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Comparative Analysis of Halcyon IMRT and VMAT Plans with DMX IMRT Plans for Tongue Cancer

Vadivel Naveen Prasath [1], Chinnamuthu Mahendran[1], Rajendiran Gomathi[1], Bhandari Virendra[1*]

1. Department of Radiation Oncology, Sri Aurobindo Institute of Medical Sciences, India.

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ABSTRACT

Introduction: To determine the most effective treatment plan for tongue cancers, a comparative analysis is being conducted between Intensity-Modulated Radiation Therapy (IMRT_D) plans on the Clinac DMX system and both Volumetric Modulated Arc Therapy (VMAT_H) and IMRT_H plans for Halcyon Elite machine.

Material and Methods: A retrospective study was conducted on 20 patients with tongue cancers. A total dose of 60 Gy was delivered in two phases (i.e., 50 Gy for Elective and 10 Gy for Boost). All patients were treated using VMAT plans with unflattened beams from Varian Halcyon Elite (VMAT_H). For comparison, 40 equivalent IMRT plans with unflattened and flattened beams were created for Varian Halcyon Elite and Varian Clinac DMX (IMRT_H and IMRT_D). Plan parameters such as Homogeneity, Conformity, and Gradient Indices, along with OAR doses, were compared across the three plans.

Results: This study reveals that the HI of IMRT_H plans is significantly lower ($P<0.05$) compared to IMRT_D and VMAT_H plans. The CI and GI of IMRT_H and VMAT_H plans are significantly lower ($P<0.05$) than those of IMRT_D plans. VMAT_H plans and IMRT_H treatment plans achieve lower doses of OARs, showing a significant difference in statistics compared to IMRT_D plans. The Monitor Units required by VMAT_H plans are significantly lower ($P<0.05$) than those of IMRT_D and IMRT_H plans.

Conclusion: Volumetric Modulated Arc Therapy planned with Halcyon Elite configuration is suggested for the treatment of patients with tongue cancers. VMAT_H and IMRT_H plans were similar in plan parameters and OAR sparing, but VMAT_H required fewer Monitor Units.

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Introduction

Oral cancer encompasses malignancies that arise within the oral cavity, including the lips, tongue, gums, palate, and floor of the mouth. Data from the International Agency for Research on Cancer (GLOBOCAN, 2022) reported approximately 389,846 newly diagnosed cases worldwide, leading to nearly 188,438 deaths [1].Tongue cancer accounts for 30% - 50% of oral cancer. The highest mortality rate is reported in patients with tongue cancer among oral cancer patients [2]. The mobile portion is the front two-thirds of the tongue, which ends at the circumvallate papilla. Cancer that develops in this area is termed carcinoma of the tongue. On the other hand, cancer that occurs in the back third of the tongue is referred to as the base of tongue cancer. Several factors contribute to the development of tongue carcinoma, including poor oral hygiene, excessive alcohol use, and smoking [3].

Radiation therapy is a key component in the treatment of tongue cancers, often combined with other modalities like chemotherapy or surgery, depending on the stage and nature of the cancer. Treatment of tongue cancers is carried out with different modalities of radiation therapy such as 3-D Conformal Radiation Therapy, Intensity Modulated Radiation Therapy, and Volume Modulated Arc Therapy. Conventionally these modalities of radiation therapy are delivered with a flattening filter in between the primary collimator and monitor chamber to compensate for the forward peak nature of the bremsstrahlung in the mega voltage range. Recent advances in Treatment Planning Systems (TPS) algorithms increased the utilization of unflattened beams in radiotherapy, leading to the production of linear accelerators without flattening filters by manufacturers such as Halcyon by Varian. Removing the flattening filter offers several advantages, including reduced scatter radiation, faster treatment delivery times due to increased dose rate, and decreased neutron contamination from interacting with the filter.

This study compares the dosimetric differences in the treatment plans of IMRT plans using flattened beams from a C-ring gantry linear accelerator (Varian Clinac DMX) with VMAT and IMRT plans using unflattened beams from an O-ring gantry linac (Varian Halcyon Elite). Additionally, this study compares the

*Corresponding Author: Tel: 9893115337; Email: virencancer@yahoo.co.in

dosimetric differences in the IMRT and VMAT plans using unflattened beams from an O-ring gantry.

Materials and Methods

Patient selection

Retrospectively, 20 patients diagnosed with carcinoma tongue were selected for this study. The selected patients were between 35 and 65 years old, and the majority of them were male. All the patients were treated using the VMAT plans with unflattened beams from Varian Halcyon Elite (VMAT_H). For this study, 40 equivalent IMRT plans with unflattened and flattened beams were created for Varian Halcyon Elite and Varian Clinac DMX (IMRT_H and IMRT_D).

Simulation and Contouring

All patients were positioned head-first in a supine orientation and immobilized using Orfit thermoplastic masks with 4 clamps and a Meditronix C-Headrest (Timo headrest). For additional immobilization, mouth bites were created using dental impression materials. Each patient underwent simulation using a 128-slice Philips Incisive CT scanner (Philips, Kolkata, India). CT scans were taken from the top of the head to the tracheal carina, capturing all cancerous lymph nodes, with a slice thickness of 3 mm. The acquired images were contoured in Eclipse Version 17.0.1 by dedicated physicians.

Treatment Units

The Halcyon^{TM} 3.0 system, featuring the Elite (Varian Medical Systems, USA) linear accelerator with O-ring gantry, incorporates a 6MV unflattened FFF beam and a jawless design for optimized performance. Its patient throughput is enhanced by a dual-layer, stacked, and staggered MLC system, with two banks: proximal and distal. These MLCs, with 114 leaves (29 pairs in the proximal bank and 28 pairs in the distal), are offset by 5 mm to minimize transmission, leakage, and leaf effects, providing a 5 mm resolution at the isocenter for patient treatments. The system is capable of delivering radiation at a maximum dose rate of 800 MU/min. It incorporates multi-leaf collimators (MLCs) with a motion speed of 5 cm/sec and enables up to four gantry rotations per minute (4 RPM). The system accommodates a maximum treatment field size of 28 × 28 cm for clinical use. For imaging, it employs a megavoltage (MV) detector panel based on a 1200-element amorphous silicon (a-Si) design, positioned 154 cm from the radiation source. This panel has a physical area of 43 × 43 cm, yielding isocentric coverage of 28 × 28 cm, and supports imaging dose rates of 27 MU/min and 45 MU/min. Unlike conventional linear accelerators, the unit does not provide a light field.

The Varian Clinac DMX medical linear accelerator (Varian Medical Systems, USA) is a C-ring system that offers photon energies of 6 MV and 15 MV, along with electron energies of 6 MeV, 9 MeV, 12 MeV, and 15 MeV. It is equipped with an 80-leaf multi-leaf collimator (MLC), with 40 leaves on each side (Bank A and Bank B), each leaf having a thickness of 1 cm at the isocenter. The system can produce a maximum field size of 40 cm × 40 cm and supports a gantry rotation speed of 1 revolution per minute (1 RPM). It can deliver both photons and electrons at dose rates of 100, 200, 300, and 400 MU/min. The MV imager features a 1000-amorphous silicon (a-Si) detector panel, with a maximum field size of 30 cm × 40 cm that can be irradiated.

Treatment Planning

After delineating the tumors and surrounding normal tissues, treatment plans were created using the Eclipse Treatment Planning System Version 17.0.1 (Varian Medical Systems, USA). Each patient received a total dose of 60 Gy, administered in 30 fractions, via the Varian Halcyon Elite linear accelerator. The total dose was delivered in two phases: 1) in the first phase a dose of 50 Gy was delivered in 25 fractions, and 2) Boost plan with 10 Gy in 5 fractions. After completing 25 fractions, all patients underwent a second CT simulation, and new treatment plans were created based on the updated images. The treatment plans utilized the double arc VMAT technique with photons of energy 6 MV FFF (Flattening Filter Free). Each plan involves two arcs: the first rotating clockwise and the second rotating counterclockwise, with gantry angles ranging from 181˚ to 179˚ and 179˚ to 181˚, respectively. To ensure the leakage due to interleaves of MLC is distributed to the entire plane and not on a single plane due to gantry rotation, the collimators were rotated to 30˚ for the clockwise arc and 330˚ for the counterclockwise arc. Each plan was verified by portal dosimetry before treating the patients. The plans were generated in such a way that they achieved the following goals.

a) The PTV receives the prescribed dose.
b) The maximum dose to the spinal cord, brain stem, brain, and eye lenses doesn't exceed 45 Gy, 54 Gy, 60 Gy, and 7 Gy respectively.
c) The mean dose to both parotids, and larynx doesn't exceed 26 Gy, and 45 Gy respectively.

For this study, two additional IMRT treatment plans were developed for both the Halcyon and Clinac DMX configurations. The Halcyon configuration utilized 6 MV FFF photon energy, while the Clinac DMX configuration employed 6 MV photon energy, respectively. Seven-field IMRT plans were used for the first phase of treatment with gantry angles of 0°, 52°, 104°, 156°, 208°, 260°, and 312°, while five-field IMRT plans were used for the second phase with gantry angles of 0°, 72°, 114°, 216°, and 288°. The treatment objectives remain the same as those of the VMAT plan while creating the additional two IMRT plans.

The primary distinction between the treatment plans lies in the type of radiation beam and the delivery technique. The IMRT_D and VMAT_H plans differ mainly in the beam configuration, with IMRT_D using flattened beams (6 MV) and VMAT_H using unflattened beams (6 MV FFF). Similarly, IMRT_H also employs unflattened beams, but differs from

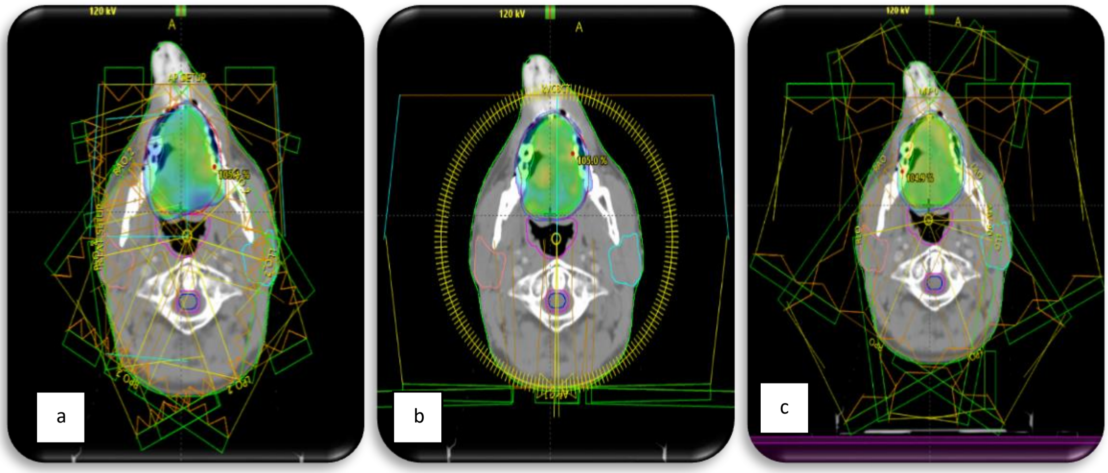


Figure 1. Dose distribution and field arrangement of one of the selected patients for a) IMRT_D b) VMAT_H and c) IMRT_H plans

VMAT_H in its delivery technique. In IMRT plans (both IMRT_D and IMRT_H), radiation is delivered from static gantry angles, meaning the gantry stops at predetermined positions to deliver the dose (seven fields in the first phase and five in the second phase). In contrast, the VMAT_H plan involves continuous gantry rotation during dose delivery, which allows for dynamic modulation of the beam as the gantry moves around the patient. This fundamental difference in beam modulation and delivery technique distinguishes the three plans, despite similarities in the treatment objectives and target coverage. Figure 1 shows the dose distribution and field placement of one of the selected patients in all three techniques.

The plans are optimized using the Plan Optimizer (PO) algorithm. Dose calculations were carried out using the Analytical Anisotropic Algorithm (AAA), which involves two main components: the configuration module and the dose calculation module. The configuration module defines the photon beam's phase space (particle, fluence, energy) from the linear accelerator. In contrast, the dose calculation module divides the clinical beam into smaller beamlets and the patient's body into a 3D matrix of calculation voxels, with voxel dimensions determined by the selected grid size for volumetric dose calculation [4].

Treatment Plan Evaluation Tools

Dose Volume Histogram (DVH) was created for all the plans with the help of DVH estimation algorithm version 17.0.1 for target volumes and OARs. Dosimetric indices such as Homogeneity Index, Conformity Index, and Gradient index were calculated using DVH. For the evaluation of OARs, the maximum dose to the spine, brain stem, and eye lenses were studied. Additionally, mean dose to both parotids, oropharynx, and larynx were also studied.

Homogeneity index

The homogeneity index measures the uniformity of the dose distribution across the target volume. Although there are many formulae for calculating the homogeneity index the one used for this study is the one recommended by ICRU 83. The ideal value of the homogeneity index recommended by ICRU 83 is 0 [5].

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

$D_{2\%}$ = Dose received by 2% volume of PTV

$D_{98\%}$ = Dose received by 98% volume of PTV

$D_{50\%}$ = Dose received by 50% volume of PTV

Conformity Index

Conformity Index is an objective measure of how well the distribution of radiation conforms to the shape of the target. Ian Paddick proposed the formula used here for calculating CI. The ideal value suggested by the Paddick Conformity Index is 1 [6].

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

TV_{PIV}= volume of prescribed isodose in area of interest

TV= PTV volume

PIV= volume of prescribed isodose

Gradient Index

The Gradient Index measures the dose falloff outside the target. Ian Paddick proposed the formula used for measuring GI in this study. GI of less than 3 reflects a reasonably selected prescription isodose level [7].

$GI = (V_{50\%})/(PIV)$

$V_{50\%}$ = volume of half the prescription isodose.

Statistical Analysis

Data are presented as Mean ± Standard Deviation and were processed using Minitab statistical software (Version 22.1.0, Minitab LLC, State College, PA, USA). The Shapiro–Wilk test was applied to confirm data normality. Comparisons between IMRT_D and VMAT_H, IMRT_D and IMRT_H, as well as

VMAT_H and IMRT_H, were evaluated using a paired t-test. Statistical significance was defined at a p-value < 0.005.

Results

Clinically acceptable IMRT plans with flattened beams, as well as VMAT and IMRT plans with unflattened beams, were achieved for all 20 selected cases. The PTV volumes across these cases for the first phase range from 321 cc to 533.6 cc, while those for the second phase range from 65.9 cc to 286 cc. Tables 1 and 2 present the plan evaluation metrics, including HI, CI, GI, $D_{2\%}$, and $D_{98\%}$ as well as the monitor units for IMRT_D, VMAT_H, and IMRT_H plans for both phase one and phase two (PTV Elective and PTV Boost), along with P-values from paired T-tests. Table 3 summarizes the cumulative dosimetric evaluation of various OARs for the IMRT_D, VMAT_H, and IMRT_H plans. All parameters are reported as mean ± standard deviation to compare the different treatment plans.

Planning Target Volume

Target coverage was observed to be superior in IMRT_H plans across both treatment phases.

Homogeneity Index

IMRT plans using unflattened beams for the Halcyon Elite configuration achieved better homogeneity indices, with values of 0.08 ± 0.02 for PTV-Elective and 0.05 ± 0.01 for PTV-Boost, compared to the VMAT_H and IMRT_D plans. No significant differences were observed in the homogeneity indices of PTV-Elective and PTV-Boost between VMAT_H and IMRT_D plans.

Table 1. Dosimetric comparison of PTV elective

Parameter	IMRT_D (Mean±Std)	VMAT_H (Mean±Std)	IMRT_H (Mean±Std)	p	p*	p**
$D_{2\%}$ (Gy)	51.91±0.31	52.15±0.47	51.69±0.25	0.1063	0.0292	0.0015
$D_{98\%}$(Gy)	47.29±0.20	47.75±0.78	47.87±0.87	0.0231	0.0023	0.3604
HI	0.092±0.02	0.09±0.02	0.08±0.02	0.303	<0.0001	0.02
CI	1.4±0.17	1.26±0.11	1.3±0.24	0.003	0.117	0.477
GI	5.74±1.02	4.29±0.46	4.27±0.61	<0.0001	<0.0001	0.8882
MU	1322.3±159.9	645.45±53.75	1642.4±157.9	<0.0001	<0.0001	<0.0001

p - Paired t-test analysis of IMRT_D vs VMAT_H; p* - Paired t-test analysis of IMRT_D vs IMRT_H; p** - Paired t-test analysis of IMRT_H vs VMAT_H

Table 2. Dosimetric comparison of PTV boost

Parameter	IMRT_D (Mean±Std)	VMAT_H (Mean±Std)	IMRT_H (Mean±Std)	p	p*	p**
$D_{2\%}$ (Gy)	10.35±0.08	10.42±0.08	10.36±0.07	0.0208	0.5899	0.0048
$D_{98\%}$(Gy)	9.49±0.19	9.63±0.18	9.82±0.16	0.008	0.001	0.003
HI	0.085±0.022	0.08±0.02	0.05±0.01	0.1059	0.0001	0.0002
CI	1.4±0.19	1.15±0.14	1.09±0.25	0.0003	0.0002	0.1221
GI	4.48±0.75	3.26±0.31	3.22±0.39	<0.0001	<0.0001	0.6133
MU	560.2±84.47	520.74±33.37	682.405±79.41	0.0269	<0.0001	<0.0001

p - Paired t-test analysis of IMRT_D vs VMAT_H; p* - Paired t-test analysis of IMRT_D vs IMRT_H; p** - Paired t-test analysis of IMRT_H vs VMAT_H.

Table 3. Dosimetric comparison of organs at risks

Organ	Parameter	IMRT_D (Mean±Std)	VMAT_H (Mean±Std)	IMRT_H (Mean±Std)	p	p*	p**
Spinal Cord	Maximum Dose (Gy)	30.53±3.43	22.74±3.80	28.59±3.14	<0.001	0.004	<0.001
Right Parotid	Mean Dose (Gy)	20.93±3.34	18.35±4.19	18.68±3.37	<0.001	<0.001	0.449
Left Parotid	Mean Dose (Gy)	21.06±3.08	18.14±3.97	18.41±3.09	<0.001	<0.001	0.568
Larynx	Mean Dose (Gy)	37.81±8.45	39.55±5.78	36.17±5.62	0.122	0.042	0.008
Brainstem	Maximum Dose (Gy)	24.30±9.87	20.47±9.70	20.65±10.5	0.004	0.002	0.880
Brain	Maximum Dose (Gy)	24.54±12.54	19.8±12.32	20.54±11.5	<0.001	<0.001	0.361
Left Eye Lens	Maximum Dose (Gy)	1.3±0.3	1.24±0.24	1.27±0.22	0.042	0.319	0.044
Right Eye Lens	Maximum Dose (Gy)	1.32±0.32	1.26±0.24	1.29±0.22	0.089	0.282	0.217
Healthy Tissue*	$V_{10\,Gy}$ (%)	26.54±5.05	23.91±4.28	24.64±4.63	<0.001	<0.001	0.010
	$V_{15\,Gy}$ (%)	21.45±4.23	19.20±3.41	20.16±3.71	0.002	0.030	<0.001
	$V_{20\,Gy}$ (%)	17.88±3.30	15.47±2.83	16.28±3.05	<0.001	<0.001	<0.001
	Integral Dose ($*10^4$ Gy cm^3)	8.72±1.97	8.04±1.91	8.14±1.86	<0.001	<0.001	0.198

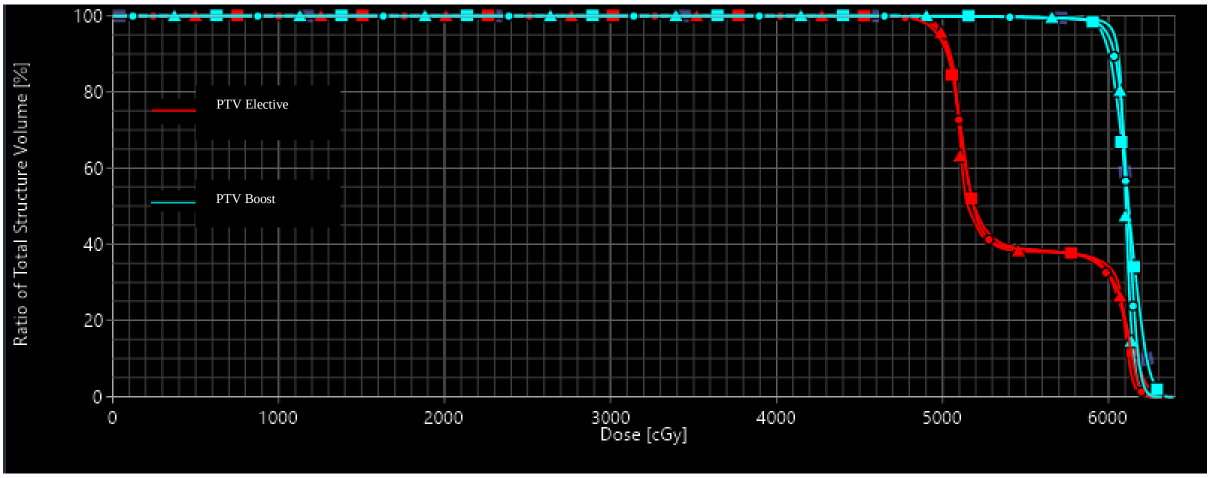
p - Paired t-test analysis of IMRT_D vs VMAT_H; p* - Paired t-test analysis of IMRT_D vs IMRT_H; p** - Paired t-test analysis of IMRT_H vs VMAT_H. Healthy Tissue* - the normal tissues that are not part of the Planning Target Volume (PTV) or delineated Organs at Risk (OARs)

Conformity Index

The VMAT_H plans achieved conformity indices of 1.26 ± 0.11 for PTV-Elective and 1.15 ± 0.14 for PTV-Boost, while the IMRT_H plans achieved conformity indices of 1.3 ± 0.24 and 1.09 ± 0.25 for the respective phases. Both VMAT_H and IMRT_H plans showed better conformity indices compared to the IMRT_D plan, with no statistically significant differences observed between the conformity indices of the IMRT_H and VMAT_H plans.

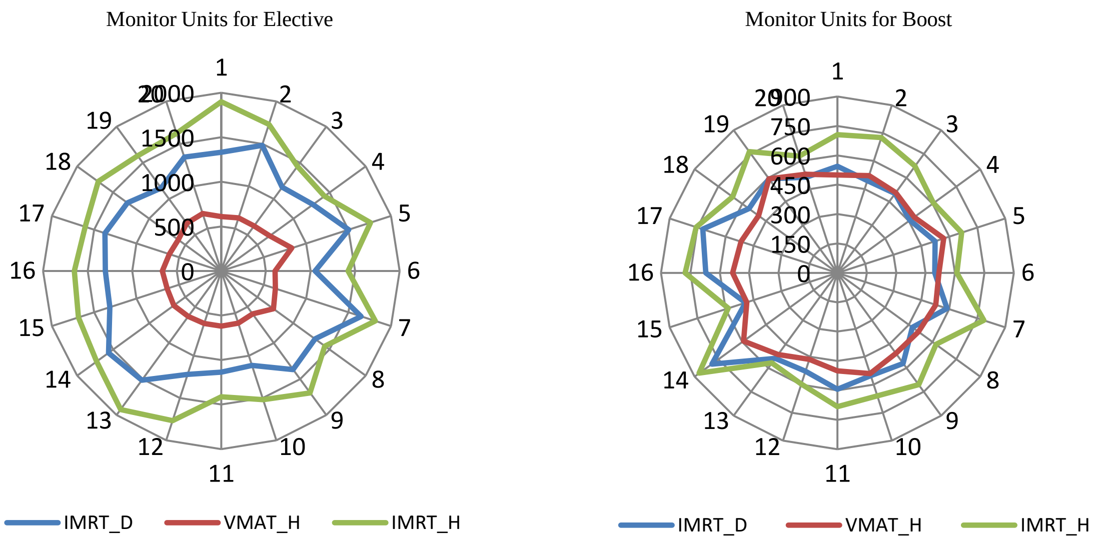
Gradient Index

Both VMAT_H and IMRT_H plans showed better gradient indices of 4.29 ± 0.46, and 4.27 ± 0.61 respectively for the first phase and 3.26 ± 0.31, and 3.22 ± 0.39 for the second phase, with no statistically significant differences observed between the conformity indices of the IMRT_H and VMAT_H plans. Figure 2 shows the DVH of the PTV for one of the selected patients comparing all three plans.



■ – IMRT_D ● – VMAT_H ▲ – IMRT_H

Figure 2. DVH for PTV comparing IMRT_D, VMAT_H, and IMRT_H



a b

Figure 3. Monitor unit distribution comparison between IMRT_D vs VMAT_H vs IMRT_H for a) elective plans and b) boost plans.

Monitor Units

To deliver 200 cGy per fraction in the first phase of treatment, the monitor units required were 1322.3 ± 159.9 MU for IMRT_D, 645.45 ± 53.75 MU for VMAT_H, and 1642.4 ± 157.9 MU for IMRT_H plans. The VMAT_H plans required significantly fewer monitor units to deliver 200 cGy per fraction than the IMRT plans in both the Halcyon and DMX configurations. When comparing the IMRT_D and IMRT_H plans, IMRT_D required fewer monitor units to deliver 200 cGy per fraction in the first fraction. Similar results were observed in the second phase of the treatment, with monitor units required were 560.2±84.47 MU for IMRT_D, 520.74±33.37 MU for VMAT_H, and 682.405±79.41MU for IMRT_H plans. Figures 3 a and b show the comparison of Monitor Units of elective and boost plans across all three treatment plans, respectively. In the figure, the circular axis corresponds to the number of patients, whereas the vertical axis represents the monitor units (MUs) necessary for delivering the IMRT_D, VMAT_H, and IMRT_H treatment plans.

Organs at Risk (OARs)

All plans met the planning objectives for maximum doses: 45 Gy to the spinal cord, 54 Gy to the brainstem, 60 Gy to the brain, and 7 Gy to the eye lenses.

Spinal cord

The spinal cord was better spared in VMAT_H with a maximum dose of 22.74 ± 3.80 Gy compared to the maximum dose to the spine achieved by IMRT_H and IMRT_D plans. The IMRT_D plan has a relatively higher spinal cord dose.

Brainstem

The IMRT_H and VMAT_H plans achieved lower maximum doses to the brain stem, showing a significant difference compared to the IMRT_D plans. The maximum doses to the brain stem for the IMRT_D, VMAT_H, and IMRT_H plans were 24.30 ± 9.87 Gy, 20.47 ± 9.70 Gy, and 20.65 ± 10.53 Gy, respectively.

Brain

The IMRT_H and VMAT_H plans provided improved sparing of the brain, with maximum doses of 20.54 ± 11.53 Gy and 19.80 ± 12.32 Gy, respectively, showing no significant difference between them. In contrast, the maximum dose to the brain achieved by the IMRT_D plan show a significantly lower sparing compared to other plans.

Bilateral eye lens

The maximum dose was evaluated separately for the left and right eye lenses. The maximum doses achieved by the IMRT_D, VMAT_H, and IMRT_H plans were 1.32 ± 0.32 Gy, 1.26 ± 0.24 Gy, and 1.29 ± 0.22 Gy, respectively, showing no significant difference among them. However, the VMAT_H plan achieved a maximum dose of 1.24 ± 0.24 Gy for the left eye lens, significantly lower than the maximum doses for the left eye lens generated by the IMRT_H and IMRT_D plans. Figure 4 provides us with a comparison of different OAR doses for case 6 achieved by all three plans.

For the larynx and parotids, all plans achieved the planning goals of 45 Gy and 26 Gy mean dose limits, respectively

Larynx

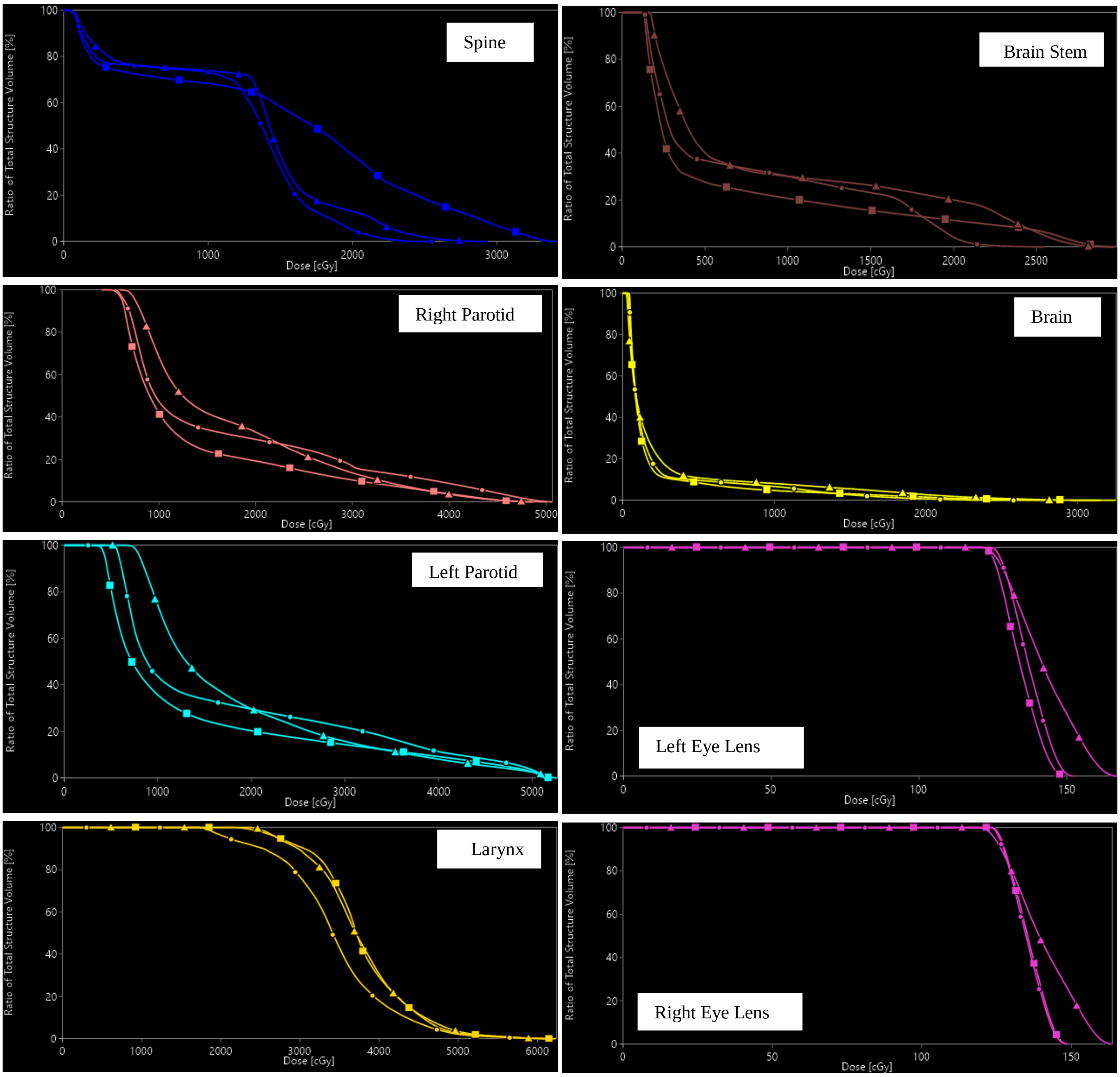
The sparing of the larynx in terms of the mean dose was better achieved in the IMRT_H plan with a mean dose of 36.17 ± 5.62 Gy. The mean doses achieved by IMRT_D and VMAT_H plans are 37.81 ± 8.45 Gy and 39.55 ± 5.78 Gy respectively and there was no significant difference achieved between these two plans.

Bilateral Parotids

The mean dose was assessed separately for the left and right parotids. Both VMAT_H and IMRT_H plans achieved lower mean doses for each parotid, with no significant difference between them. For the right parotid, the mean doses for VMAT_H and IMRT_H plans were 18.35 ± 4.19 Gy and 18.68 ± 3.37 Gy, respectively, while for the left parotid, they were 18.14 ± 3.97 Gy and 18.41 ± 3.09 Gy, respectively. The IMRT_D plan showed relatively higher mean doses to the parotids

Healthy Tissues

Healthy Tissue represents the normal tissues that are not part of the Planning Target Volume (PTV) or delineated Organs at Risk (OARs)The VMAT_H plan demonstrates a reduction in the volume of healthy tissue receiving 10 Gy (by 9.9% for IMRT_D plans and 3% for IMRT_H plans), 15 Gy (by 10.5% for IMRT_D plans and 4.7% for IMRT_H plans), and 20 Gy (by 13.5% for IMRT_D plans and 5% for IMRT_H plans). Additionally, IMRT_H plans show a reduction in the volume of healthy tissue irradiated at these dose levels when .compared to IMRT_D plans. The integral dose, calculated as the mean dose multiplied by the volume of healthy tissue, was lower in both VMAT_H and IMRT_H plans compared to IMRT_D plans



■ – IMRT_D ● – VMAT_H ▲ – IMRT_H

Figure 4. DVH of all OARs comparing IMRT_D, VMAT_H, and IMRT_H

Discussion

VMAT and IMRT plans in the Halcyon configuration provide better target coverage compared to IMRT plans in the DMX configuration. When comparing VMAT_H and IMRT_H plans, no dosimetric advantages were observed for VMAT plans in terms of Conformity and Gradient indices. IMRT_H plans showed an advantage over VMAT plans only in terms of the Homogeneity Index. Halcyon plans provided superior sparing of OARs compared to DMX plans. When comparing the VMAT_H and IMRT_H plans in terms of OAR sparing, most of the OARs were spared equally by both plans. However, the VMAT plans provided additional sparing, with a mean reduction of 5 Gy for the spine and 1 Gy for healthy tissue.

Numerous earlier studies have compared IMRT and VMAT plans using flattened beams. In one study on head and neck cancer by Syam Kumar et al., no significant differences in conformity index (CI) were observed between IMRT and VMAT plans. However, double arc VMAT plans demonstrated better homogeneity index (HI) and delivered significantly lower doses to organs at risk (OARs) than IMRT plans. VMAT plans required only 40% of the monitor units (MUs) needed for nine-field sliding window IMRT techniques [8]. Similar findings were reported by Wilko F. A. R. Verbakel et al., who concluded that double arc VMAT plans provide improved planning target volume (PTV) homogeneity and achieve comparable OAR sparing as IMRT [9].

Several studies have explored the advantages of flattening filter-free (FFF) beams over conventional flattened (FF) beams. Alaettin Arslan et al. compared lung cancer IMRT plans using FF and FFF beams, finding no significant differences in $D_{2\%}$, $D_{98\%}$, $D_{50\%}$, homogeneity index (HI), or conformity index (CI). FFF plans required more monitor units (MUs) but had shorter beam-on times and slightly lower lung V_{20Gy}% (28.81% vs. 29.65%), suggesting potential dosimetric benefits [10]. These results support the clinical feasibility of FFF beams, relevant for Halcyon, which uses only FFF photons. Our study further evaluates how Halcyon's FFF characteristics impact treatment efficiency and organ-at-risk sparing in tongue cancer IMRT and VMAT plans compared with DMX IMRT plans.

A study by Oleg N. Vassiliev *et al.* on prostate cancer intensity-modulated radiotherapy without a flattening filter reveals that using a flattening filter–free IMRT plan results in better PTV coverage. It was also found that the CI was improved in the IMRT FFF plan with a reduced rectal dose. It was also found that the total number of MUs per treatment was reduced by a factor of 2.0 [11]. Similarly, Treutwein et al. compared VMAT and IMRT treatment strategies for prostate cancer using both flattened and unflattened beams, and concluded that VMAT delivered in FFF mode offers a preferable balance of efficiency and plan quality for prostate carcinoma. These outcomes reinforce the broader advantages of FFF technology, which is of particular importance in the present work, as the Halcyon system operates solely with FFF beams. Our analysis of Halcyon IMRT and VMAT plans against DMX IMRT for tongue cancer provides additional evidence on how FFF implementation impacts dosimetric quality and delivery efficiency in head-and-neck radiotherapy [12].

In this study, treatment plans were generated using both flattened (FF) and unflattened (FFF) photon beams across two linac platforms—Varian Clinac DMX and Varian Halcyon. While previous studies such as Nithya et al. (2014) [13] have compared VMAT and IMRT techniques using conventional flattened beams, our work focuses on evaluating the dosimetric differences resulting from beam type and machine configuration. This approach provides insights into how beam quality and delivery method influence treatment outcomes in tongue cancer, particularly in settings where both machine types are available.

A study by Ian Paddick *et al.* [7] provided a novel formula for measuring Gradient Index (GI). In this study, 58 plans treated on gamma knife were retrospectively analyzed for GI calculation. The volume of the targets taken for the study ranges from 0.2 cc to 12.9 cc. The author suggests thet an ideal gradient index (GI) is typically considered to be below 3.0. In our study, the GI values obtained for both VMAT_H and IMRT_H were higher than this benchmark, which is expected in head-and-neck cases where complex anatomy and the presence of multiple organs-at-risk make it difficult to achieve very steep dose fall-off.

Several studies have explored the feasibility of treating various cancer sites using the Halcyon treatment unit. All authors reported that Halcyon dosimetric plans provided acceptable results regarding target coverage, dose conformity, and meeting OAR dose constraints. A comparative study by Steven Michiels and colleagues examined the plan quality and delivery time of a fast-rotating O-ring Linac versus a C-arm Linac. They found that the fast-rotating O-ring Linac (Halcyon) maintained at least the same plan quality as two arcs on a C-arm Linac, while significantly reducing both image acquisition and plan delivery time. The study also noted that triple-arc VMAT plans on the Halcyon system provided reduced doses to organs at risk (OARs). However, it was observed that the homogeneity achieved by the C-arm Linac (Varian TrueBeam) was superior to that of the Halcyon treatment plans [14].

In their comparative study of VMAT-based CSI plans on Halcyon and TrueBeam linacs, Biplab Sarkar *et al*. concluded that the Halcyon linear accelerator can produce clinically and dosimetrically acceptable CSI plans. Notably, Halcyon's plans demonstrated superior OAR sparing and reduced dose spillage compared to those of the TrueBeam [15]. Similarly, Damodar Pokhrel *et al*., in their study validating Halcyon for lung SBRT, found that Halcyon enables safe, feasible, and accurate lung treatment with SBRT. When comparing coplanar Halcyon VMAT plans to non-coplanar SBRT-dedicated TrueBeam VMAT plans, they showed similar tumor conformity, tumor dose heterogeneity, and GTV doses. Although Halcyon resulted in statistically higher GI and doses to some OARs—specifically, the $D_{3\ cc}$ of the esophagus, $D_{10\ cc}$ of the skin, and the normal lung—the differences were not clinically significant. Additionally, Halcyon's beam-on time was 1.5 times longer than that of TrueBeam, as Halcyon has a maximum dose rate of 800 MU/min, while TrueBeam can reach 1400 MU/min [16].

The Halcyon Linac plan offers a significant advantage in reducing the risk of radiation-induced secondary malignancies by utilizing flattening filter-free (FFF) beams and higher dose rates to deliver the required monitor units (MU) [17]. VMAT plans have a significant advantage over IMRT plans in reducing the risk of secondary tumors from radiation. The monitor units (MU) required by VMAT plans are 51.2% lower than those for IMRT_D plans and 60.7% lower than for IMRT_H plans. Although IMRT_H plans require 19.7% more MU than IMRT_D plans, the removal of the flattening filter in IMRT_H reduces scatter dose, thereby lowering the risk of secondary malignancies compared to IMRT_D plans.

The findings of the present study are in agreement with the observations of Palanivelu et al. [18], who reported that VMAT planning in oral cancer patients achieved effective sparing of the contralateral parotid gland, with mean doses ranging between 14 Gy and 17 Gy, thereby reducing the risk of xerostomia. In our study, the parotid mean dose was similarly low, confirming that advanced IMRT and VMAT techniques can provide superior parotid sparing while maintaining adequate PTV coverage. This concordance further supports the efficacy of modern treatment delivery systems such as Halcyon in achieving optimal organ-at-risk protection.

Conclusion

After a comprehensive review of all the results, VMAT plans generated using the Halcyon Elite configuration are recommended for the treatment of patients with carcinoma of the tongue. It is to be noted that IMRT plans generated for DMX configuration, perform statistically lower across all parameters analyzed in this study. The advantages of Halcyon plans include a relatively higher dose rate, faster MLC movement and quicker gantry rotation, all of which significantly reduce treatment time and minimize patient intrafraction motion. Additionally, Halcyon utilizes FFF (flattening filter-free) beams, leading to a rapid dose fall-off outside the target area compared to FF beams.

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