainstem, spinal cord, Lt parotid, and Rt parotid), the average number of MUs per plan, and BOT among three VMAT plans represented by boxplots is shown in Figure 1.

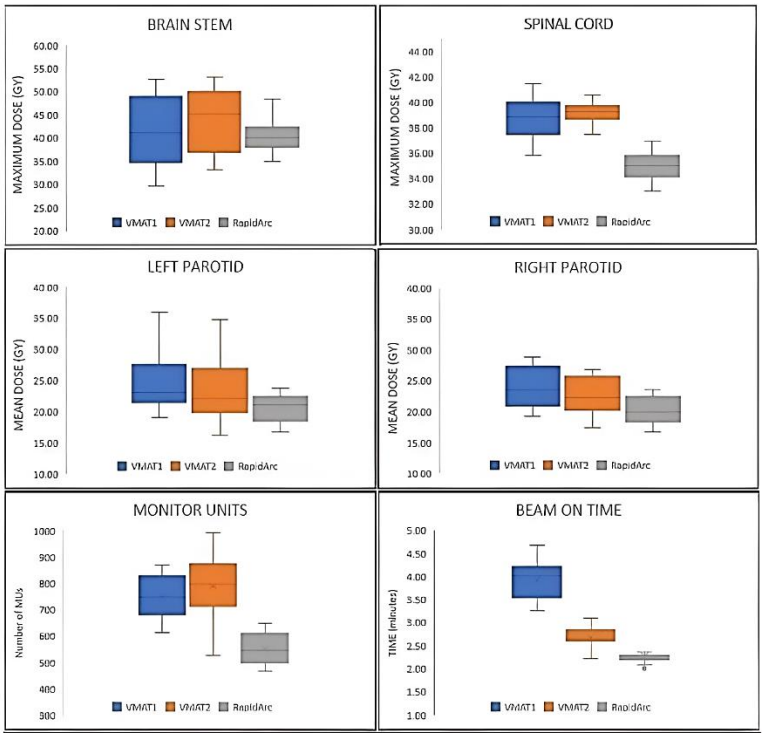

Figure 1. The distribution of key dose metrics for critical structures—spinal cord, brainstem, left and right parotids—alongside treatment delivery parameters (monitor units and beam-on time) for VMAT1 (MLCi2, blue), VMAT2 (Agility, orange) and RapidArc (HDMLC120, grey).

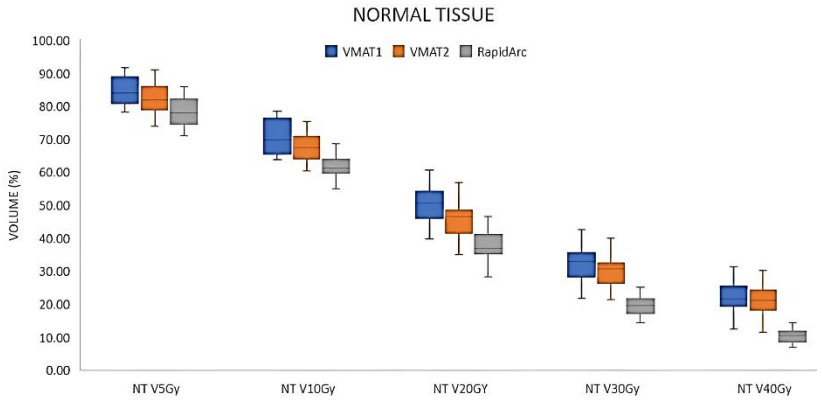

Figure 2. Boxplots illustrate the percentage volume of normal tissue (NT) receiving doses ≥5 Gy (V5Gy), ≥10 Gy (V10Gy), ≥20 Gy (V20Gy), ≥30 Gy (V30Gy) and ≥40 Gy (V40Gy) across three VMAT techniques: VMAT1 (MLCi2, blue), VMAT2 (Agility, orange) and RapidArc (HDMLC120, grey).

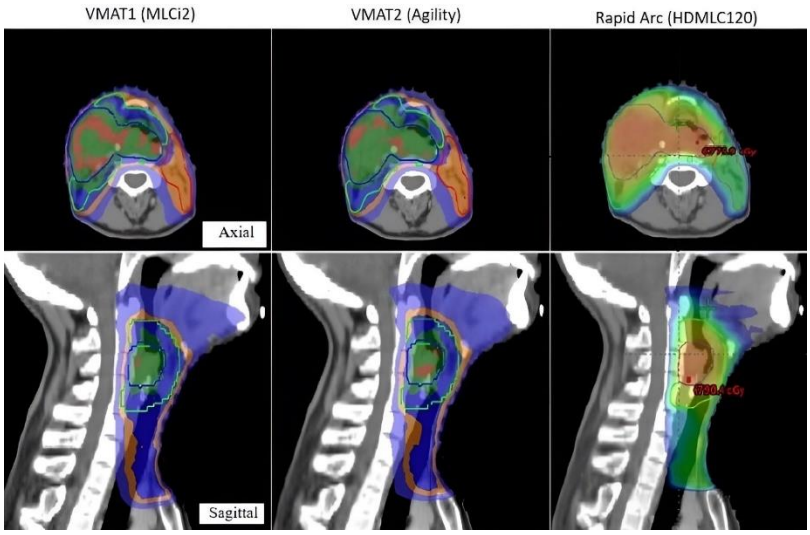

Figure 3: Dose distribution overlays are shown 40 Gy spillage for VMAT1 (MLCi2), VMAT2 (Agility) and RapidArc (HDMLC120) plans in both axial (top row) and sagittal (bottom row) slices.

Normal Tissue

The percentage volume of NT receiving doses ≥5 Gy; ≥10 Gy; ≥20 Gy; ≥30 Gy; ≥40 Gy and the mean dose of NT were compared. The statistical analysis of NT doses represented by boxplot is shown in Figure 2. The volume of NT receiving lower, medium and higher doses was lower in the RapidArc plan than in the VMAT1 and VMAT2 plans. Also, there was a significant difference observed between VMAT1 and VMAT2 plans in the volume of NT receiving lower, medium and higher Doses. These volumes were less in the VMAT2 plan compared to the VMAT1 plan. The mean dose of NT in the RapidArc plan was lower than that in the VMAT2 plan, which was lower than the mean dose of NT in the VMAT1 plan. The doses received by NT in the RapidArc plan showed significant difference when compared to the other two VMAT plans. Comparison of high-dose (40 Gy) spillage for three VMAT plans in both axial and sagittal views is shown in Figure 3.

Delivery efficiency

The number of MUs per plan for all three plans were compared. The average number of MUs per plan for the RapidArc plan (551 ± 56) was lower than that of both VMAT1 (749 ± 82) and VMAT2 (790 ± 110) plans. The BOT (excluding patient setup time) was compared among the three plans. The BOT for the RapidArc plan was shorter (2.27 ± 0.09 min) than that of the VMAT2 (2.69 ± 0.21 min) and the VMAT1 (3.94 ± 0.39 min) plans.

Discussion

This study compared the dosimetric performance and delivery efficiency of three VMAT techniques: VMAT1, VMAT2 and RapidArc for pharyngeal cancer. All plans met the clinical planning objectives and were clinically acceptable; however, significant differences were identified in target conformity, OAR sparing and treatment efficiency.

All three techniques provided adequate dose coverage to the PTVs, with comparable mean dose distributions. RapidArc showed a statistically significant improvement in the CI_{95} for the PTV66, indicating

superior dose conformity. This advantage is likely attributable to the MLC finer central leaf width (2.5 mm), enhanced leaf positioning accuracy and AAA dose calculation algorithm. Such improved conformity is particularly valuable in pharyngeal cancers, where steep dose gradients are required near critical structures. Although the HI for PTV66 was comparable across plans, RapidArc achieved significantly better homogeneity for PTV60 and PTV54, potentially contributing to a more uniform dose distribution and reduced hot-spot related toxicity. These findings are consistent with those of Kumar et al., who compared RapidArc (Eclipse) and Elekta VMAT (Monaco) plans across multiple sites and reported similar improvements in conformity with the HDMLC system [1].

Regarding OAR sparing, RapidArc demonstrated a distinct dosimetric advantage. The maximum dose to the spinal cord was significantly lower with RapidArc, which may help reduce the risk of radiation-induced myelopathy. Although differences in brainstem Dmax were not statistically significant, a favorable trend was observed with RapidArc. None of the plans met the parotid-sparing criteria, underscoring the challenge of balancing target coverage with gland sparing in advanced pharyngeal cases. Nevertheless, RapidArc yielded lower mean parotid doses, without statistical significance.

NT dose analysis further confirmed the dosimetric advantage of RapidArc, showing reduced low- and medium-dose spillage. The NT volumes receiving ≥5 Gy to ≥40 Gy were consistently smaller in RapidArc plans, suggesting a potential reduction in long-term toxicity. These improvements likely stem from the high modulation capacity of the HDMLC system, which facilitates tighter dose gradients around irregular target geometries. Kathirvel et al. analyzed 20 head and neck cancer cases, comparing biologically based (Monaco) and physically based (Eclipse) optimization methods [16]. They found both systems produced clinically acceptable plans; however, Monaco provided better sparing for serial organs, while Eclipse achieved superior sparing for parallel structures.

Treatment delivery efficiency is another critical aspect of modern radiotherapy. RapidArc demonstrated significant reductions in both the number of MUs per plan and BOT, thereby improving patient comfort, minimizing intra-fraction motion and enhancing clinical throughput. The lower MUs requirement observed with RapidArc reflects a more efficient dose delivery process, likely resulting from optimized arc modulation and reduced leakage through the HDMLC system.

The Monaco TPS, which employs a Monte Carlo dose calculation algorithm coupled with biological cost-function based optimization, typically produces smoother dose modulation and enhanced sparing of serial organs. Conversely, Eclipse TPS utilizes the AAA algorithm with physical-dose based optimization, often resulting in steeper dose gradients and improved conformity within relatively homogeneous regions. Comparable observations have been documented by Bosse et al. [14], AbuEmira et al. [15] and Kathirvel et al. [16]. Although such differences in TPS design and optimization algorithms may partially account for the superior conformity and normal tissue protection seen with RapidArc plans, the persistent advantage observed across multiple dosimetric metrics suggests that the finer leaf width, lower transmission and higher mechanical accuracy of the HDMLC are the primary determinants of this improvement.

The novelty of this study lies in being one of the first systematic comparisons of three distinct MLC designs: MLCi2, Agility and HDMLC in VMAT planning for pharyngeal cancer. It demonstrates quantitatively how MLC parameters such as leaf width, transmission and modulation capability influence both dosimetric quality and delivery efficiency. The analysis uniquely includes detailed evaluation of normal tissue dose spillage across multiple low- and medium-dose levels and shows that advanced MLC configurations can achieve improved plan quality with a reduced number of MUs and treatment time.

The limitations of the study were as follows: Clinical outcome correlations, such as toxicity reduction or local control, were not evaluated since the analysis focused exclusively on dosimetric and delivery efficiency parameters. Additionally, the comparison involved two different TPSs: Monaco and Eclipse, which utilize distinct optimization engines and dose calculation algorithms (Monte Carlo and AAA, respectively). These inherent system differences, which cannot be completely excluded, may have partially contributed to the observed dosimetric variations.

Conclusion

All three VMAT techniques produced clinically acceptable plans for pharyngeal carcinoma, fulfilling target coverage and OAR constraints. However, the RapidArc planning technique with Eclipse TPS using AAA algorithm and HDMLC design achieved superior target conformity, improved dose homogeneity and reduced normal tissue dose spillage, along with significantly lower MUs and BOT, indicating enhanced delivery efficiency. Further studies with larger cohorts and clinical outcome correlations are warranted to validate these results.

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