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ORIGINAL ARTICLE

# A Comprehensive Analysis of Plan Quality and Normal Tissue Complications in Head and Neck Cancer Treatment: A Dosimetric Comparison of VMAT and IMRT Techniques

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**OBJECTIVE**

This study aims to compare Intensity-Modulated Radiotherapy (IMRT) and Volumetric Modulated Arc Therapy (VMAT) through dosimetric evaluation and assessment of normal tissue complication probability (NTCP).

**METHODS**

A retrospective study was conducted involving 50 HNC patients with tumors located in the oropharynx, tongue, base of tongue, and oral cavity. Treatment plans were developed using the Eclipse Treatment Planning System for a Varian TrueBeam linear accelerator. Prescribed doses of 54Gy, 60Gy, and 70Gy delivered over 35 fractions using Simultaneous Integrated Boost techniques. Both plans were analyzed for target coverage, conformity, homogeneity, External Irradiation Index, and sparing of normal tissues. NTCP was calculated for critical structures, including the parotid glands, spinal cord, and brainstem.

**RESULTS**

IMRT demonstrated superior target coverage for PTV_70Gy, with higher D95% (96.6±1.31 vs. 96.1±0.64, p=0.048) and D98% (95.3±1.37 vs. 94.3±1.00, p=0.001). In contrast, VMAT exhibited enhanced treatment efficiency, significantly lowering the number of monitor units (465±43.40 vs. 1561±187.60, p=0.001) and the External Irradiation Index. VMAT also provided better sparing of the left parotid gland (Dmean: 34.8±15.5 vs. 35.5±15.6, p=0.016). The NTCP analysis indicated similar risks of xerostomia between the two techniques.

**CONCLUSION**

VMAT presents significant dosimetric and clinical benefits compared to IMRT in the treatment of head and neck cancer. It delivers improved conformity, shorter treatment durations and better sparing of organs at risk.

**Keywords:** Head and neck cancer; intensity-modulated radiotherapy (IMRT); normal tissue complication probability (NTCP); volumetric modulated arc therapy (VMAT).



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## INTRODUCTION

Based on the Global Cancer Statistics for 2020, head and neck cancer (HNC) was identified as the third most common cancer globally, with a total of 1,464,550 new cases and 487,993 fatalities. This represented 7.6% of all cancer cases and 4.8% of deaths attributed to cancer.[1] Head and neck cancers (HNC) are a significant health concern in India, impacting both men and women, although they are more frequently diagnosed in males. These cancers represent roughly 17.7% of all newly diagnosed cancer cases in the country, with an estimated 230,000 new cases occurring each year.[2] HNC is a group of epithelial malignancies involving the in various anatomical sites including the oral cavity, pharynx (nasopharynx, oropharynx, and hypopharynx), larynx, paranasal sinuses, and salivary glands and lymphadenopathy associated with these diseases.[3]The etiology of HNC is multifactorial, with use of tobacco, the consumption of alcohol, and infection with human papillomavirus (HPV). Notably, tobacco use, whether through smoking or smokeless methods, is responsible for around 75% of HNC cases.[4,5] The prognosis for head and neck cancer (HNC) is influenced by several factors, including TNM staging, HPV status, and the specific anatomical subsite involved. Patients with early-stage disease (Stage I-II) generally exhibit 5-year survival rates ranging from 70% to 90%. In contrast, those with advanced stages (III-IV) experience survival rates between 30% and 60%.[6] Furthermore, individuals with HPV-positive tumors tend to have better outcomes, demonstrating a notable survival advantage over those who are HPV-negative.[7,8]

Management of contemporary head and neck cancer (HNC) generally employs a multidisciplinary strategy that integrates surgical intervention, radiotherapy, and systemic therapies. The choice of treatment modality is influenced by various factors, including the tumor's location, its stage, the patient's performance status, and objectives related to organ preservation.[9] Radiotherapy continues to be a fundamental component in the management of head and neck cancer (HNC), primarily aimed at achieving tumor control while reducing detrimental effects on surrounding normal tissues. A significant challenge lies in delivering the highest possible therapeutic dose to the target area while simultaneously limiting dose to organs at risk (OARs).[9] This task is especially difficult given the intricate anatomical configurations and the close proximity of various OARs to the treatment sites.[10] The traditional methods of radiotherapy have progressed from two-dimensional and three-dimensional conformal radiation therapy to more advanced techniques.

Intensity-modulated radiotherapy (IMRT) has emerged as a crucial therapeutic approach for head and neck cancer (HNC), offering significant preservation of healthy tissue while achieving effective coverage of the target area.[11] Nevertheless, the application of this technique is accompanied by specific challenges, such as extended treatment durations and the requirement for numerous fixed beam angles along with elevated monitor units (MUs).[12]

Volumetric Modulated Arc Therapy (VMAT), commonly referred to as RapidArc, overcomes specific constraints associated with Intensity-Modulated Radiotherapy (IMRT) by minimizing the number of monitor units (MUs) needed and shortening the overall treatment time. The hallmark of VMAT is its dynamic delivery method, which concurrently adjusts the dose rate, positions of the multileaf collimator, and the speed of the gantry. This innovative technique facilitates thorough coverage of the target area through continuous arc rotation; all while ensuring the effective safeguarding of organs at risk (OARs).[13] Research has shown that VMAT offers significant benefits, including enhanced dose uniformity and protection of organs at risk, along with decreased treatment durations and lower monitor unit consumption when compared to IMRT.[14] Conflicting evidence is present, as certain studies indicate that IMRT may be more effective in the treatment of head and neck cancer (HNC).[15]

The selection of treatment for head and neck cancer (HNC) necessitates a careful consideration of tumor control alongside functional outcomes, particularly regarding xerostomia and oral mucositis, which have a profound effect on the patient's quality of life.[16] This study intends to perform a thorough comparison between intensity-modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) for patients with HNC. The analysis will assess the relative effectiveness of both treatment approaches through an in-depth dosimetric evaluation, concentrating on the examination of organs at risk (OARs) such as the parotid glands, mandible, and spinal cord, in addition to their normal tissue complication probability (NTCP) values.

## MATERIALS AND METHODS

This study was performed in accordance with the principles of the Declaration of Helsinki and approved by the Indira Gandhi Institute of Medical Sciences: Sheikhpura Ethics Committee (No: 301/IEC/IGIMS/2025, Date: 09/01/2025).

This retrospective analysis involved 50 patients diagnosed with head and neck cancer (HNC) from our institute database in our radiation oncology department, specifically those with primary tumors located in the oropharynx, tongue, base of tongue, or oral cavity. These patients were treated using Simultaneous Integrated Boost (SIB) techniques, employing either VMAT or IMRT. Computed tomography (CT) scans were conducted in a supine position with a slice thickness of 2.5 mm, utilizing immobilization devices such as face masks and headrests to maintain consistent patient positioning. The delineation of Gross Target Volume (GTV), Clinical Target Volume (CTV), and Planning Target Volumes (PTV_54, PTV_60, and PTV_70) was performed, with prescribed radiation doses of 54 Gy, 60 Gy, and 70 Gy delivered over 35 fractions. The organs at risk (OARs) included the spinal cord, brainstem, parotid glands, mandible, thyroid, eyes, optic nerves, optic chiasm, cochlea, and lenses. Treatment plans were created utilizing the Eclipse Treatment Planning System (version 16.1), employing a 6 MV photon beam and a constant dose rate of 600 MU/min on a Varian True Beam medical linear accelerator (Varian Medical Systems, Palo Alto, CA) that features a 120-millennium multileaf collimator. The SIB VMAT approach utilized two arcs (clockwise: 181°–179°, counterclockwise: 179°–181°), while the SIB IMRT method employed seven fixed gantry angles (51°, 102°, 151°, 202°, 251°, 302°, 351°). The final doses were calculated using analytical anisotropic algorithm (AAA) for plannings of IMRT as well as VMAT.

The evaluation of the plans was conducted using various metrics, including Coverage Index (C), Conformity Index (CI), Homogeneity Index (HI), Dose Heterogeneity Index (DHI), Gradient Index (GI), Unified Dosimetric Index (UDI), External Volume Index (EI), and Standard Deviation (SD) to analyze dose distribution, conformity, and overall plan quality.

Qualitative evaluations of high and low dose within treatment plans, whereas dose-volume histograms (DVHs) offer quantitative data regarding dose distribution. Dose coverage, an essential parameter, indicates the proportion of the PTV that receives the prescription dose (PD), with plans achieving at least 92% coverage considered acceptable.[17]

## Coverage Index (C)

The Coverage Index is a quantitative parameter defined as the ratio of the PTV volume receiving the prescribed isodose (PTVPI) to the total PTV, expressed as:

$$C=PTVPI/PTV \quad (1)$$

This index reflects the proportion of the target volume adequately covered by the prescribed dose, providing a critical metric for assessing plan quality.

## Conformity Index (CI)

The conformity index evaluates the extent to which the prescribed dose aligns with the dimensions and configuration of the planning target volume (PTV). This index is calculated as the ratio of the volume of the target that receives a minimum of 95% of the prescribed dose (PTVRI) to the overall PTV. Generally, acceptable values for the conformity index fall within the range of 1 to 2.

$$CI=PTVRI/ PTV \quad (2)$$

The acceptable range for the Conformity Index (CI) is between 1 and 2. If the CI falls between 0.9 and 1 or between 2 and 2.5, a minor portion of the dose extends beyond the Planning Target Volume (PTV). Conversely, if the CI is below 0.9 or exceeds 2.5, a substantial volume is subjected to irradiation outside the PTV.[18]

## Homogeneity Index (HI)

The Homogeneity Index (HI), as outlined in ICRU Report 83, serves as a crucial parameter for assessing the quality of treatment plans in intensity-modulated radiation therapy (IMRT). The Homogeneity Index (HI) is defined by the following formula:

$$HI = Imax / RI \quad (3)$$

Where, Imax represents the maximum isodose of the target, and RI denotes the reference isodose. The interpretation of HI value is acceptable only when it is less than or equal to 2. A minor error occurs if the HI value falls between 2 and 2.5, while a major error is identified when the value exceeds 2.5.[19]

## Dose Homogeneity Index (DHI)

DHI is a metric used to assess the uniformity of dose distribution within the target volume during radiotherapy. It is determined using the following formula:

$$DHI = (D20\% - D80\%) / D\times100 \quad (4)$$

Where, D20% represents the dose received by 20% of the target volume (the region receiving the highest dose). D80% denotes the dose received by 80% of the target volume (the region receiving the lowest dose).D signifies the prescribed dose. A lower DHI value reflects improved dose homogeneity, with D20% consistently exceeding D80%.[20]

## Dose Gradient Index (GI)

GI assesses how quickly the dose falloff outside the PTV). It is determined by the ratio of the volume that receives the prescribed isodose line (D100%) to the volume that receives half of the prescribed isodose line (D50%):[21]

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Dose Gradient Index (GI) = D50% / D100% (5)

Where, D100% represents the volume of the prescribed dose, while D50% indicates the volume of half of that prescribed dose. This metric offers valuable information regarding the efficacy of dose distribution beyond the target area.

### External Volume Index (EI)

EI quantifies the proportion of healthy tissues receiving a dose greater than the prescribed dose (PD) relative to the Planning Target Volume (PTV).[22] It is expressed as a percentage:

EI=(VD>PD/PTV)×100 (6)

Where: VD>PDV: Volume of healthy tissues receiving a dose higher than the prescribed dose. PTV: Planning Target Volume.

### The Unified Dosimetry Index (UDI)

The UDI is defined as:

UDI = C×CI×HI×GI (7)

An ideal UDI value is close to 1, which signifies a high-quality treatment plan with optimal balance across all indices. For every treatment plan, these parameters were computed, and the UDI was determined to facilitate a quantitative assessment and ranking of plan quality.[23]

### Normal Tissue Complication Probability (NTCP) Analysis

The treatment plans IMRT and VMAT techniques were evaluated through an integrated dose-volume analysis tool, along with an optional biological assessment tool created by RaySearch Laboratories. This software enabled the computation of NTCP values for various Organs at Risk (OARs) based on the Poisson model, incorporating specific parameters and endpoints as detailed in 1. For the parotid gland, the model parameters included a D50 of 4600 cGy, a steepness parameter (γ) of 1.8, an α/β ratio of 3 Gy, a seriality of 1, and xerostomia as the endpoint. The spinal cord was assessed with a D50 of 6860 cGy, a γ of 1.9, an α/β of 3 Gy, a seriality of 4, and myelitis necrosis as the endpoint. The mandible was evaluated with a D50 of 7030 cGy, a γ of 3.8, an α/β of 3 Gy, a seriality of 1, and joint dysfunction as the endpoint. For the brain stem, the parameters included a D50 of 6510 cGy, a γ of 2.4, an α/β of 3 Gy, a seriality of 1, and necrosis or infarction as the endpoint. This assessment offered a comprehensive insight into the dose-response relationships and potential complications related to OARs within the treatment plans.

### Statistical Analysis

Statistical analysis was performed using Jamovi software (version 2.3.28)[24] (The jamovi project, 2022) and were further supported by the R statistical environment (version 4.1).[25] A paired sample t-test was utilized to evaluate the differences between the VMAT and IMRT techniques. The mean values along with 95% confidence intervals were regarded as equivalent under the null hypothesis. A statistical significance level was set at $p \leq 0.05$.

## RESULTS

Table 1 demonstrates the assessment of dosimetric indices for PTV_70Gy, IMRT exhibited superior target coverage, achieving a higher D95% (96.6±1.314 compared to 96.1±0.643, p=0.048) and D98% (p=0.001), which indicates significant differences ($p<0.05$). Conversely, VMAT recorded a marginally lower D2% (104±0.667 versus 103±1.037, p=0.007), highlighting significant differences in hotspot doses. Both techniques did not show significant differences in Dmax (p=0.361), CI (p=0.327), and HI (p=0.361), as all p-values exceeded 0.05. Regarding Dmean, VMAT (70.0±0.139) achieved a slightly elevated mean dose compared to IMRT (69.7±0.675, p=0.008), indicating significant differences in the mean dose delivered to the target. The Dose Homogeneity Index (DHI) values for both modalities were closely aligned (p=0.881), reflecting no significant differences in dose uniformity.

While VMAT presented improved dose coverage with reduced dose spillage and a marginally lower Coverage Index value (1.04±0.049 versus 1.07±0.078), this difference was not statistically significant ($p>0.05$).

Additionally, VMAT (1.32±0.187) exhibited a slightly higher Gradient Index (GI) than IMRT (1.27±0.168, p=0.064), yet this difference was also not statistically significant ($p>0.05$). In terms of the External Irradiation Index (EI), VMAT (0.0334±0.0609) demonstrated a significant sparing effect on healthy tissues, presenting a lower EI compared to IMRT (0.2022±0.2632, p=0.001).

For PTV_60Gy, the use of VMAT resulted in a notably lower Dmax (67.7±1.93) in comparison to IMRT (68.7±2.64, p=0.011), demonstrating a significant reduction in hotspot occurrences. Additionally, VMAT achieved a marginally lower Dmean (60.4±0.314 vs. 60.1±0.728, p=0.005), indicating marked improvements in dose management. Furthermore, VMAT displayed a significantly lower EI (5.78±4.32 vs. 8.32±5.32,

**Table 1** Comparison of dosimetric parameters for PTV (PTV_70Gy, PTV_60Gy and PTV_54Gy and organs at risk (OARs) between VMAT and IMRT techniques

| Parameters | VMAT Mean±SD | IMRT Mean±SD | p |
|---|---|---|---|
| PTV_70Gy | | | |
| Dmax | 75.1±1.33 | 74.8±1.75 | 0.361 |
| Dmean | 70.0±0.14 | 69.7±0.68 | 0.008 |
| D98% | 94.3±1.00 | 95.3±1.37 | 0.001 |
| D95% | 96.1±0.64 | 96.6±1.31 | 0.048 |
| D2% | 104±0.67 | 103±1.037 | 0.007 |
| C | 1.04±0.05 | 1.07±0.08 | 0.075 |
| CI | 0.97±0.01 | 0.97±0.02 | 0.327 |
| HI | 1.07±0.019 | 1.07±0.02 | 0.361 |
| DHI | 4.365±0.56 | 4.38±1.01 | 0.881 |
| GI | 1.32±0.19 | 1.27±0.17 | 0.064 |
| UDI | 1.43±0.19 | 1.41±0.23 | 0.731 |
| EI | 0.0334±0.06 | 0.2022±0.26 | 0.001 |
| PTV_60Gy | | | |
| Dmax | 67.7±1.93 | 68.7±2.64 | 0.011 |
| Dmean | 60.4±0.31 | 60.1±0.73 | 0.005 |
| PTV_60Gy EI | 5.78±4.32 | 8.32±5.32 | 0.001 |
| PTV_54Gy | | | |
| Dmax | 59.9±2.89 | 60.3±4.00 | 0.271 |
| Dmean | 54.3±0.22 | 54.1±0.66 | 0.088 |
| EI | 21.2±10.70 | 25.8±10.40 | 0.001 |
| MU | 465±43.40 | 1561±187.60 | 0.001 |
| OARs | | | |
| Spinal cord (Dmax) | 38.3±4.30 | 38.9±3.53 | 0.157 |
| Brain steam (Dmax) | 38.3±4.30 | 38.7±10.70 | 0.834 |
| Mandible (Dmax) | 72.8±1.07 | 72.1±1.35 | 0.006 |
| Left parotid (Dmax) | 64.5±7.85 | 64.1±7.80 | 0.201 |
| Left parotid (Dmean) | 34.8±15.5 | 35.5±15.6 | 0.016 |
| Left parotid (D50%) | 31.0±20.1 | 32.0±19.7 | 0.047 |
| Right parotid (Dmax) | 64.1±8.93 | 63.8±8.0 | 0.429 |
| Right parotid (Dmean) | 35.4±16.1 | 35.4±15.6 | 0.865 |
| Right parotid (D50%) | 32.5±20.6 | 33.1±20.0 | 0.114 |
| Thyroid (Dmax) | 61.3±2.26 | 61.1±3.47 | 0.817 |
| Thyroid (Dmean) | 54.6±10.73 | 53.5±9.34 | 0.175 |

PTV: Planning target volumes; VMAT: Volumetric modulated arc therapy; IMRT: Intensity-modulated radiotherapy; SD: Standard deviation; Dmax: Maximum dose; Dmean: Mean dose; D98% and D95%: Doses received by 98% and 95% of the volume, respectively; C: Conformity index; CI:Conformity index; HI: Homogeneity index; DHI: Dose homogeneity index; GI: Gradient index; UDI: Uniformity dose index; EI: External index; MU: Monitor units; D50%: Dose received by 50% of the volume

p=0.001), which suggests enhanced control over radiation exposure beyond the intended target. In the case of PTV_54Gy, no significant differences were found in Dmax (p=0.271) or Dmean (p=0.088) between VMAT and IMRT. Nevertheless, VMAT demonstrated a significantly reduced EI (21.2±10.7 vs. 25.8±10.4, p=0.001), indicating improved protection of adjacent tissues. Moreover, VMAT required a significantly lower number of Monitor Units (MU) (465±43.4) when compared to IMRT (1561±187.6, p=0.001), underscoring the more efficient delivery mechanism of VMAT. The dosimetric comparison of the organs at risk (OARs) between VMAT and IMRT. In the case of the Spinal Cord, the Dmax values did not exhibit a significant difference between VMAT (38.3±4.30) and IMRT (38.9±3.53, p=0.157). Likewise, for the Brain Stem, the Dmax values were found to be similar (VMAT: 38.3±4.30, IMRT: 38.7±10.7, p=0.834). Conversely, a significant difference was noted for the Mandible, where VMAT resulted in a marginally higher

Turk J Oncol 2025;40(2):151–162
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**Table 2** Comparison of dosimetric parameters for PTV (PTV_70Gy, PTV_60Gy and organs at risk (OARs) between VMAT and IMRT techniques

| Parameters | VMAT Mean±SD | IMRT Mean±SD | p |
|---|---|---|---|
| PTV_70Gy | | | |
| Dmax | 75.1±1.04 | 74.6±1.68 | 0.146 |
| Dmean | 70.1±0.18 | 70.1±0.39 | 0.319 |
| D98% | 94.6±1.39 | 95.9±1.48 | 0.001 |
| D95% | 96.1±0.948 | 97.2±1.04 | 0.001 |
| D2% | 104±0.78 | 103±0.79 | 0.013 |
| C | 1.06±0.83 | 1.13±0.032 | 0.001 |
| CI | 0.973±0.017 | 0.983±0.032 | 0.161 |
| HI | 1.07±0.02 | 1.06±0.052 | 0.202 |
| DHI | 4.34±0.91 | 4.18±1.18 | 0.459 |
| GI | 1.47±0.78 | 1.53±1.013 | 0.364 |
| UDI | 1.49±1.34 | 1.56±1.45 | 0.263 |
| EI | 0.217±0.45 | 0.692±1.2 | 0.013 |
| PTV_60Gy | | | |
| Dmax | 68.01±1.48 | 70.05±1.92 | 0.001 |
| Dmean | 60.26±0.34 | 59.97±1.92 | 0.543 |
| EI | 9.22±9.15 | 12.62±9.87 | 0.001 |
| MU | 493±51.5 | 1671±101.7 | 0.001 |
| OARs | | | |
| Spinal cord (Dmax) | 38.2±3.28 | 39.9±3.60 | 0.003 |
| Brain steam (Dmax) | 35.3±13.6 | 33.8±12.9 | 0.134 |
| Mandible (Dmax) | 72.4±1.03 | 72.7±1.66 | 0.464 |
| Left parotid (Dmax) | 66.7±5.06 | 66.3±5.69 | 0.144 |
| Left parotid (Dmean) | 28.6±6.77 | 29.1±6.71 | 0.87 |
| Left parotid (D50%) | 21.4±9.43 | 21.7±9.10 | 0.594 |
| Right parotid (Dmax) | 69.5±4.28 | 69.6±4.45 | 0.654 |
| Right parotid (Dmean) | 36.6±12.3 | 36.5±12.2 | 0.619 |
| Right parotid (D50%) | 32.2±17.2 | 31.8±17 | 0.450 |
| Thyroid (Dmax) | 65.02±4.89 | 65.55±5.58 | 0.255 |
| Thyroid (Dmean) | 58.26±7.73 | 57.95±7.15 | 0.099 |

PTV: Planning target volumes; VMAT: Volumetric modulated arc therapy; IMRT: Intensity-modulated radiotherapy; SD: Standard deviation; Dmax: Maximum dose; Dmean: Mean dose; D98% and D95%: Doses received by 98% and 95% of the volume, respectively; C: Conformity index; CI:Conformity index; HI: Homogeneity index; DHI: Dose homogeneity index; GI: Gradient index; UDI: Uniformity dose index; EI: External index; MU: Monitor units; D50%: Dose received by 50% of the volume

Dmax (72.8±1.07 compared to 72.1±1.35, p=0.006). Regarding the Left Parotid, VMAT demonstrated a significantly lower Dmean (34.8±15.5 versus 35.5±15.6, p=0.016) and a significantly lower D50% (31.0±20.1 versus 32.0±19.7, p=0.047) in comparison to IMRT, indicating enhanced sparing of the parotid gland. For the Right Parotid, no significant differences were observed in Dmax (64.1±8.93 versus 63.8±8.0, p=0.429), Dmean (35.4±16.1 versus 35.4±15.6, p=0.865), and D50% (32.5±20.6 versus 33.1±20.0, p=0.114). With respect to the Thyroid, there were no significant differences in Dmax (VMAT: 61.3±2.26, IMRT: 61.1±3.47, p=0.817) or Dmean (VMAT: 54.6±10.73, IMRT: 53.5±9.34, p=0.175).

Table 2 demonstrated for PTV_70Gy, the results indicated that VMAT exhibited a marginally lower Dmax (75.1±1.04 vs. 74.6±1.68, p=0.146) while maintaining comparable Dmean values (70.1±0.183 vs. 70.1±0.391, p=0.319) in comparison to IMRT. Notably, VMAT surpassed IMRT in terms of D98% (94.6±1.39 vs. 95.9±1.48, p=0.001) and D95% (96.1±0.948 vs. 97.2±1.045, p=0.001), demonstrating superior dose distribution at the target's periphery. Additionally, VMAT resulted in a higher D2% (104±0.775 vs. 103±0.794, p=0.013), indicating a slight increase in hotspot formation relative to IMRT. The Conformity Index (CI) and Homogeneity Index (HI) were found to be similar for both techniques (CI: 0.973±0.0171 vs. 0.983±0.0323, p=0.161;

**Table 3** Comparison of normal tissue complication probability (NTCP) for various organs at risk (OARs) between VMAT and IMRT using the poisson-LQ model

| Structure | VMAT Mean±SD | IMRT Mean±SD | p |
|---|---|---|---|
| Left parotid (NTCP Poisson-LQ) (Xerostomia) | 37.1±25.0 | 36.6±24.7 | 0.679 |
| Right parotid (NTCP Poisson-LQ) (Xerostomia) | 42.2±28 | 42.5±27.9 | 0.427 |
| Mandible (NTCP Poisson-LQ) (Joint Dysfunction) | 17.5±11.9 | 18.6±11 | 0.127 |
| Spinal cord (NTCP Poisson-LQ) (Myelitis Necrosis) | 0.560±0.750 | 0.095±0.06 | 0.567 |
| Brain stem (NTCP Poisson-LQ) (Necrosis/Infraction) | 0.00 | 0.00 | – |

VMAT: Volumetric modulated arc therapy; IMRT: Intensity-modulated radiotherapy; SD: Standard deviation

HI: 1.07±0.014 vs. 1.06±0.052, p=0.202). No significant differences were observed in DHI (4.34±0.911 vs. 4.18±1.18, p=0.459), GI (1.47±0.781 vs. 1.53±1.013, p=0.364), and UDI (1.49±1.34 vs. 1.56±1.45, p=0.263). However, VMAT showed a significantly lower External Irradiation Index (EI) compared to IMRT (0.217±0.453 vs. 0.692±1.257, p=0.013), indicating enhanced protection of surrounding healthy tissues.

For the PTV_60Gy, the use of VMAT resulted in a significantly reduced Dmax (68.01±1.48 compared to 70.05±1.92, p=0.001) while demonstrating comparable Dmean values (60.26±0.345 versus 59.97±1.92, p=0.543). The EI for VMAT was notably lower (9.22±9.15 versus 12.62±9.87, p=0.001), indicating improved management of radiation exposure outside the target area. Additionally, VMAT required a significantly lower number of monitor units (MU) than IMRT (493±51.5 versus 1671±101.7, p=0.001), suggesting a more efficient treatment delivery method.

The dosimetric analysis comparing the organs at risk (OARs) between VMAT and IMRT is detailed in the results demonstrated in Table 2, the Spinal Cord, VMAT demonstrated a significantly lower Dmax (38.2±3.28) compared to IMRT (39.9±3.60, p=0.003), indicating superior protection of the spinal cord with VMAT. Regarding the Brain Stem, no significant difference was found in the Dmax values, with VMAT measuring 35.3±13.6 and IMRT at 33.8±12.9 (p=0.134). In the case of the Mandible, the Dmax values were similar, with VMAT at 72.4±1.03 and IMRT at 72.7±1.66 (p=0.464). For the Left Parotid, there were no significant differences observed in Dmax (VMAT: 66.7±5.06 vs. IMRT: 66.3±5.69, p=0.144), Dmean (VMAT: 28.6±6.77 vs. IMRT: 29.1±6.71, p=0.87), or D50% (VMAT: 21.4±9.43 vs. IMRT: 21.7±9.10, p=0.594). Similarly, for the Right Parotid, no significant differences were noted in Dmax (VMAT: 69.5±4.28 vs. IMRT: 69.6±4.45, p=0.654), Dmean (VMAT: 36.6±12.3 vs. IMRT: 36.5±12.2, p=0.619), or D50% (VMAT: 32.2±17.2 vs. IMRT: 31.8±17, p=0.450). Lastly, for the Thyroid, the Dmax values were comparable between VMAT (65.02±4.89) and IMRT (65.55±5.58, p=0.255), and the Dmean values were also similar, with VMAT at 58.26±7.73 and IMRT at 57.

Table 3 illustrates the comparative analysis of VMAT and IMRT techniques, focusing on the Normal Tissue Complication Probability (NTCP) for various organs at risk (OARs) as assessed by the Poisson-LQ model. In the case of the left parotid gland, the mean NTCP for VMAT was recorded at 37.1±25.0, while IMRT presented a value of 36.6±24.7 (p=0.679), indicating no statistically significant difference in the risk of xerostomia. For the right parotid gland, the NTCP values were 42.2±28.0 for VMAT and 42.5±27.9 for IMRT (p=0.427), again reflecting no significant difference. Regarding the mandible, the NTCP for joint dysfunction was 17.5±11.9 for VMAT compared to 18.6±11.0 for IMRT (p=0.127), with no significant difference in risk observed. The spinal cord NTCP for myelitis necrosis was 0.560±0.750 for VMAT and 0.095±0.060 for IMRT (p=0.567), which also indicated no significant difference. Finally, both treatment modalities exhibited an NTCP of 0.00 for the brain stem, with no detected risk of necrosis or infarction.

## DISCUSSION

This study presents a comprehensive comparative evaluation of VMAT and IMRT treatment planning methodologies for head and neck cancer, emphasizing dosimetric outcomes, treatment efficiency, and the preservation of surrounding healthy tissue. The results underscore the unique benefits and drawbacks associated with these sophisticated radiotherapy approaches, thereby providing valuable insights into their respective advantages and constraints within clinical settings.

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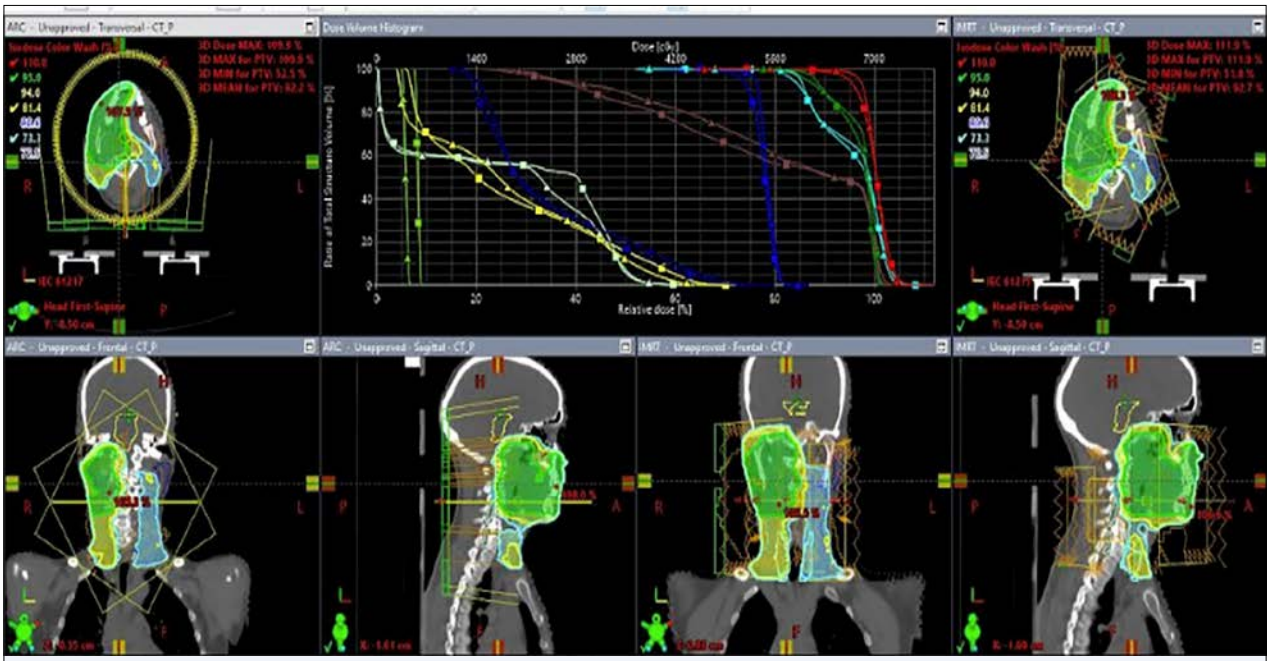

**Fig. 1.** Illustrates isodose line coverage and the dose volume histogram (DVH) for VMAT and IMRT techniques. Squares represent the VMAT plan, while triangles indicate the IMRT plan in the DVH.
VMAT: Volumetric modulated arc therapy; IMRT: Intensity-modulated radiotherapy.

## Target Coverage and Dose Distribution

The evaluation of target coverage metrics revealed that both treatment techniques yielded clinically acceptable outcomes, albeit with significant distinctions. IMRT demonstrated enhanced high-dose target coverage for the planning target volume (PTV_70Gy), exhibiting notably higher D95% (96.6±1.314 vs 96.1±0.643, p=0.048) and D98% values. This is depicted in Figure 1, which presents the dose distribution from axial, sagittal, and coronal views, along with isodose lines and a dose-volume histogram (DVH) curve. These results are consistent with the findings of Lee et al.,[26] who noted similar benefits in target coverage when utilizing IMRT for complex cases in head and neck oncology. Conversely, our analysis indicated that Volumetric Modulated Arc Therapy (VMAT) achieved comparable conformity indices (CI: 0.97±0.014 vs 0.97±0.014, p=0.327), implying that both methodologies can effectively conform to the target volumes. This demonstrated equivalent target conformity between the two treatment modalities in the context of head and neck cancer.[27]

## Treatment Efficiency and Delivery Parameters

VMAT demonstrates a notable enhancement in treatment delivery efficiency, achieving an estimated 70% decrease in Monitor Units when compared to IMRT (465±43.4 versus 1561±187.6, p=0.001). This significant reduction is consistent with findings.[28] Who indicated a 65–75% reduction in Monitor Units with VMAT for nasopharyngeal carcinoma. The improvement in efficiency carries critical clinical implications, particularly in minimizing treatment delivery duration and potentially mitigating risks associated with intrafractional motion, as highlighted by recent systematic reviews.[29]

## Dose Homogeneity and Healthy Tissue Protection

Figure 2 illustrates a comparison of Dose Homogeneity Index (DHI) and Uniformity Dose Index (UDI) between Volumetric Modulated Arc Therapy (VMAT) and Intensity-Modulated Radiation Therapy (IMRT) across a cohort of 50 patients. In terms of DHI (Fig. 2a), VMAT exhibited marginally superior homogeneity, with values ranging from 2 to 7, whereas IMRT displayed a slightly greater degree of variation. Regarding UDI (Fig. 2b), both methodologies revealed similar levels of uniformity, with values falling between 0.5 and 2.5; however, IMRT occasionally recorded higher peaks. Collectively, the findings indicate that VMAT may provide a more consistent dose distribution, although both approaches yield clinically acceptable planning results.

The evaluation of External Index (EI) values across different PTV dose levels reveals a consistent

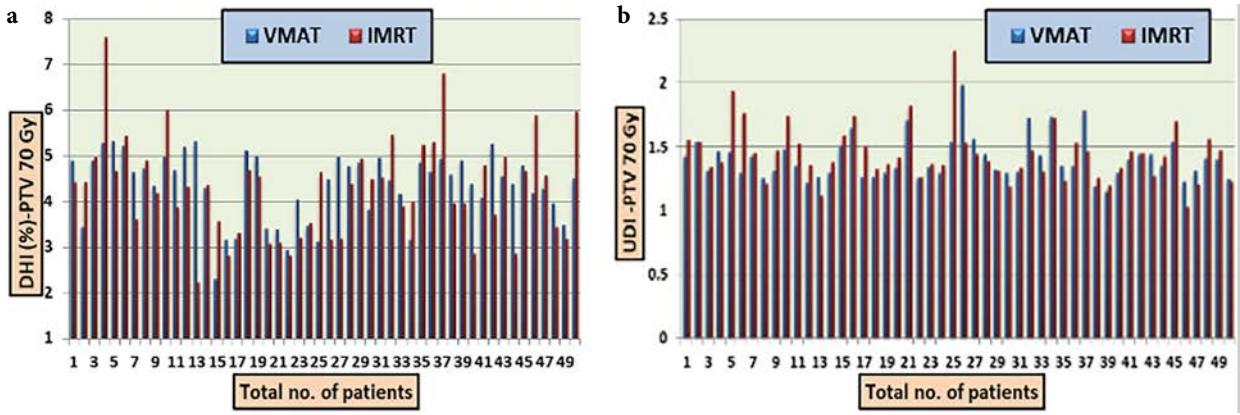


**Fig. 2.** Comparison of (a) dose homogeneity index (DHI) and (b) uniformity dose index (UDI) for PTV (70 Gy) in VMAT and IMRT plans across all patients.
PTV: Planning target volumes; VMAT: Volumetric modulated arc therapy; IMRT: Intensity-modulated radiotherapy.

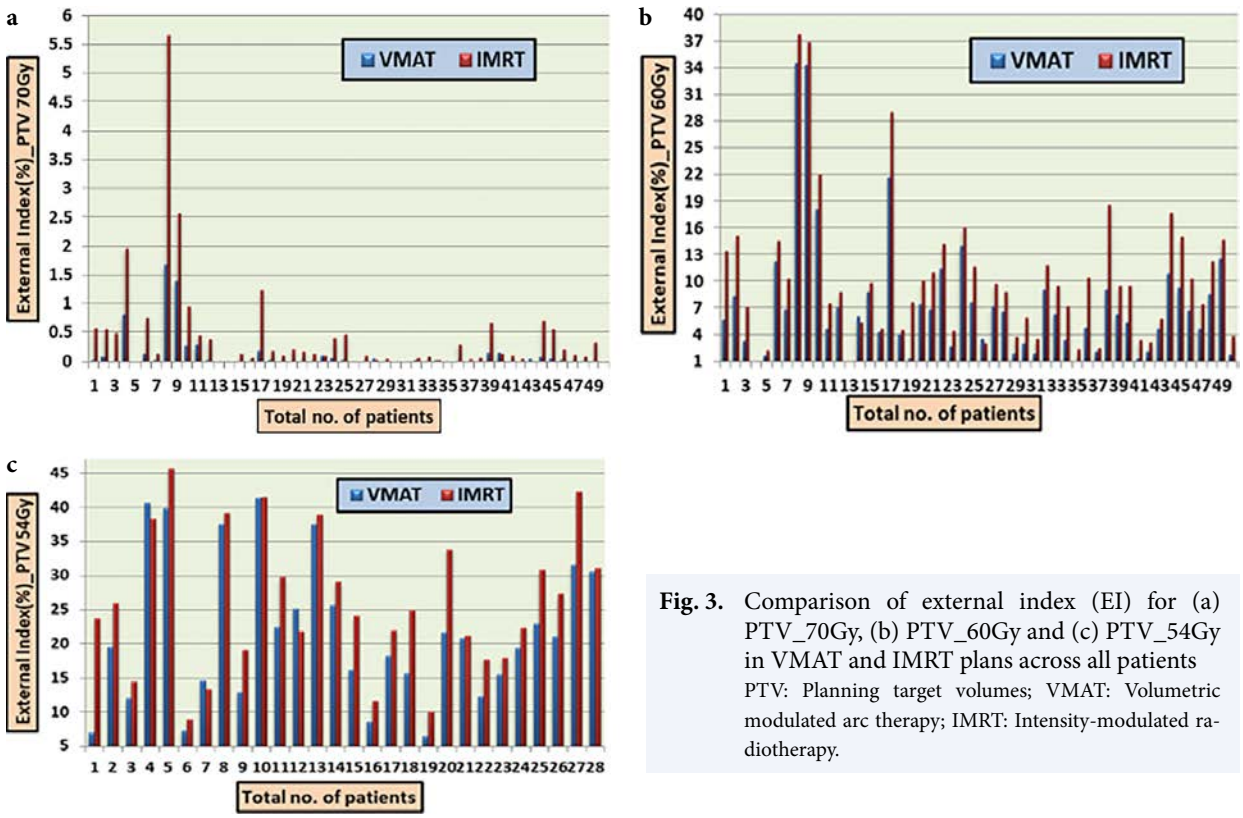


**Fig. 3.** Comparison of external index (EI) for (a) PTV_70Gy, (b) PTV_60Gy and (c) PTV_54Gy in VMAT and IMRT plans across all patients
PTV: Planning target volumes; VMAT: Volumetric modulated arc therapy; IMRT: Intensity-modulated radiotherapy.

advantage of VMAT over IMRT in terms of protecting healthy tissues demonstrated in Figure 3. In the PTV_70Gy group, which included data from 50 patients, VMAT achieved an 83.5% decrease in EI when compared to IMRT (0.0334 versus 0.2022). This finding underscores the significantly enhanced dose conformity associated with VMAT, particularly illustrated in the graphical data (Fig. 3a), where the majority of VMAT values remained below 1.0, indicating a substantial reduction in high-dose areas. In the PTV_60Gy group, also consisting of 50 patients, VMAT exhibited a 30.5% lower EI than IMRT (5.78 versus 8.32). Figure 3b depicts a consistently lower trend for VMAT across most patient cases, characterized by fewer and

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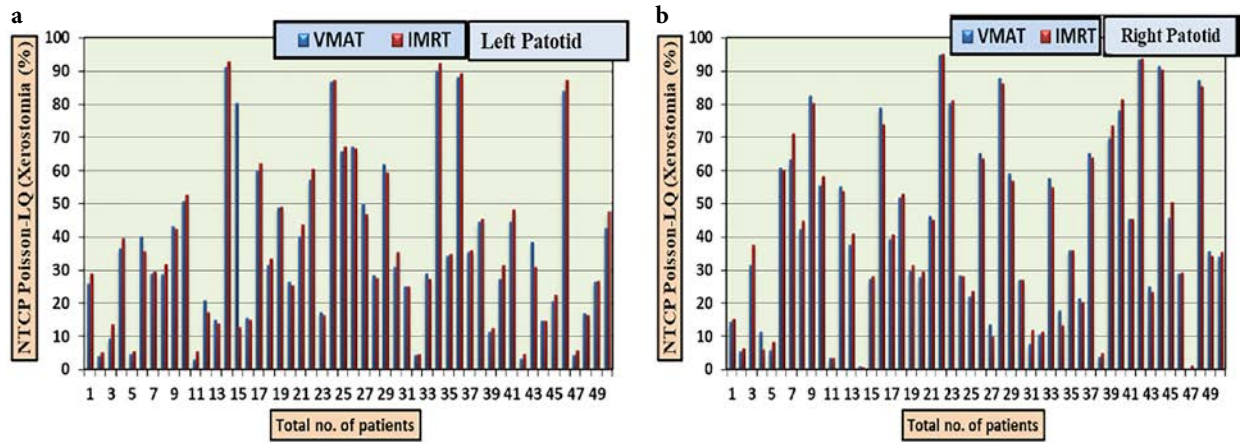


**Fig. 4.** Comparison of NTCP (poisson-LQ model) for xerostomia in the (a) left parotid and (b) right parotid gland across all patients in VMAT and IMRT plans.
NTCP: Normal tissue complication probability; VMAT: Volumetric modulated arc therapy; IMRT: Intensity-modulated radiotherapy.

less pronounced peaks compared to IMRT, which suggests superior performance in the intermediate-dose regions. For the PTV_54Gy cohort, comprising 28 patients, VMAT showed a 17.8% reduction in EI relative to IMRT (21.2 versus 25.8). As illustrated in Figure 3c, both VMAT and IMRT presented higher EI values compared to other PTV dose levels; however, VMAT consistently maintained lower values despite fluctuations. Statistical analysis validated that the enhancements associated with VMAT were significant across all three dose levels (p=0.001). The most substantial improvement was observed in the PTV_70Gy region, followed by PTV_60Gy and PTV_54Gy. These results reinforce the efficacy of VMAT in achieving superior dose conformity and minimizing exposure to adjacent healthy tissues, highlighting its status as a preferred method for high-precision radiotherapy.

### Organ-at-Risk Sparing and NTCP Analysis

The evaluation of NTCP values related to xerostomia in a cohort of 50 patients indicated no statistically significant differences between Volumetric Modulated Arc Therapy (VMAT) and Intensity-Modulated Radiation Therapy (IMRT) concerning the left and right parotid glands. Specifically, the NTCP values for the left parotid gland were recorded at 37.1±25.0% for VMAT and 36.6±24.7% for IMRT (p=0.679). For the right parotid gland, the NTCP values were 42.2±28.0% for VMAT and 42.5±27.9% for IMRT (p=0.427). The percentage differences between the two treatment modalities were minimal, approximately 1.35% for the left parotid and -0.71% for the right parotid. These results are illustrated in Figures 4a and (b), where the NTCP values for both treatment techniques show overlapping distributions, indicating similar sparing effects on the parotid glands. This outcome aligns with findings from prior research, including the previous work,[30] which concluded that VMAT and IMRT are comparably effective in mitigating the risk of xerostomia.

Mandible, Spinal Cord, and Brainstem NTCP Analysis: The results indicate that both VMAT and IMRT offer similar protection for non-target bone structures and essential nervous system components, including the mandible, spinal cord, and brainstem. The absence of statistically significant differences in NTCP values for these structures (Table 3) underscores the clinical relevance of both methods in reducing the likelihood of adverse effects. This is consistent with the conclusions drawn by Thompson et al.[31]

## CONCLUSION

This study evaluated the dosimetric efficacy of VMAT versus IMRT in the treatment of Head and Neck cancer. The findings indicated that VMAT provided enhanced target coverage, reduced external radiation exposure, and a more efficient treatment delivery, requiring fewer Monitor Units than IMRT. Although both modalities achieved similar levels of target homogeneity, VMAT was more effective in preserving healthy tissues, particularly in the PTV_60Gy and PTV_54Gy areas. In terms of sparing organs at risk, both techniques were found to be comparable, with VMAT exhibiting a slight advantage in protecting the spinal cord and minimizing toxicity risks.

**Ethics Committee Approval:** The study was approved by the Indira Gandhi Institute of Medical Sciences: Sheikhpura Ethics Committee (no: 301/IEC/IGIMS/2025, date: 09/01/2025).

**Conflict of Interest:** The authors have no conflicts of interest to declare.

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**Authorship Contributions:** Concept – M.Z., D.P.; Design – M.Z., D.P.; Supervision – M.Z., D.P.; Data collection and/or processing – M.Z., D.P.; Data analysis and/or interpretation – M.Z., D.P.; Literature search – M.Z., D.P.; Writing – M.Z., D.P.; Critical review – M.Z., D.P., D.S.

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