RESEARCH ARTICLE

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Dosimetric Comparison of Three-dimensional Conformal Radiation Therapy (3D-CRT) vs Volumetric Modulated Arc Therapy (VMAT) for Primary Malignant Brain Tumors

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Abstract

Background: Advances in radiotherapy planning have led to better dose delivery and protection of organs at risk (OAR) in malignant brain tumors. Though three-dimensional conformal radiotherapy (3D-CRT) is still commonly used, Volumetric modulated arc therapy (VMAT) delivers highly precise doses with dynamic adjustments. This study compares dosimetric differences prospectively between 3D-CRT and VMAT in primary malignant brain tumors. **Methods:** Fifty (50) patients with confirmed malignant primary brain tumors who received postoperative or definitive radiotherapy were assessed. Each patient had CT simulations, target and OAR contouring, and two distinct plans: 3D-CRT and VMAT using 6 MV photons. Treatment was delivered as per VMAT planning. The dosimetric endpoints included PTV coverage (D2%, D50%, D98%), conformity index (CI), homogeneity index (HI), and OAR doses (optic nerves, optic chiasm, brainstem, cochlea, retina, lens, pituitary, and spinal cord). **Results:** VMAT delivered significantly lower doses to some OARs compared to 3D-CRT. The Dmax to the right and left optic nerves was significantly lower with VMAT (24.77 Gy vs. 32.34 Gy, p=0.002; 27.35 Gy vs. 32.86 Gy, p=0.032). For the optic chiasm, both the Dmax and Dmean doses were significantly lower with VMAT (31.28 Gy vs. 36.32 Gy, p=0.036; 24.27 Gy vs. 30.77 Gy, p=0.019). The Dmean for the right cochlea was greatly reduced (7.27 Gy vs. 15.97 Gy, p=0.007). Differences in doses to the brainstem, pituitary, retina, and lens were minimal and not statistically significant. The PTV metrics (D2%, D50%, D98%) showed no significant differences between the techniques. The conformity index was acceptable for both plans (VMAT 0.903; 3D-CRT 1.089). Homogeneity indices were similar. **Conclusion:** VMAT offers better sparing of several critical OARs, such as the optic pathways and cochleae, while maintaining similar PTV coverage compared to 3D-CRT. Both techniques meet acceptable dose limits, but VMAT may be preferred for tumors near sensitive structures.

Keywords: VMAT- 3D-CRT- brain tumors- dosimetry- organ at risk

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Introduction

Primary malignant brain tumors are a diverse group of central nervous system neoplasms that remain a significant cause of morbidity and mortality worldwide [1]. They account for the majority of primary CNS tumors and demonstrate poor long-term survival despite advances in neurosurgery, imaging, radiotherapy, and systemic therapies [2, 3]. Glioblastoma multiforme (GBM), the most common malignant brain tumor in adults, is particularly aggressive, with infiltrative growth patterns that limit the effectiveness of surgical resection and contribute to high recurrence rates [3, 4].

Radiotherapy (RT) is an essential component of the multidisciplinary management of malignant brain tumors [5]. Delivered postoperatively or as definitive therapy in unresectable cases, RT improves local control and prolongs survival by targeting residual microscopic disease [6]. The evolution of external beam radiotherapy has been driven by the need to maximize tumor dose while sparing surrounding healthy brain tissue and critical structures such as the optic apparatus, brainstem, cochlea, and pituitary gland [7].

Significant technological advances have improved the precision and quality of radiotherapy delivery [8]. Image-guided CT simulation integrated with MRI fusion enhances target delineation and organ-at-risk (OAR) identification [9]. Conventional three-dimensional conformal radiotherapy (3D-CRT) marked a major step forward by enabling tailored beam arrangements based on

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patient-specific anatomy [10]. While 3D-CRT provides acceptable target coverage in many clinical situations, its reliance on static fields and limited modulation reduces its ability to spare adjacent OARs an important limitation for tumors situated near critical neural structures [11].

Intensity-modulated radiotherapy (IMRT) introduced dynamic fluence modulation using multi leaf collimators, allowing improved conformity and better sparing of sensitive structures [12]. Volumetric modulated arc therapy (VMAT) represents a further refinement by delivering continuously modulated radiation through gantry rotation. VMAT simultaneously varies with dose rate, gantry speed, and MLC position, generating highly conformal dose distributions around irregular tumor shapes [13]. Compared with IMRT, VMAT achieves similar or superior dosimetric outcomes with significantly shorter treatment times and fewer monitor units, enhancing patient comfort and workflow efficiency [14]. Unlike tomotherapy, which requires dedicated infrastructure, VMAT is widely accessible on conventional linear accelerators.

In resource-limited settings, cost, infrastructure availability, and technical expertise significantly influence radiotherapy technique selection. While advanced modalities such as IMRT, VMAT, and Tomotherapy offer superior dosimetric advantages, their implementation is often constrained by equipment availability, planning complexity, treatment time, and maintenance costs [15]. Consequently, 3D-CRT remains widely utilized.

Literature comparing 3D-CRT and VMAT in brain tumor radiotherapy shows variable results. Some studies demonstrate superior conformity and OAR sparing with VMAT, while others report acceptable outcomes with 3D-CRT in selected cases. Given that survival outcomes for high-grade gliomas remain poor regardless of technique, the choice between modalities often reflects considerations of resource availability, planning complexity, and the degree of OAR proximity [16].

Because malignant brain tumors often lie close to critical structures, even modest reductions in radiation dose to the optic pathways, brainstem, or cochlea can make a clinically meaningful difference in preserving neurological, visual, auditory, and endocrine function [17]. Therefore, evaluating the true dosimetric advantages of VMAT over 3D-CRT in a real-world clinical cohort is important for optimizing treatment selection and improving therapeutic ratio.

The present study addresses this need by performing a comprehensive dosimetric comparison of 3D-CRT and VMAT in patients with primary malignant brain tumors. By assessing planning target volume (PTV) coverage, conformity index (CI), homogeneity index (HI), and OAR doses across both techniques in the same patient dataset, this study aims to determine whether VMAT provides clinically relevant dosimetric improvements that justify its increasing use in contemporary practice.

Materials and Methods

Study Design and Patient Selection

This was a prospective intra-patient dosimetric planning comparison study conducted on patients diagnosed with primary malignant brain tumors who underwent radiotherapy at a single tertiary care center between November 2020 and November 2020. Institutional Ethics Committee (IEC) granted the necessary permission to conduct this study (KAMS&RC-IEC No. 57/2020). A total of 50 patients were enrolled based on predefined eligibility criteria. Adult patients (≥18 years) with radiologically and histopathologically confirmed primary malignant brain tumors of WHO Grade II–IV were included. Both postoperative cases and those treated definitively without surgery were eligible, provided they had undergone CT simulation and had adequate MRI imaging for fusion-based contouring.

Exclusion criteria were: (i) pediatric patients, (ii) tumors requiring craniospinal irradiation (CSI), such as medulloblastoma, germ cell tumors, or leptomeningeal spread, due to the complexity and different dosimetric objectives of CSI fields, and (iii) patients with incomplete imaging or suboptimal immobilization that precluded accurate planning. All included patients received external beam radiation therapy (EBRT) to a total dose of 54 Gy, 59.4 Gy, or 60 Gy delivered in once-daily fractions of 1.8–2 Gy as per departmental protocols, tumor grade, and postoperative status.

Simulation, Immobilization, and Imaging Acquisition

All patients were immobilized in the supine position using a customized thermoplastic head mask to minimize setup variations. A dedicated headrest was used for optimal cervical alignment and reproducibility. Following immobilization, CT simulation was performed using a single-slice helical CT scanner. Axial images were acquired at 3-mm slice thickness without interslice gaps, covering the region from the vertex to the second cervical vertebra.

Magnetic Resonance Imaging (MRI) was performed prior to radiotherapy planning, typically within two weeks of simulation. Contrast-enhanced T1-weighted images and T2/FLAIR sequences were obtained for accurate tumor delineation. MRI datasets were imported into the Eclipse treatment planning system and rigidly fused with CT simulation images. Automated image fusion was verified manually by the treating radiation oncologist to ensure alignment of bony landmarks, ventricles, and tumor boundaries.

Target Volume Delineation

The gross tumor volume (GTV) included the postoperative tumor bed and any visible residual tumor as visualized in contrast-enhanced MRI sequences. In cases treated definitively without surgery, the GTV represented the enhancing tumor and associated edema.

The clinical target volume (CTV) accounted for microscopic disease spread, defined as a 1–2 cm margin expansion from the GTV, modified according to natural anatomic boundaries such as falx cerebri, ventricles, skull bone, and tentorium. CTV reductions were made where tumor infiltration was anatomically improbable. The planning target volume (PTV) was generated by expanding the CTV by an isotropic margin of 0.5 cm

to account for residual setup uncertainties and daily positioning variations.

Organs at risk (OARs) were contoured according to RTOG and QUANTEC guidelines [17]. These included bilateral optic nerves, optic chiasm, brainstem, spinal cord, pituitary gland, bilateral lenses, retinas, and cochleae. The absence of contouring variations was ensured by consistency with departmental contouring protocols.

Treatment Planning Techniques

For each patient, VMAT treatment planning was done, and the treatment was delivered as per VMAT planning. Another separate theoretical plan was generated for 3D-CRT for comparison.

VMAT Planning

For the VMAT plan, a single 360° arc was employed using dynamic modulation of MLC positions, gantry speed, and dose rate. A total of 177 control points were automatically generated for each arc. The MLC aperture, dose rate (0–600 MU/min), and gantry rotation speed were optimized simultaneously using inverse planning algorithms to achieve desired dose distributions. Photon energy was 6 MV for all arcs. The optimization objectives emphasized PTV coverage, dose homogeneity, and OAR sparing. Planning constraints were based on prescribed department protocols and QUANTEC recommendations [18].

3D-CRT Planning

For each patient, a 3D-CRT plan was generated using Eclipse (Version 16.1, AAA algorithm). Treatment was planned with 6 MV photon beams using 2–6 static fields arranged according to lesion location and dosimetric objectives. Beam angles were selected to optimize PTV coverage while minimizing OAR exposure. Physical wedges or field-in-field segments were used when necessary to improve dose uniformity. Beam weighting and normalization were adjusted to achieve adequate PTV coverage (≥95% of the prescribed dose covering ≥98% of the PTV). All plans were normalized to isocenter, and a fixed dose rate of 600 MU/min was used.

For both techniques, plans were calculated using the Anisotropic Analytical Algorithm (AAA) with a calculation grid size of 2.5 mm. Dose-volume histograms (DVHs) were generated for each plan to quantify dose delivery to the PTV and OARs.

Dosimetric Evaluation

Dosimetric comparison included both target volume parameters and OAR doses.

Target Dosimetry Parameters

-D2%: near-maximum dose, D50%: median dose and D98%: near-minimum dose

• Conformity Index (CI):

CI=TV95%V95%CI = \frac{TV_{95\%}}{V_{95\%}}CI=V95% TV95%

where TV95%TV_{95\%}TV95% is the target volume receiving 95% of the prescribed dose.

•Homogeneity Index (HI) using ICRU-83 formula:

HI=D2%−D98%D50%HI = \frac{D2\% - D98\%}{D50\%}HI=D50%D2%−D98%

• Gradient index (GI):

GI = (Volume of 50% Prescription Isodose) / (Volume of 100% Prescription Isodose).

Organ-at-Risk Parameters

For each OAR, the following were evaluated:

• D_{max} and D_{mean} for optic nerves, chiasm, brainstem, pituitary, spinal cord

• Mean doses for cochlea, retina, and lenses

• All doses were compared against departmental tolerances (e.g., brainstem $D_{max} \leq 54$ Gy, spinal cord, $D_{max} \leq 45$ Gy, optic nerve $D_{max} \leq 55$ Gy, pituitary gland, $D_{max} \leq 50$ Gy, optic chiasm, $D_{max} \leq 56$ Gy, lens, $D_{mean} \leq 6$ Gy, eyeballs, $D_{mean} \leq 25$ Gy and cochlea, $D_{mean} \leq 45$ Gy.

Statistical Analysis

All dosimetric parameters were exported to Microsoft Excel and analyzed using SPSS Version 22. Continuous variables were expressed as mean ± standard deviation (SD). Paired t-tests were used to compare dosimetric parameters between 3D-CRT and VMAT for the same patient. Pearson's correlation coefficient assessed linear relationships between dosimetric variables across techniques. A two-tailed p-value <0.05 was considered statistically significant.

Results

A total of 50 patients with primary malignant brain tumors were included in this dosimetric comparison. All patients completed CT simulation, contouring, and generation of both 3D-CRT and VMAT plans, allowing for direct intra-patient comparison. The results are presented under patient characteristics, organ-at-risk (OAR) dosimetry, and planning target volume (PTV) analysis.

Patient and Tumor Characteristics

A total of 50 patients were included in this prospective intra-patient dosimetric comparison (demographics and clinical characteristics summarized in Table 1). Among the 50 patients, 31 (62%) were male and 19 (38%) were female. The mean age was 44.49 years (SD: 17.39), spanning 16–71 years. Glioblastoma multiforme (GBM) was the most common diagnosis (56%), followed by astrocytoma (32.0%). Other tumor types include ependymoma, oligodendroglioma, and recurrent astrocytoma (each 4%). WHO grade distribution showed Grade IV as the most frequent (52%), followed by Grade II (28%), Grade III (10%), and Grade I (10%) indicating a mixed cohort of low- and high-grade tumors.

Tumor location varied considerably: the frontal lobe was most common (31.4%), followed by fronto-parietal (14.3%) and temporo-parietal regions (11.4%). Less frequent sites included thalamus, parietal, occipital, suprasellar, intraventricular, and CP angle tumors. This diversity resulted in different spatial relationships between PTVs and OARs, highlighting the need to evaluate how

Table 1. Demographic, Clinical, and Treatment Characteristics (n = 50)

S.No	Characteristic	Patients (n = 50)
1	Age (years)	
	Mean (SD)	44.49 (17.39)
	Range	16–71
2	Sex	
	Male	31 (62.0%)
	Female	19 (38.0%)
3	Diagnosis	
	Glioblastoma multiforme	28 (56.0%)
	Astrocytoma	14 (32.0%)
	Ependymoma	2 (4.0%)
	Oligodendroglioma	2 (4.0%)
	Recurrent astrocytoma	2 (4.0%)
4	Tumour grade (WHO)	
	Grade I	5 (10.0%)
	Grade II	14 (28.0%)
	Grade III	5 (10.0%)
	Grade IV	26 (52.0%)
5	Tumour location	
	Frontal	12 (24.0%)
	Fronto-parietal	6 (12.0%)
	Temporo-parietal	5 (10.0%)
	Thalamic	4 (8.0%)
	Parieto-occipital	3 (6.0%)
	Parietal	4 (8.0%)
	Temporal	3 (6.0%)
	Suprasellar	3 (6.0%)
	Occipital	2 (4.0%)
	Capsulo-ganglionic	1 (2.0%)
	Intraventricular	2 (4.0%)
	CP angle	3 (6.0%)
6	Radiation dose	
	54.0 Gy/ 30 #	23 (46%)
	59.4 Gy/ 30 #	4 (8%)
	60.0 Gy/ 30 #	23 (46%)

each planning technique performs across various anatomic scenarios.

Radiotherapy prescriptions included 60 Gy in 30 fractions in 48.6% of patients, 54 Gy in 42.9%, and 59.4 Gy in 8.6%, depending on tumor type and postoperative condition.

Dosimetric comparison analysis for PTV parametres and OAR dosimetry was summarized in Table 2, and Figures 1, 2, 3.

Planning Target Volume (PTV) Dosimetry

D_{max}

VMAT produced slightly higher peak dose values compared to 3D-CRT (63.94 vs 62.03 Gy, p=0.021). This reflects typical VMAT characteristics where tighter modulation may result in more localized hotspots.

D_{mean}

VMAT delivered marginally higher mean PTV dose (57.92 vs 56.63 Gy, p=0.044), though the difference is small and clinically acceptable.

D95%

There was no significant difference in PTV D95% (54.88 vs 54.21 Gy, p=0.118), confirming that target coverage is comparable between techniques.

Dose Parameters (D2%, D50%, D98%)

Both techniques demonstrated comparable PTV coverage. D2%: 60.06 Gy (VMAT) vs. 60.32 Gy (3D-CRT), p = 0.269, D50%: 59.01 Gy vs. 59.20 Gy, p = 0.476 and D98%: 58.72 Gy vs. 58.62 Gy, p = 0.326. These near-parallel values demonstrate that both modalities deliver adequate and equivalent target coverage, ensuring tumor-directed dose deposition.

Conformity and Homogeneity

Conformity Index (CI)

The mean CI for VMAT was 0.903 and for 3D-CRT was 1.089. Both fell within acceptable limits (0.9–2.0). While VMAT tended to provide slightly tighter conformity, the difference was not statistically significant (p=0.051).

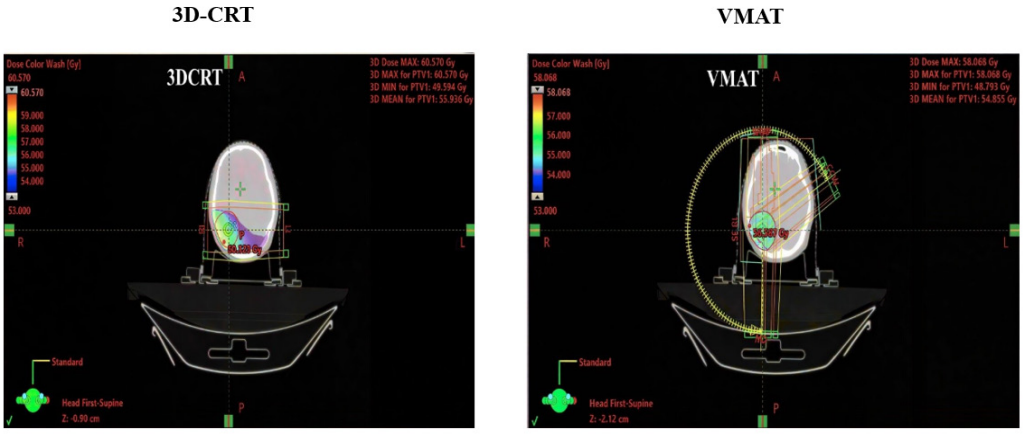

Figure 1. Comparison of 95% Prescribed Dose (V95%) Coverage of the Planning Target Volume (PTV) for 3D-CRT and VMAT Techniques Illustrating Respective Field Arrangements and Target Dose Distribution.

Table 2. Dosimetric Comparison of VMAT vs 3D-CRT

S.N	Structure / Parameter	VMAT (Mean ± SD)	3D-CRT (Mean ± SD)	p-value
1	PTV Parameters			
	• D_{max} (Gy)	63.9 ± 4.44	62.03 ± 4.55	0.021
	• D_{mean} (Gy)	57.92 ± 4.07	56.63 ±3.93	0.044
	• D95% (Gy)	54.88 ±4.37	54.21 ±3.86	0.118
	• D2% (Gy)	60.06 ± 4.22	60.32 ± 3.92	0.269
	• D50% (Gy)	59.01 ± 4.24	59.20 ± 3.76	0.476
	• D98% (Gy)	58.72 ± 4.00	58.62 ± 3.91	0.326
2	Conformity Index (CI)			
	CI	0.903 ± 0.082	1.089 ± 0.531	0.051
3	Homogeneity Index (HI)			
	HI	0.0224 ± 0.0125	0.0287 ± 0.0198	0.092
4	Gradient Index (GI)			
	GI	1.91 ± 0.6	4.74 ± 1.1	0.023
5	Monitor Unit (MU)			
	MUs	535 ± 224	255 ± 64.7	0.001
4	Optic Nerve – Right			
	D_{max} (Gy)	24.77 ± 18.31	32.34 ± 24.96	0.002
	D_{mean} (Gy)	14.20 ± 12.14	19.37 ± 18.83	0.006
5	Optic Nerve – Left			
	D_{max} (Gy)	27.35 ± 19.24	32.86 ± 24.78	0.032
	D_{mean} (Gy)	15.68 ± 12.83	19.26 ± 19.38	0.079
6	Optic Chiasm			
	• D_{max} (Gy)	31.28 ± 21.15	36.32 ± 23.84	0.036
	• D_{mean} (Gy)	24.27 ± 17.78	30.77 ± 23.38	0.019
7	Brainstem			
	• D_{max} (Gy)	36.16 ± 21.50	37.40 ± 22.79	0.709
8	Pituitary Gland			
	• D_{max} (Gy)	28.57 ± 22.76	28.75 ± 24.28	0.879
9	Spinal Cord			
	• D_{max} (Gy)	3.87 ± 1.52	2.83 ± 1.54	0.008
10	Cochlea – Right			
	• D_{mean} (Gy)	7.27 ± 10.77	15.97 ± 21.08	0.007
11	Cochlea – Left			
	• D_{mean} (Gy)	12.23 ± 15.80	15.24 ± 20.20	0.119
12	Lens – Right			
	• D_{mean} (Gy)	3.97 ± 0.47	3.95 ± 1.56	0.989
13	Lens – Left			
	• D_{mean} (Gy)	4.05 ± 0.45	4.24 ± 1.78	0.911
14	Retina – Right			
	• D_{mean} (Gy)	7.08 ± 0.84	13.00 ± 5.65	0.292
15	Retina – Left			
	• D_{mean} (Gy)	7.97 ± 0.88	8.74 ± 2.27	0.684

Homogeneity Index (HI)

No significant differences; both techniques (VMAT-0.0224 vs 3D-CRT-0.0287) delivered clinically acceptable uniformity.

Gradient Index (GI)

The mean GI for VMAT was 1.91, and 3D-CRT was 4.74. Both fell within acceptable limits. VMAT produced a much steeper dose gradient (lower GI) compared to 3DCRT; the difference was statistically significant (p=0.023).

Monitor Unit (MU)

The mean MUs for VMAT were 535 units and 3D-CRT

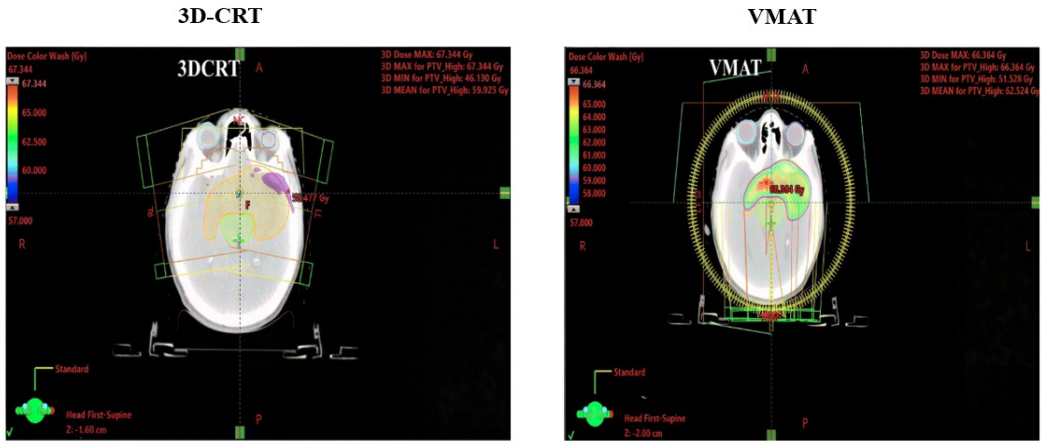

Figure 2. PTV Coverage Near OAR for 3D-CRT and VMAT, Showing Superior Sparing of Critical OARs by VMAT Technique

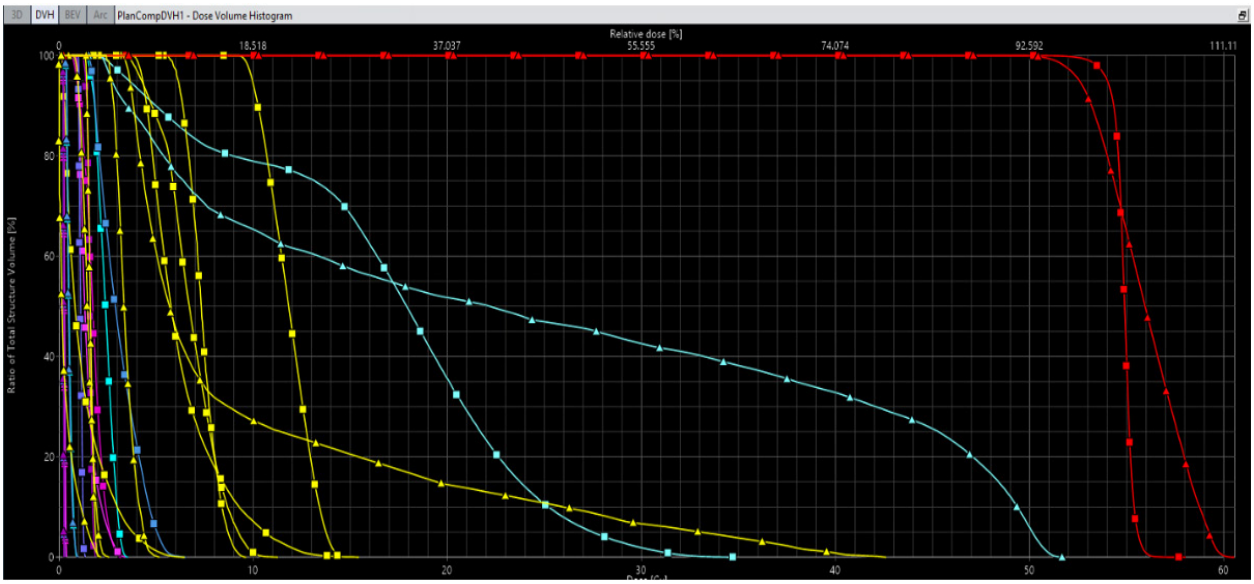

Figure 3. Dose Volume Histogram (DVH) for PTV and OARs in 3D-CRT vs VMAT (Δ 3D-CRT □ VMAT)

were 255. More MUs were needed for VMAT planning compared to 3DCRT; the difference was statistically significant (p=0.001).

Organ-at-Risk (OAR) Dosimetry

Optic Nerves

VMAT significantly reduced radiation to both optic nerves. For, right optic nerve, D_{max} decreased from 32.34 Gy (3D-CRT) to 24.77 Gy (VMAT) (p = 0.002), whereas D_{mean} decreased from 19.37 Gy to 14.20 Gy, (p = 0.006). For left optic nerve, D_{max} reduced from 32.86 Gy to 27.35 Gy (p = 0.032), but D_{mean} showed a non-significant decrease from 19.26 Gy to 15.68 Gy (p = 0.079). The optic nerves are highly radiosensitive, and the observed dose reductions may improve clinical outcomes, especially in tumors involving the frontal, parasellar, or suprasellar regions.

Optic Chiasm

VMAT plans delivered significantly lower doses to the optic chiasm, with D_{max} decreased from 36.32 Gy in 3D-CRT to 31.28 Gy in VMAT (p = 0.036) and D_{mean} decreased from 30.77 Gy in 3D-CRT to 24.27 Gy in VMAT (p = 0.019). Given the strict tolerance limits for chiasmal radiation, this reduction may improve safety with arc-based planning, particularly for midline tumors.

Cochlea

The cochleae demonstrated significant dose reductions, on the right side with D_{mean} decreased from 15.97 Gy (3D-CRT) to 7.27 Gy (VMAT) (p = 0.007). For left cochlea, D_{mean} decreased from 15.24 Gy to 12.23 Gy, which was not statistically significant (p = 0.119).

Though gliomas are not typically cochlea-adjacent tumors, when fields pass near the temporal bone, reduced cochlear dose decreases the risk of long-term hearing impairment.

Brainstem and Pituitary

Both techniques achieved similar sparing with no significant difference. Brainstem D_{max} was 37.40 Gy (3D-CRT) vs. 36.16 Gy (VMAT), (p = 0.709) and pituitary

D_{max} was nearly identical 28.75 (3D-CRT) vs 28.57 Gy (VMAT), (p = 0.879).

Retina and Lens

Retina and lens doses remained low across both techniques with no significant difference. Right retina D_{mean} was 13.00 Gy (3D-CRT) vs. 7.08 Gy (VMAT), (p = 0.292) and left retina D_{mean} was 8.74 Gy (3D-CRT) vs. 7.97 Gy (VMAT), (p = 0.684).

Lens doses were approximately 4 Gy for both eyes with no significant differences. Though not statistically significant, the trend favored VMAT. Importantly, both techniques remained well within toxicity thresholds.

Spinal Cord

A small but statistically significant increase in spinal cord dose occurred with VMAT with D_{max} of 3.87 Gy vs 2.83 Gy with 3D-CRT (p = 0.008). This is possibly due to the characteristic low-dose spread of VMAT techniques. However, the absolute doses were far below clinical tolerance (≤45 Gy), making the difference negligible in practical terms.

Summary

Overall, VMAT provides superior sparing of critical OARs primarily optic nerves, optic chiasm, and right cochlea while maintaining equivalent PTV coverage compared to 3D-CRT. Differences in brainstem, pituitary, retina, and lens doses were minimal. The slight increase in low-dose exposure to the spinal cord with VMAT may be clinically insignificant. These findings support the preferential use of VMAT when tumors are close to radiosensitive structures, while confirming that 3D-CRT remains acceptable for cases where OAR proximity is not a major concern.

Discussion

This study provides a detailed dosimetric comparison between VMAT and 3D-CRT for the treatment of primary malignant brain tumors and highlights meaningful differences in organ-at-risk sparing while demonstrating comparable planning target volume coverage. As radiotherapy remains a cornerstone of management for malignant gliomas and other primary CNS tumors, optimizing dose distribution is crucial for improving long-term functional outcomes. Given the delicate anatomy of the brain and the proximity of critical structures to target volumes, even modest reductions in radiation dose to organs such as the optic nerves, chiasm, cochlea, and brainstem can translate into clinically significant reductions in late toxicity [17].

The most prominent finding of this analysis is the superiority of VMAT in sparing critical OARs, particularly the optic apparatus and cochleae. The significant reduction in D_{max} and D_{mean} for the optic nerves and chiasm observed in this study is consistent with previously published dosimetric evaluations showing that VMAT techniques offer enhanced dose modulation capabilities compared with 3D-CRT [19, 20]. VMAT achieves this through continuous gantry rotation, simultaneous modulation of MLC positions, and dynamic dose-rate adjustments, allowing for tighter sculpting of dose distributions around curved or complex anatomical boundaries. This is especially important in frontal, suprasellar, and parasellar tumors locations that dominated our study cohort where even small increases in optic pathway dose can lead to irreversible visual complications.

The cochlear dose reductions observed with VMAT, particularly on the right side, are another clinically meaningful result. Radiation-induced ototoxicity remains an important quality-of-life concern, especially in younger patients [21]. The substantial halving of mean cochlear dose achieved by VMAT offers a clear dosimetric advantage. While differences for the left cochlea did not reach statistical significance, likely due to inter-patient variability in tumor laterality and location, the trend toward reduced dose still favors VMAT. These findings align with earlier work demonstrating that VMAT and IMRT allow better protection of inner ear structures compared with conventional techniques [22].

In contrast, the brainstem and pituitary gland showed only minimal differences in dose between the two techniques. This may reflect the fact that, in most cases, these structures were anatomically distant from the PTVs, reducing the complexity of sparing requirements. For the retina and lens, both techniques achieved low radiation doses, well below tolerance levels, consistent with their peripheral location relative to most tumor sites. Although VMAT reported slightly lower mean values, the differences were not clinically significant.

An interesting observation was the slightly higher maximum dose to the upper spinal cord in VMAT plans. This is likely attributable to VMAT's characteristic low-dose bath, where continuous rotation produces a wider distribution of low-intensity radiation outside the primary field. Nevertheless, the absolute spinal cord doses remained far below thresholds for deterministic injury, and the difference is therefore not clinically concerning.

Importantly, PTV coverage remained comparable between VMAT and 3D-CRT across all evaluated high-, mid-, and low-dose metrics (D2%, D50%, D98%). The nearly identical values demonstrate that both techniques are capable of delivering the prescribed therapeutic dose reliably. This also reflects meticulous contouring and planning processes. The conformity and homogeneity indices were acceptable and similar between techniques. Though typical of VMAT, it achieved slightly improved conformity. Although these differences did not reach statistical significance, they indicate the inherent capability of arc therapy to wrap dose more closely around complex tumor shapes.

A key strength of this study lies in its intra-patient comparison design, in which each patient served as their own control. This allowed for direct dosimetric comparison without confounding differences in tumor size, shape, or anatomical relationships. Furthermore, the sample reflected a realistic distribution of tumor sites and grades encountered in clinical practice, enhancing the applicability of findings.

Our results support the growing body of evidence indicating that VMAT techniques provide meaningful

OAR sparing advantages without compromising target coverage. Various studies have similarly demonstrated improved conformity and OAR protection with arc-based therapies in brain tumors [23, 24]. However, it is also important to acknowledge that 3D-CRT remains a viable approach especially in settings with limited access to advanced radiotherapy technology when the tumor lies at a safe distance from critical structures. In such cases, 3D-CRT can achieve adequate coverage with minimal OAR risks at lower cost, and simpler workflows.

Nevertheless, for tumors adjacent to optic pathways, cochlea, or other radiosensitive structures, the dosimetric benefits of VMAT demonstrated in this study suggest it may be the preferred modality. Although this analysis did not include clinical outcome data, the dosimetric improvements particularly reductions in optic nerve, chiasm, and cochlear doses are well recognized to correlate with improved clinical tolerability.

Although this study focused on comparing VMAT and 3D-CRT, several published studies have evaluated other advanced techniques such as fixed-field IMRT and Tomotherapy in brain tumors [25, 26]. These reports consistently show that IMRT and Tomotherapy provide improved conformity and organ-at-risk sparing compared with 3D-CRT; however, they are associated with longer treatment times, higher monitor units, and greater infrastructural requirements. VMAT offers similar conformity without the need for dedicated platforms, making it more adaptable to routine clinical practice, particularly in resource-constrained settings.

Overall, the study reinforces that VMAT achieves superior OAR sparing while maintaining comparable PTV dose metrics to 3D-CRT. This enhanced precision may support reductions in long-term treatment-related toxicities, particularly visual and auditory impairments, and may therefore improve the therapeutic ratio in the treatment of malignant brain tumors.

Limitations

This study has some limitations. The study evaluated only dosimetric analysis; it did not assess clinical outcomes such as toxicity, neurocognitive effects, vision or hearing preservation, or survival, so the clinical impact of the observed dose reductions cannot be confirmed. Minor contouring variations, especially for small OARs like the cochlea and optic pathway structures, may influence dose estimates. The sample size was relatively small and derived from a single institution, which may limit generalizability. Additionally, only single-arc VMAT plans were evaluated, and comparisons with dual-arc VMAT or IMRT were not performed. Daily image-guided dose variations were also not considered.

In conclusion, VMAT demonstrated clear dosimetric advantages over 3D-CRT by significantly reducing doses to critical structures particularly the optic nerves, optic chiasm, and cochlea while maintaining equivalent PTV coverage, conformity, and homogeneity. Both techniques met acceptable planning standards, but VMAT provided superior normal tissue sparing, making it preferable for tumors located near sensitive neural and sensory organs. Although 3D-CRT remains feasible for anatomically favorable cases or resource-limited settings, these findings support the broader use of VMAT for improved treatment precision. Further clinical studies are needed to correlate these dosimetric benefits with functional clinical outcomes.

Author Contribution Statement

AS and NP contributed to the conception and design of the study. NP conducted the study with AS overseeing the project. NP recruited study participants, collected data, and supported preparation of data. KM did the treatment plan. KAK, CR, TM, and KND collated data for statistical analyses, and conducted statistical analyses. KAK drafted the manuscript. All other authors provided comments and critical revisions. The final manuscript was approved by all authors prior to submission.

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None.

Ethical declaration

Ethical committee approval was granted by the Institutional Ethics Committee (KAMS&RC-IEC No. 57/2020). All study participants provided written informed consent for study participation.

Availability of data

The data that supports the findings of this study are available on request from the corresponding author.

Conflict of interest

None declared.

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