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The Dosimetric Performance of Volumetric Modulated Arc Therapy and Intensity Modulated Radiation Therapy in the Treatment of Locally Advanced Laryngeal Cancer

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Abstract

Background: This study aims to compare the performance of intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) in treating laryngeal cancer.

Method: In this retrospective dosimetric study, 15 patients diagnosed with locally advanced laryngeal cancer (LALC) were selected. The dosimetric performance of the two techniques was analyzed using 6 MV X-rays, based on dose-volume histograms for primary and boost planning target volumes (PTV_p and PTV_b, respectively), relevant organs at risk (OARs), mean Dose (D_{mean}), maximum Dose (D_{max}), 95% Dose (D_{95}), 2% Dose ($D_{2\%}$), 5% Dose ($D_{5\%}$), monitor units per segment (MU/segment), number of MU/cGy, treatment delivery time, along with conformity and homogeneity indices.

Results: Both techniques were able to achieve favorable equivalent uniform doses and low doses to OARs. The average total number of monitor units for IMRT was significantly greater than that for VMAT (1724.5 ± 249.5 and 475.3 ± 47.0, respectively for PTV_p and 601.4 ± 81.7 and 458.0 ± 62.6, respectively for PTV_b). The modulation factor (MU/cGy) of IMRT was significantly greater than that for VMAT for both the primary and the boost phases. The mean treatment delivery time for all cases of IMRT was significantly longer than that of VMAT.

Conclusion: The primary distinction between IMRT and VMAT in the treatment of LALC is that VMAT requires significantly fewer monitor units (one-third) compared with IMRT. This reduction contributes to a decrease in treatment time, which in turn positively impacts patient comfort and the accuracy of treatment.

Keywords: Radiotherapy, Intensity-modulated, DVH, Organs at risk, PTV

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Introduction

Head and neck cancers originate from the mucous lining of the respiratory and digestive tracts, salivary glands, and lymph nodes.[1] According to Ciolofan et al., well-differentiated squamous cell carcinomas make up more than 98% of all laryngeal cancers. In contrast, chondrosarcomas, leiomyosarcomas, and melanomas account for only 2 to 5% of all laryngeal cancers.[2]

There has been substantial advancement in the field of radiotherapy over the past decade. The introduction of intensity-modulated radiation therapy (IMRT) and subsequently, volumetric modulated arc therapy (VMAT), mark significant contributions to the field. These techniques are anticipated to significantly enhance the precision of targeting various tumor sites, shapes, types, and volumes while ensuring heightened protection of critical organs.[3]

Earlier studies have proposed that three-dimensional conformal radiotherapy (3D-CRT) can lead to increased toxicity.[4] Randomized controlled trials have demonstrated that radiation of the neck heightens the risk of long-term cerebrovascular complications.[5]

Utilizing newer radiotherapy techniques such as IMRT can mitigate this increased toxicity. IMRT enables greater dose conformity to treatment target volumes and avoids uninvolved nearby structures by providing sharp dose

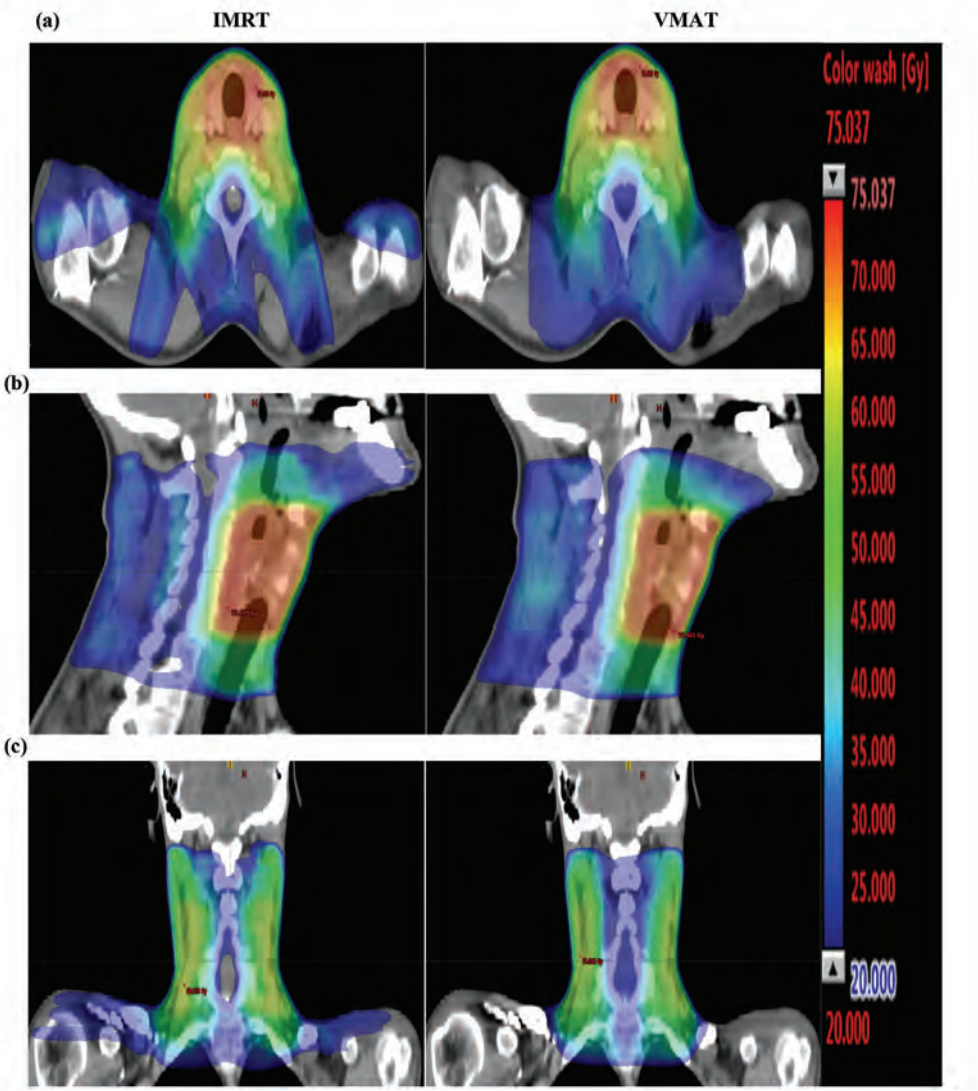

Figure 1. This figure presents (a) axial, (b) sagittal, and (c) coronal views for a patient under study as an example of dose distribution in the plan sum (Left: IMRT, Right: VMAT).
IMRT: Intensity modulated radiation therapy; VMAT: Volumetric modulated arc therapy

Table 1. Planning target volume for all larynx cancer cases in the current study

Patient number	PTV50 (PTV_p, cm^3)	PTV70 (PTV_b, cm^3)
1	836.9	80.2
2	853.9	97.5
3	889.5	179.5
4	640.4	85.8
5	597.9	111.5
6	594.6	131.0
7	513.1	55.5
8	747.8	150.0
9	811.4	53.9
10	482.8	120.4
11	730.5	75.8
12	212.4	20.1
13	547.3	85.4
14	491.5	141.1
15	958.9	81.5
Average volume of PTV (cm^3)	660.5 ± 198.1	97.9 ± 41.5

PTV: Planning target volume

gradients.[6] Regrettably, this comes at the expense of a heightened risk of secondary malignancy.[7] Another potential drawback of IMRT is the increase in the number of monitor units (MUs), which results in a larger integral dose.[8]

VMAT is a recent iteration of IMRT that administers a meticulously tailored 3D dose distribution via a 360-degree gantry rotation in single or multi-arc treatments. This innovation, a significant progression from Varian Medical Systems, is notable for reducing the number MUs and facilitating shorter treatment durations. Current research indicates that, compared to IMRT, VMAT can significantly cut down treatment time and MUs.[9]

Typically, the target volume for advanced head and neck cancer adopts an irregular concave shape, presenting a considerable challenge in the treatment planning process. The proximity of critical organs to the target volume, and the need to spare them, further complicates this process. Hence, head and neck cancers pose a unique challenge for radiotherapy.

Prior research has drawn comparisons between IMRT and VMAT across various treatment sites, concluding that VMAT generates dose distributions on par with IMRT.[10, 11]While several studies propose that VMAT achieves superior conformal dose distributions and enhances dose delivery efficiency over IMRT,[12-15] other research suggests slightly better conformity with IMRT.[16] When it comes to the homogeneity index (HI), comparisons between IMRT and VMAT have yielded varying results. Some studies report no significant[3,14, 17] differences, contrasting with others that indicate VMAT's superiority in terms of HI. This contradicts findings[16] that IMRT slightly surpasses VMAT in providing better homogeneity. Although a significant number of studies demonstrate that VMAT matches IMRT in sparing organs at risk (OARs) and producing similar plans,[18] others suggest that VMAT plans fare better in terms of OAR sparing.[14,17] The question of whether VMAT surpasses IMRT in plan quality for treatment planning of head and neck cancer remains unresolved.

In the present study, we undertake a comparison of IMRT and VMAT to ascertain which technique offers superior plan quality. Our goal is to better understand which technique may provide the desired benefits in sparing healthy tissues and risk organs, while ensuring similar coverage of the prescribed dose to the tumor.

A perennial question emerges at this juncture: Which strategy is optimal for a given treatment condition? Consequently, this research is primarily focused on comparing the accuracy of VMAT with IMRT in terms of dose distribution in locally advanced laryngeal cancer (LALC) patients.

Materials and Methods

Patients' selection, target and critical volumes delineation

This dosimetric retrospective study selected 15 patients with LALC. Ethical approval was granted by the Augusta Victoria Hospital's ethical committee (ethics code: 2022/400). All patients underwent computed tomography (CT) simulations in a supine position. A radiation oncologist delineated the target volume and critical organs according to the Radiation Therapy Oncology Group (RTOG 1016) guidelines.[19] The dose calculations were performed using the treatment planning system (TPS). The crucial OAR structures for laryngeal cancer patients included the mandible, the right parotid, the left parotid, the spinal cord, and the brainstem.

Dose prescription, planning and techniques

Dose prescription

For laryngeal carcinoma, the dose prescription was 70 Gy to the planning target volumes (PTV70) and 50 Gy to the lymph nodes, administered in two phases. In phase one, 50 Gy was delivered to PTV50 and PTV70 in 25 fractions. In phase two, 20 Gy was delivered solely to PTV70. Planning objectives were optimized to achieve the following parameters: the prescribed dose for PTV, a maximum dose of 54 Gy to the brain stem, a maximum dose of 45 Gy to the spinal cord, and a mean dose below 26 Gy for both the left

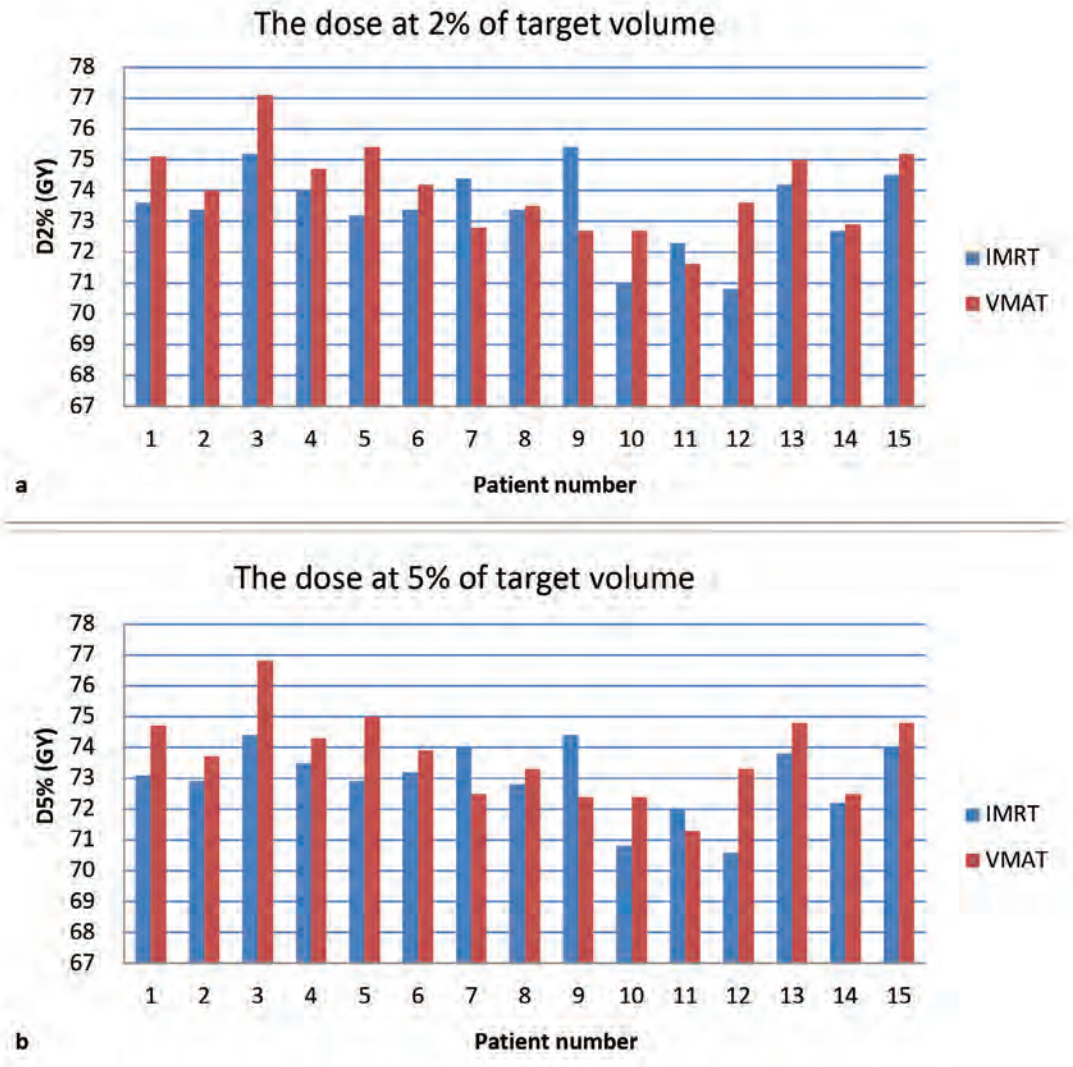

Figure 2. This figure shows (a) the dose at 2% (GY) of target volume and (b) the dose at 5% (GY) of target volume in IMRT and VMAT techniques in sum plans.
IMRT: Intensity modulated radiation therapy; VMAT: Volumetric modulated arc therapy

Table 2. CI and HI, in addition to D_{min} (Gy), D_{max} (Gy), D_{mean} (Gy),$D_{2\%}$ (GY) and $D_{5\%}$ (GY) for PTV in IMRT and VMAT plans

Variable	IMRT	VMAT
Primary plans (mean ± standard deviation)		
CI	0.79 ± 0.05	0.78 ± 0.06
HI	0.16 ± 0.02	0.18 ± 0.03
D_{min} to PTV_p (Gy)	34.1 ± 3.4	34.4 ± 3.1
D_{max} to PTV_p (Gy)	55.7 ± 1.6	55.5 ± 1.3
D_{mean} to PTV_p (Gy)	50.4 ± 0.57	50.9 ± 0.8
Boost plans (mean ± standard deviation)		
CI	0.79 ± 0.02	0.81 ± 0.02
HI	0.11 ± 0.03	0.13 ± 0.04
D_{min} to PTV_p (Gy)	15.5 ± 1.4	15.4 ± 1.4
D_{max} to PTV_p (Gy)	21.1 ± 0.5	21.5 ± 0.5
D_{mean} to PTV_p (Gy)	19.8 ± 0.2	19.9 ± 0.3
Sum (primary + boost) plans (mean ± standard deviation)		
D_{mean} to PTV_p (Gy)	57.9 ± 1.8	58.4 ± 1.9
D_{mean} to PTV_p (Gy)	70.9 ± 0.9	71.8 ± 1.2
$D_{2\%}$ (GY)	73.4 ± 2.6	74.0 ± 2.4
$D_{5\%}$ (GY)	72.9 ± 2.4	73.7 ± 2.4

IMRT: Intensity modulated radiation therapy; VMAT: Volumetric modulated arc therapy; CI: Conformity index; HI: Homogeneity index; D_{min}: Minimum dose; D_{max}: Maximum dose; D_{mean}: Mean Dose; $D_{2\%}$: the dose at 2% (GY) of target volume;$D_{5\%}$: the dose at 5% (GY) of target volume

and right parotids. According to ICRU-83, the normal tissue volume was defined as the entire patient volume minus the clinical target volume.[20]

Planning techniques (IMRT/VMAT)

To evaluate dosimetric characteristics, plans were created and compared for two different treatment techniques. The details of the beam arrangements and plan objectives are as follows: For phase one of the IMRT technique, seven fields were placed at gantry angles of 0°, 51°, 102°, 154°, 205°, 257°, and 308°. For phase two, five fields were arranged at gantry angles of 0°, 72°, 144°, 216°, and 288°. Each of the VMAT's first and second stages consisted of two opposing full arc rotations.

CT simulations and TPS

All patients underwent CT simulations in a supine position. CT images were acquired with a 3 mm slice thickness, and the image data was transferred to the Eclipse Planning System version 10.0 (Varian Medical Systems, Palo Alto, CA) for planning. The anisotropic analytical algorithm (AAA) dose calculation algorithm was employed with a computation grid size of 2.5 mm. The inverse plan dose volume optimizer (DVO version 10.0.28) was utilized to optimize IMRT plans. All plans were generated at 6MV X-rays using the Eclipse TPS at a dose rate of 300 MU/min. Both IMRT and VMAT plans were generated and normalized so that 95% of the PTV was covered by exactly 95% of the prescribed dose, with hotspots ≤ 107%, as recommended by ICRU-50, and without violating OAR sparing guidelines.[21]

Dosimetric comparison of plans at PTV and OARs

We created a plan sum of two stages to compare IMRT and VMAT procedures. The dosimetric data, utilized for this comparison, were derived from the dose volume histogram (DVH) curve. The parameters included the mean dose (D_{mean}), maximum dose (D_{max}), 95% dose ($D_{95\%}$), 2% dose ($D_{2\%}$), and 5% dose ($D_{5\%}$). The DVH for OARs was also employed to determine the minimum dose (D_{min}), D_{mean}, D_{max}, 30%, 60% in addition to 90% doses ($D_{30\%}$, $D_{60\%}$ and D90%, respectively) to non-target tissues.

Plan quality

The primary goal of radiotherapy is to deliver a sufficiently homogeneous and conformal dose to the tumor volume, while excluding critical normal tissue from the high-dose region.[22] The DVH serves as the standard evaluation tool, outlining dose distribution and defining parameters such as D_{max}, D_{min}, and D_{mean} for each volume of interest.[23] This tool can also be employed to determine the best plans that fulfill the objectives of radiotherapy.

As outlined in the International Commission on Radiation Units and Measurements (ICRU) Report 83,[20] the Radiation Therapy Oncology Group (RTOG) proposed measurements such as the HI and the conformity index (CI).

RTOG defined the HI as:HIRTOG = Imax/RI, Where, Imax is the maximum isodose in the target, and RI is the reference isodose. If HI ≤ 2, the treatment is deemed to comply with the protocol. If 2 < HI ≤ 2.5, it constitutes a minor breach, but if HI > 2.5, this is viewed as a major violation of the protocol, although in limited cases, it may still be considered acceptable.[24, 25]

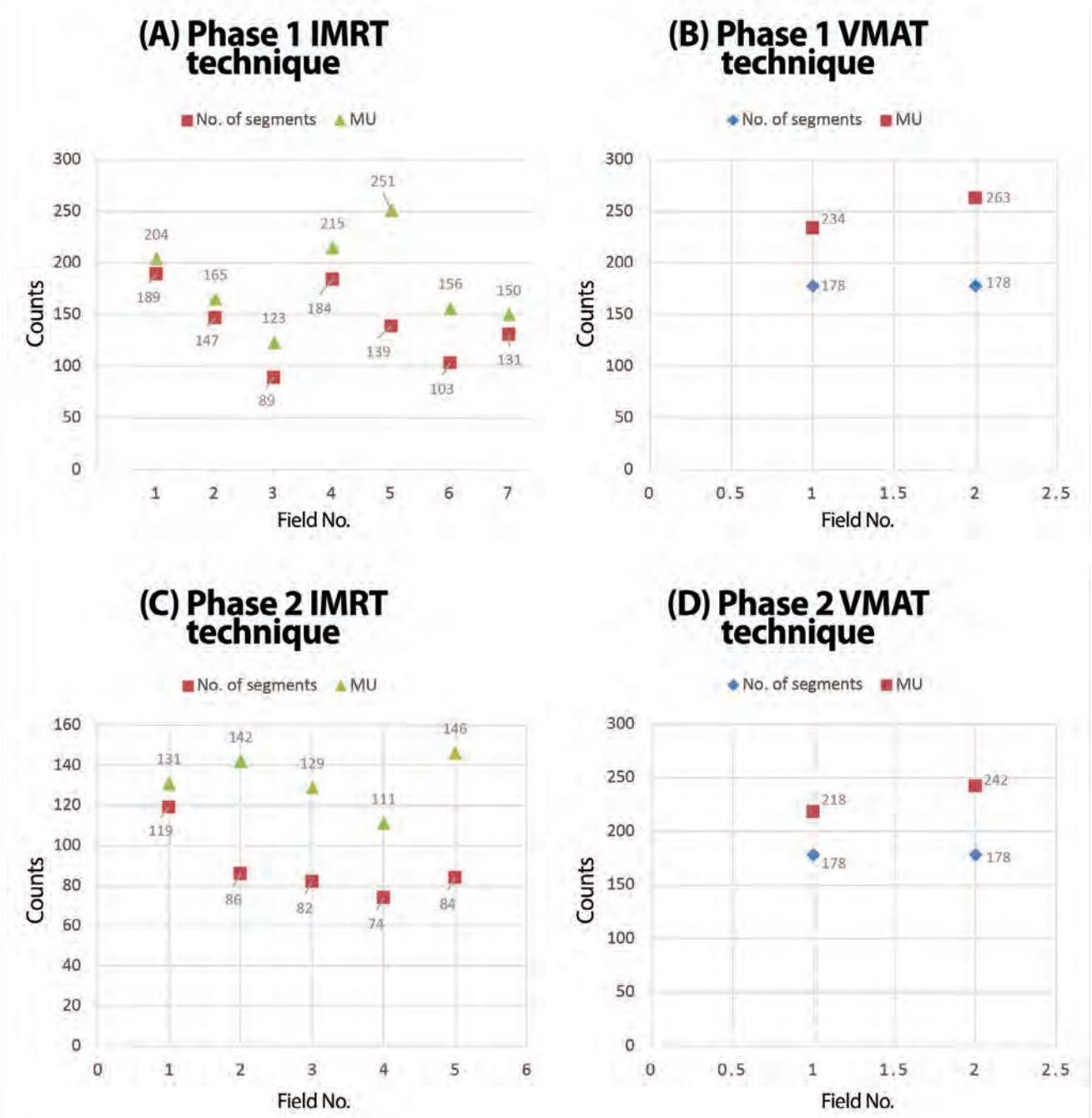

Figure 3. The number of segments (or control points) and MUs of each field (from field 1 at zero gantry angle ascending to field 7 at a 308° gantry angle) for IMRT and two full rotation VMAT (360° for each field). This is shown for one patient as an example of IMRT and VMAT dose delivery in (a) phase 1 IMRT technique, (b) phase 1 VMAT technique, (c) phase 2 IMRT technique, and (d) phase 2 VMAT technique.

IMRT: Intensity modulated radiation therapy; VMAT: Volumetric modulated arc therapy; MU: Monitor Unit

Table 3. Dose-volume parameters for various non-target OARs using IMRT and VMAT techniques in the primary, boost, and sum plans

Non-target tissue	Variable	IMRT	VMAT
Primary plans (mean ± standard deviation)			
Mandibular	D_{min} (Gy)	1.2 ± 0.4	1.3 ± 0.6
	D_{max} (Gy)	51.8 ± 4.8	50.7 ± 5.9
	D_{mean} (Gy)	23.4 ± 7.1	21.7 ± 8.3
RT parotid	D_{min} (Gy)	2.1 ± 1.1	2.4 ± 1.8
	D_{max} (Gy)	52.2 ± 2.6	52.0 ± 2.9
	D_{mean} (Gy)	17.4 ± 8.8	20.2 ± 10.2
LT parotid	D_{min} (Gy)	2.3 ± 2.0	2.4 ± 2.2
	D_{max} (Gy)	50.2 ± 6.7	48.7 ± 10.9
	D_{mean} (Gy)	15.7 ± 9.3	17.8 ± 10.5
Spinal cord	D_{min} (Gy)	1.4 ± 1.2	1.6 ± 1.4
	D_{max} (Gy)	31.3 ± 4.6	31.6 ± 5.3
	D_{mean} (Gy)	17.0 ± 3.0	19.7 ± 5.0
Brainstem	D_{min} (Gy)	0.6 ± 0.4	0.6 ± 0.6
	D_{max} (Gy)	5.8 ± 4.1	7.0 ± 13.1
	D_{mean} (Gy)	1.2 ± 0.5	1.8 ± 1.0
Boost plans (mean ± standard deviation)			
Mandibular	D_{min} (Gy)	0.04 ± 0.02	0.04 ± 0.02
	D_{max} (Gy)	7.6 ± 7.6	6.7 ± 7.3
	D_{mean} (Gy)	0.9 ± 1.5	0.9 ± 1.5
RT parotid	D_{min} (Gy)	0.1 ± 0.03	0.1 ± 0.1
	D_{max} (Gy)	2.2 ± 4.7	2.1 ± 5.1
	D_{mean} (Gy)	0.7 ± 1.6	0.3 ± 0.4
LT parotid	D_{min} (Gy)	0.1 ± 0.03	0.1 ± 0.03
	D_{max} (Gy)	1.2 ± 1.8	1.1 ± 1.8
	D_{mean} (Gy)	0.2 ± 0.2	0.2 ± 0.3
Spinal cord	D_{min} (Gy)	0.04 ± 0.04	0.04 ± 0.04
	D_{max} (Gy)	5.7 ± 1.6	3.7 ± 1.0
	D_{mean} (Gy)	0.9 ± 0.3	0.9 ± 0.3
Brainstem	D_{min} (Gy)	0.02 ± 0.01	0.02 ± 0.01
	D_{max} (Gy)	1.1 ± 0.1	1.1 ± 0.1
	D_{mean} (Gy)	0.1 ± 0.02	0.1 ± 0.02
Sum plans (mean ± standard deviation)			
Mandibular	D_{min} (Gy)	1.2 ± 0.5	1.4 ± 0.6
	D_{max} (Gy)	55.5 ± 9.4	54.6 ± 9.9
	D_{mean} (Gy)	23.8 ± 8.3	22.1 ± 9.5
	$D_{30\%}$ (Gy)	29.7 ± 12.4	27.6 ± 11.7
	$D_{60\%}$ (Gy)	20.3 ± 10.1	19.8 ± 10.4
	$D_{90\%}$ (Gy)	4.2 ± 3.6	5.0 ± 4.5
RT parotid	D_{min} (Gy)	2.2 ± 1.1	2.6 ± 1.8
	D_{max} (Gy)	54.2 ± 5.6	54.0 ± 5.8
	D_{mean} (Gy)	18.5 ± 8.7	21.5 ± 10.1
	$D_{30\%}$ (Gy)	22.8 ± 14.6	29.6 ± 15.1
	$D_{60\%}$ (Gy)	11.1 ± 8.5	15.0 ± 12.3
	$D_{90\%}$ (Gy)	3.8 ± 2.3	4.8 ± 3.4
LT parotid	D_{min} (Gy)	2.4 ± 2.1	2.6 ± 2.3
	D_{max} (Gy)	51.6 ± 7.5	50.1 ± 11.5
	D_{mean} (Gy)	16.6 ± 9.3	18.8 ± 10.6
	$D_{30\%}$ (Gy)	21.7 ± 14.9	25.3 ± 15.8
	$D_{60\%}$ (Gy)	9.6 ± 8.9	12.1 ± 11.5
	$D_{90\%}$ (Gy)	3.8 ± 3.8	4.5 ± 5.1
Spinal cord	D_{min} (Gy)	1.4 ± 1.2	1.6 ± 1.5
	D_{max} (Gy)	35.6 ± 4.8	34.8 ± 5.6
	D_{mean} (Gy)	18.2 ± 3.2	20.7 ± 5.2
	$D_{30\%}$ (Gy)	23.0 ± 5.6	27.5 ± 5.5
	$D_{60\%}$ (Gy)	18.3 ± 6.7	21.0 ± 8.4
	$D_{90\%}$ (Gy)	5.0 ± 4.9	8.8 ± 11.9
Brainstem	D_{min} (Gy)	0.6 ± 0.4	0.7 ± 0.6
	D_{max} (Gy)	6.5 ± 7.5	7.5 ± 7.8
	D_{mean} (Gy)	1.4 ± 0.6	1.8 ± 1.0
	$D_{30\%}$ (Gy)	1.4 ± 0.6	1.9 ± 1.0
	$D_{60\%}$ (Gy)	1.1 ± 0.6	1.2 ± 0.8
	$D_{90\%}$ (Gy)	0.7 ± 0.4	0.8 ± 0.6

IMRT: Intensity modulated radiation therapy; VMAT: Volumetric modulated arc therapy; D_{min}: Minimum dose; D_{max}: Maximum dose; D_{mean}: Mean dose; $D_{30\%}$: Dose at 30% of volume; $D_{60\%}$: Dose at 60% of volume; $D_{90\%}$: Dose at 90% of volume; Rt: Right; Lt: Left; OAR: Organs at risk

Various formulae describing HI

Among the formulas describing HI, one is; HI = $D_{5\%}/D_{95\%}$; where $D_{5\%}$ is the minimum dose in 5% of the PTV, indicating the "maximum dose", and $D_{95\%}$ indicating the "minimum dose". Lower values of HI (closer to one) indicate a more homogeneous dose distribution.[26]

Another widely used formula is HI=$D_{5\%}$–$D_{95\%}/D_p$; where D_p where D_p represents the prescribed dose. The formula selected for use in this study is:

$$HI=(D_{2\%}-D_{98\%})/D_p \quad (1)$$

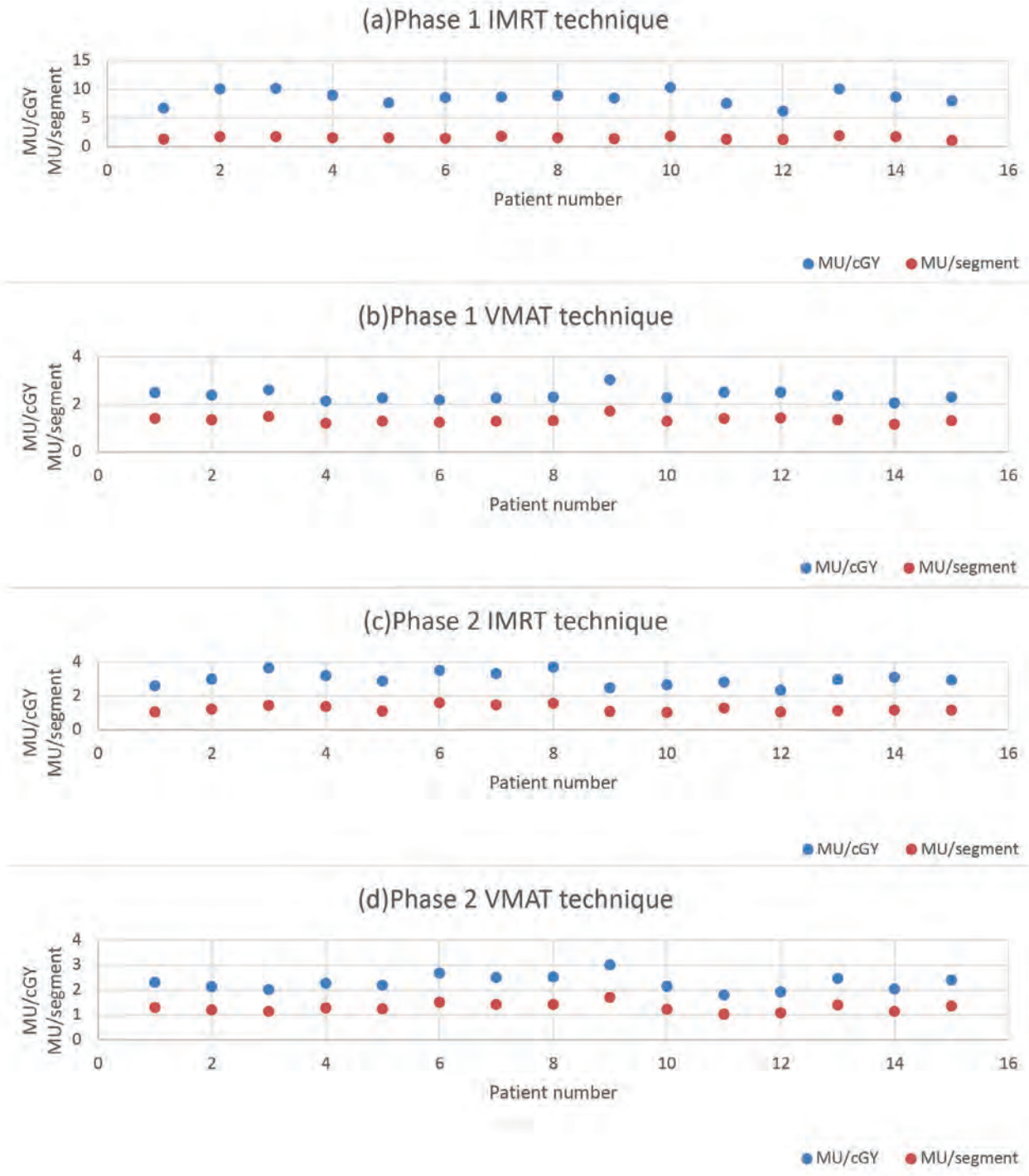

Figure 4. This figure depicts the number of MUs per cGy as a modulation factor and MUs per segment (or MUs per control points) for IMRT and VMAT dose delivery for each patient in (a) phase 1 IMRT technique, (b) phase 1 VMAT technique, (c) phase 2 IMRT technique, and (d) phase 2 VMAT technique.

IMRT: Intensity modulated radiation therapy; VMAT: Volumetric modulated arc therapy; MU: Monitor units

Table 4. Treatment efficiency comparison between IMRT and VMAT techniques in the primary and boost plans

Variable	IMRT	VMAT
Primary plan (mean ± standard deviation)		
MU/fx	1724.5 ± 249.5	475.3 ± 47.0*
Total number of segments or control points	1110.9 ± 140.4	354.0 ± 0*
MU/(segment or control points)	1.6 ± 0.2	1.3 ± 0.1*
Modulation factor (MU/cGy)	8.6 ± 1.2	2.4 ± 0.2*
Boost plan (mean ± standard deviation)		
MU/fx	601.4 ± 81.7	458.0 ± 62.6*
Total number of segments or control points	482.1 ± 31.3	354.0 ± 0*
MU/(segment or control points)	1.3 ± 0.2	1.3 ± 0.2
Modulation factor (MU/cGy)	3.0 ± 0.4	2.3 ± 0.3*

*: significant ($P < 0.05$) difference compared with IMRT values; IMRT: Intensity modulated radiation therapy; VMAT: Volumetric modulated arc therapy; MU/Fx: Montior unit /fraction

In this equation, HI is more sensitive to point dose-related parameters, such as grid size and grid placement, compared with other formulas. The ideal HI value here is zero, which increases as homogeneity decreases.[27, 28]

In our department, we made a slight modification to the equation used to calculate HI (D_1 instead of D_2) so that:

$$HI=(D_{1\%}-D_{98\%})/D_p \quad (2)$$

Where D_1 is the minimum dose in 1% of the target volume. The HI in this equation is more sensitive to point dose-related parameters, such as grid size and grid placement. As described by Wu et al.[27] the ideal HI value in this case is zero, and it increases as homogeneity decreases.

RTOG defined CI as the ratio between the volume covered by the reference isodose ($D_{95\%}$ according to ICRU-83) to PTV and given by: CIRTOG = VRI/TV, where the reference isodose volume is VRI, and the target volume is TV. As the TV and PTV are not necessarily concentric and symmetrical, the latter definition was considered unsatisfactory. This work applied the Paddick conformity index (PCI), which provides a better definition of CI.[29] A perfect plan should have a score of 1, while less perfect plans should have a score of < 1.

$$CI_{Paddick}=(TV_{PIV2})/(TV \,.\, V_{RI}) \quad (3)$$

Where TV_{PIV} is the target volume covered by the prescription isodose.

Treatment efficiency

The modulation factor, defined as the ratio of doses in the dynamic and corresponding open fields, is estimated in our clinic's process using dose calculations made within our TPS. The MUper centigray MU/cGy, also known as the modulation factor, along with MU per fraction (MU/fx) and MU per segment, have been investigated and analyzed for both techniques.

Statistical analyses

The collected data were analyzed using SPSS v22.0 (SPSS Inc., Chicago, IL). A paired t-test was employed to determine if there was a statistically significant difference in any of the parameters examined, with statistical significance defined as $P < 0.05$.

The effects of dose on sensitive organs

To mitigate side-effects, numerous dose tolerance thresholds have been recommended, all of which are based on scientifically verified dose-risk relationships. Known as dose-volume criteria, these thresholds are measured as points on a DVH. Because the treatment tumor volume varies between individuals, standardization is challenging. In contrast, OARs tend to be more consistent, making standardization less problematic. Despite the existence of criteria (RTOG, ASTRO, and ESTRO ACROP), some OARs can be classified based on their distance from the tumor or anatomical extensions.

Mandible

Ben-David et al.[30] observed a significant reduction in high-dose exposure over the mandible with the use of advanced radiotherapy techniques

such as IMRT and VMAT. In their study, half of the patients received a dose of 70 Gy to 1% of the mandibular volume without any grade 2 osteoradionecrosis (ORN). Other research; however, has reported an ORN rate of approximately 5% when using the IMRT technique to treat oral cavity malignancies.[31] Consequently, we recommend limiting the mandible to a D_{max} (point dose of 70 Gy during IMRT.

Parotid

Late salivary dysfunction is the most common side-effect of radiation therapy for head and neck cancers, with recovery taking up to two years.[32] Blanco et al. found that preserving at least one parotid gland (D_{mean} 20 Gy) reduced the risk of grade 4 xerostomia. Similarly, decreasing both parotids to a mean dose of 25 Gy significantly curtailed the occurrence of grade 4 xerostomia. As salivary function improves with lower parotid mean doses, these should be reduced as much as clinically possible.[33]

Spinal cord

Radiation-induced spinal cord injuries are rare but can be severe, leading to paralysis, sensory impairments, pain, and bowel or bladder incontinence.[34] Research indicates that at 50 Gy, the risk of myelopathy is 0.2%, and at 59.3 Gy, the risk escalates to 5%.[34]

Brainstem

According to the QUANTEC review summary, the entire brainstem can receive up to 54 Gy with a 5% likelihood of necrosis or neurologic injury. Small volumes (1 to 10 cc) may receive up to 59 Gy, while a point (<1 cc) can tolerate up to 64 Gy.

In our study, the dose limitation for normal tissues aligns with the RTOG recommendations:

mandible $D_{max} \leq 70$ Gy; brainstem+0.5cm $D_{max} \leq 54$ Gy; parotid $D_{mean} \leq 25$ Gy and spinal cord $D_{max} \leq 45$ Gy (spnal cord + 0.5cm $D_{max} \leq$ 50 Gy).[35]

Results

PTV

This study incorporated 15 patients diagnosed with LALC. Both IMRT and VMAT plans were deemed clinically acceptable across all cases. PTV_p and PTV_b exhibited variability among the patients included in this study. The mean volumes and the volume ranges of PTV_p and PTV_b were 660.5 ± 198.1 (range 212.4 - 958.9) cm^3 and 97.94 ± 41.5 (range 20.1-179.5) cm^3, respectively. The PTV values used for all cases in this research work, concerning laryngeal cancer patients, are outlined in table 1.

Variation of dose within the target volume

DVHs were utilized to evaluate all treatment plans. Tables 2 and 3 provide a summary of the numerical results derived from an average DVH analysis on PTV and OARs, presented as mean values ± standard deviation (SD) to estimate the relative variability across cases. The coverage of PTV was evaluated using the HI, the (CI, D_{min}, D_{max} and D_{mean} (Table 2). Both IMRT and VMAT plans for the two stages demonstrated acceptable dose homogeneity and conformity, and the differences were statistically insignificant ($P > 0.05$). For primary plans, boost plans, and summation plans (primary + boost) of the two stages, the values of D_{min}, D_{max} and D_{mean} were remarkably similar to each other and statistically insignificant ($P > 0.05$). Figure 1 displays the dose distribution in the plan sum for one patient under study as an example in axial, sagittal, and coronal views.

Dosimetric comparison of PTV coverage at $D_{2\%}$ and $D_{5\%}$

In the summation plans, the dose at 2% (GY) and the dose at 5% (GY) of the target volume in both IMRT and VMAT were evaluated for 15 patients and are depicted in table 2 and figure 2. It can be noted that there is no significant difference between all values of both techniques.

Mandible

According to the quantic, the maximum dose to the mandible, excluding PTV, should not exceed 70 Gy during planning. In summation plans, all plans adhered to the maximum dose tolerance, with the lowest doses attained with IMRT and VMAT being 55.5 ± 9.4 and 54.6 ± 9.9, respectively.

Parotid

Both techniques achieved satisfactory equivalent uniform doses and minimal doses,

Table 5. Treatment delivery time using IMRT and VMAT techniques in primary and boost plans

Patient number	IMRT Primary (min)	VMAT Primary (min)	IMRT Boost (min)	VMAT Boost (min)
1	7.9	3.6	6.2	3.5
2	9.3	3.7	6.5	3.1
3	9.5	3.8	7.1	3.1
4	8.8	3.5	6.9	3.4
5	8.3	3.5	6.3	3.2
6	8.5	3.5	7.1	3.8
7	8.5	3.5	6.9	3.4
8	8.7	3.6	7.3	3.5
9	8.2	3.8	6.0	3.9
10	9.5	3.5	6.2	3.2
11	8.2	3.7	6.2	2.8
12	7.9	3.7	5.7	3.0
13	9.4	3.6	6.5	3.4
14	8.6	3.2	6.7	3.1
15	8.3	3.6	6.4	3.8
Mean ± SD	8.6 ± 0.9	3.6 ± 0.4	6.5 ± 0.8	3.3 ± 0.5

$P < 0.05$; IMRT: Intensity modulated radiation therapy; VMAT: Volumetric modulated arc therapy

with no statistically significant difference. Therefore, the adoption of either technique remains a viable option. The mean dose to the right parotid gland using IMRT and VMAT techniques was 18.5 ± 8.7 Gy and 21.5 ± 10.1 Gy, respectively. Conversely, the mean dose for the left parotid gland was 16.6 ± 9.3 Gy and 18.8 ± 10.6 Gy, respectively.

Spinal cord

The ideal maximum dose to the spinal cord should be significantly reduced, preferably to well below 45 Gy, and all plans were successful in achieving this goal. The maximum dose to the spinal cord is slightly lower with VMAT plans (34.8 ± 5.6 Gy) than with IMRT plans (35.6 ± 4.8 Gy), though the difference is not statistically significant ($P > 0.05$).

Brain stem

In terms of the maximum dose, no significant difference was observed between the plans. The planning objective for the maximum dose to the brainstem should ideally be set significantly lower than 55 Gy. The maximum dose to the brainstem in the sum plan was 6.5 ± 7.5 Gy and 7.5 ± 7.8 Gy for VMAT.

Treatment efficiency

The total MUs exhibited a significant difference between the two planning techniques. IMRT has a higher average total number of MUs than VMAT. As illustrated in table 4, the average total number of MUs for IMRT PTV_p and VMAT PTV_p was 1724.5 ± 249.5 and 475.3 ± 47.0 ($P < 0.05$), respectively. The average total number of MUs for IMRT PTV_b and VMAT PTV_b was 601.4 ± 81.7 and 458.0±62.6 ($P < 0.05$), respectively (Figure 3).

The IMRT treatment plan included seven fields (beam orientations) for the primary stage, with each IMRT field containing a minimum of 89 segments and a maximum of 249 segments (totaling a minimum of 954 and a maximum of 1518 segments). The boost plans included five fields with 74–131 control points for each field (totaling 439–532 control points). All VMAT plans contained two full rotation arcs; each field consisted of 178 control points (totaling 356 control points).

There was a significant difference between the two planning techniques in terms of the overall number of segments (or control points). In the primary phase, the total number of segments for IMRT (from field 1 at zero gantry angle ascending to field 7 at 308° gantry angle) and VMAT techniques (two full arcs) was 1110.9 ± 140.4 and 354.0 ± 0 ($P < 0.05$), respectively. In the boost phase, the total number of segments (or control points) of IMRT (from field 1 at zero gantry angle ascending to field 5 at 288° gantry angle) and VMAT (two full arcs) was 482.1 ± 31.3 and 354.0 ± 0 ($P < 0.05$), respectively (Table

4 and Figure 3).

The degree of modulation, represented by the average value of MU/cGy, is shown in table 4. The term "MU/segment" means that each segment possesses a different number of MUs and delivers a different dose to the target voxel[36] (Figure 4). This implies that as the total number of segments increases, the dose per segment decreases. The modulation factor (MU/cGy) showed a significant difference ($P < 0.05$) between IMRT (8.6 ± 1.24) and VMAT (2.4 ± 0.2) for the primary phase. The modulation factor (MU/cGy) of IMRT and VMAT for the boost phase was 3.0 ± 0.4 and 2.3 ± 0.3, respectively, demonstrating a statistically significant difference ($P < 0.05$).

Treatment delivery time

The mean treatment delivery time in the primary stage of IMRT was found to be (8.6 ± 0.9 min), which is significantly longer than the (3.6 ± 0.4 min) observed in VMAT. This difference was statistically significant ($P < 0.05$). Similarly, in the boost plan, the mean treatment delivery time for IMRT (6.5 ± 0.8 min) was also significantly longer than that for VMAT (3.3 ± 0.5 min) with the difference being statistically significant ($P < 0.05$). Table 5 provides a summary of the estimated treatment delivery times for larynx plans for all patients.

Discussion

In this study, both IMRT and VMAT techniques achieved favorable equivalent uniform doses and low doses for OARs. The dosimetric comparison between IMRT and VMAT for PTV in primary plans, boost plans, and summation plans (primary + boost) from two stages revealed values of D_{min}, D_{max} and D_{mean} that were so closely aligned they could be overlooked ($P > 0.05$).

Furthermore, IMRT and VMAT plans for the two stages demonstrated acceptable dose homogeneity and conformity, with differences that were statistically insignificant ($P > 0.05$). IMRT had a significantly higher average total number of MUs than VMAT, with the average total number of MUs for IMRT consistently exceeding that for VMAT (1724.5 ± 249.5 and 475.3 ± 47.0, respectively, for PTV_p, and 601.4 ± 81.7 and 458.0 ± 62.6, respectively, for PTV_b).

The total number of segments (or control points) showed significant differences between the IMRT and VMAT techniques; for the primary phase, the total number of segments (or control points) was 1110.9 ± 140.4 for IMRT and 356.0 ± 0 for VMAT. The modulation factor (MU/cGy) of IMRT was significantly greater than that of VMAT for both the primary phase (8.6 ± 1.2 and 2.4 ± 0.2, respectively) and the boost phase (3.0 ± 0.4 and 2.3 ± 0.3, respectively).

The mean treatment delivery time in the primary stage of IMRT (8.6 ± 0.9 min) was significantly longer than that of VMAT (3.6 ± 0.4 min). This finding was also consistent in the boost plans, where IMRT (6.5 ± 0.8 min) was significantly longer than VMAT (3.3 ± 0.5 min).

Each radiation beam is typically modulated by continuously moving multi-leaf collimators (MLCs) using the sliding window (SW) or dynamic IMRT technique, which increases the amount of MU.[37] Concerns have arisen regarding the extremely high risk of secondary radiation-induced malignancies due to the higher MU and the subsequent increase in lower radiation dose. This issue is particularly relevant for pediatric patients or patients with long life expectancies.[7] Consequently, we conducted this study to examine the dosimetric performance of VMAT and IMRT in the treatment of LALC patients.

IMRT plans use more MUs than VMAT plans, leading to an increase in the quantity of low-dose radiation delivered to the rest of the body. A comparative study of IMRT and VMAT planning techniques for head and neck cancer, conducted by Pursley J et al.[38] presented results for a total of 14 patients. The study indicated that all VMAT plans required fewer MUs than IMRT plans to deliver treatment, with an average reduction of 35% for ipsilateral plans and 67% for bilateral plans.

According to literature estimates, the number of MUs used in the IMRT technique was two to three times higher than that used in the VMAT technique.[14, 15] These findings align with our results, which showed that IMRT plans required a significantly higher number of MUs compared

with VMAT plans. Therefore, the noticeable decrease in the number of MUs in VMAT plans significantly shortened the treatment delivery time.

Our study suggests that the performance of VMAT aligns closely with that of IMRT in sparing OARs, producing plans akin to IMRT. The majority of planning studies revealed that VMAT plans, compared with IMRT, were either insignificantly different or marginally superior concerning OAR sparing.[14, 17] Several studies in the past have drawn comparisons between single-arc and double-arc VMAT plans with IMRT plans. The findings underscored that single-arc or double-arc VMAT significantly spared OARs without undermining target coverage when juxtaposed with the IMRT technique. The merits of employing double-arc included an upswing in the modulation factor during optimization, and more MLC control points than single-arc, culminating in superior dose distribution. The most conspicuous, and perhaps relevant outcome, was the augmentation in conformity and HIs with the application of double-arc VMAT. This reasoning guided us to select double-arc VMAT for our current study.

Our findings revealed no considerable deviation in PTV coverage, conformity, and homogeneity (CI and HI) indices in either technique. Both IMRT and VMAT yielded highly conformal dose distribution and relatively comparable proportions. Collectively, the insights from several retrospective planning studies harmonize with our findings. Studies by Verbakel et al.,[14] Vanetti et al.,[17] Johnston et al.,[16] Bertelsen et al.,[3] and Rao et al.[39] reported statistically similar PTV coverage, which corroborates our findings. Vanetti et al.[17] observed no significant difference in conformity, which is in line with our results. However, Johnston et al.[16] proposed that IMRT exhibits slightly superior conformity than VMAT, contrasting with the findings of Bertelsen et al.,[3] which suggested that VMAT provides a better CI than IMRT. For the HI, our results concur with Bertelsen et al.,[3] indicating no significant difference. This contrast with the findings of Verbakel et al.[14] and Vanetti et al.,[17] who suggested that VMAT excels over IMRT in terms of HI. This contradicts Johnston's et al.'s[16] findings, which indicate that IMRT provides marginally superior homogeneity than VMAT.

The current work may function as a versatile platform for physicists for additional prospective studies that advocate the preeminence of the VMAT technique over the IMRT technique. This research contributes to the growing body of studies that harbor the same consideration. However, we faced some limitations. Primarily, the sample size used for comparison was confined to 15, necessitating more prospective studies for a more dependable conclusion. Secondly, regarding patient follow-up, this was a dosimetric study lacking a clinical correlation to evaluate treatment-related locoregional disease control and overall survival statistics.

Conclusion

The purpose of this study was to compare the dosimetric performance of VMAT and IMRT in the treatment of LALC. The primary distinction between IMRT and VMAT in LALC treatment lies in the significantly fewer MUs required by VMAT—approximately one-third of those needed for IMRT. This reduction in required MUs subsequently decreases treatment time. Consequently, this positively impacts patient comfort, healthcare team efficiency, and treatment accuracy. The latter is enhanced due to minimized fraction movements, thus enabling the treatment of more patients within an optimal timeframe. However, when considering dose conformity, homogeneity, organs at risk, mean dose (D_{mean}), maximum dose (D_{max}), dose 2% ($D_{2\%}$) and dose 5% ($D_{5\%}$). IMRT's performance parallels that of VMAT.

Conflict of Interest

None declared.

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