Natural Resources for Human Health

eISSN: 2583-1194

Original Research

Received 15 May 2026
Revised 25 June 2026
Accepted 10 July 2026

Natural Resources for Human Health 2026, Vol. 6 (11s): 297–323

KEYWORDS:
VMAT, IMRT, Brain Cancer, Treatment Planning, Reference Points (MU), Dose Coverage.

Comprehensive and Comparative Dosimetric Characterization of VMAT and IMRT in Brain Cancer Treatment Planning: Target Coverage, OAR Sparing, Monitor Units, Dose Distribution, Low-Dose Volumes, and Delivery Efficiency

Abbood Abbas Abbood [1, 6], Ahmad Lutfi Yusoff [2], Norazlina Binti Mat Nawi [3], Hayday Hamza Alabedi [4], Ibrahim H. Alnidawi [5]

[1, 2, 3] Department of Nuclear Medicine, Radiotherapy & Oncology, School of Medical Sciences, Universiti Sains Malaysia, 16150 Kubang Kerian, Kelantan, Malaysia,
[4, 5] Department of Radiation Oncology, Warith International Cancer Institute (WICI), Al-Thaqalayne Cancer Hospital, Basra, Iraq.
[6] Department of Radiation Oncology, Baquba Teaching Hospital, Ministry of Health, Baquba, Iraq

ABSTRACT:

Purpose: A detailed dosimetric comparison is conducted between VMAT and IMRT modalities for brain tumor treatment plans concerning prescription doses of 60, 66, and 70 Gy.

Material and Methods: A total number of forty-three brain tumor patients were selected by means of a retrospective study in the Radiotherapy Department at Baquba Teaching Hospital. Two different treatment plans were made for each patient; one by VMAT, and another by IMRT, for a total of 86 treatment plans. All treatment plans were designed under the same conditions of CT scan images, target contouring, and organ-at-risk constraints.

Results: Overall high PTV coverage was achieved with both techniques and no significant difference was observed in D95 D98 D50 or D2 HI and CI were also comparable, however, higher mean values were obtained for V5 V10 and V20 for the IMRT and a lower number of monitor units were used for treatment delivery in VMAT.

Conclusion: VMAT and IMRT were comparable in terms of target coverage and normal tissue protection, but VMAT needed fewer monitor units and had a significantly lower V20 with numerically lower V5 and V10 although these were not statistically significant.

1. INTRODUCTION

A brain tumor stands out among the hardest conditions to treat in today's radiation oncology because of its complicated anatomy and close association with radiosensitive structures within the brain. However, the treatment aims of brain tumor radiotherapy involve delivering tumoricidal doses to the targeted tissues while minimizing harm to other crucial organs such as the brainstem, optic apparatus, ears, lenses, and the neighboring healthy brain parenchyma. Balancing tumor response and normal tissue sparing continues to be an essential problem in radiation oncology (Freihat et al., 2025).

The advancement of radiotherapy has allowed the treatment of brain tumors using modern treatment planning systems with inverse optimization algorithms and accurate dose delivery techniques to adapt the treatment to the irregular target geometry and to minimize radiation exposure to surrounding healthy tissues and to provide more individualized radiotherapy.

Among the advanced methods of radiation therapy used in clinics today, Intensity Modulated Radiation Therapy (IMRT) and Volumetric Arc Modulated Radiation Therapy (VMAT) are recognized as two commonly used methods of intracranial radiation therapy. Both techniques involve inverse planning and multileaf collimator modulation, allowing for obtaining very conformal dose distributions. Nevertheless, IMRT and VMAT differ from each other with respect to how radiation is delivered. More specifically, while IMRT involves delivering radiation using several fixed gantry positions with segmented intensity-modulated fields, VMAT uses continuous delivery of radiation throughout gantry rotation at a variable dose rate, gantry rotation speed, and multileaf collimator positions (Moyano et al., 2026).

VMAT and IMRT have been extensively studied in matched brain radiotherapy patients under equivalent planning conditions are still clinically relevant due to the reduction of anatomical variation between patients; this study compared VMAT and IMRT for 43 patients with brain tumors in terms of target dose metrics: homogeneity conformity low dose volumes monitor units and doses to relevant OARs.

Though both techniques have been applied widely to clinical settings, there is still uncertainty about their respective dosimetric benefits for VMAT and IMRT. The findings of published literature concerning their conformity, homogeneity, low-dose effects, and treatment efficiency have often been contradictory because their efficacy depends on factors such as target shape, prescribed dose, optimization, and institution-specific plans (Konstantinou et al., 2026; Huang et al., 2026). Consequently, further evaluation and comparisons need to be made under certain clinical scenarios.

Target dose characteristics, plan quality, treatment delivery, low dose exposure and doses to clinically relevant OARs were evaluated in this study with the objective of identifying the relative advantages and limitations of both techniques; the originality of this study is based in the paired intra patient design in which VMAT and IMRT plans were generated for the same 43 patients using identical anatomical targets and comparable planning objectives, thus minimizing the influence of inter patient anatomical variability and allowing a more controlled assessment of technique related differences.

2. MATERIALS AND METHODS

Comprehensive and comparative analyses on the treatment plans of VMAT and IMRT techniques were performed retrospectively in radiotherapy of brain tumors. Treatment plans of forty-three patients who were subjected to radiotherapy treatment earlier at the Radiotherapy Department of Baquba Teaching Hospital were analyzed. All the treatment plans used in the analysis were generated using the Varian Eclipse treatment planning system (Varian Medical Systems, Palo Alto, CA, USA).

Two different treatment schemes were designed for the same patient using the same sets of data from CT simulations, planning target volume, and organs at risk with a total of eighty-six treatment plans. The doses applied included 60 Gy, 66 Gy, and 70 Gy. In case of VMAT, two full arcs and/or two half arcs were considered for the same patient depending on the geometry of the tumor location and critical structures. On the other hand, five to nine coplanar step and shoot fields IMRT were designed considering target size and shape.

Dose assessment was done through the performance of dose volume histogram (DVH). Target region coverage was performed through D2%, D50%, D95%, D98%, Dmax, Dmean, and Dmin. Homogeneity Index (HI) and Conformity Index (CI) were used to measure the quality of the plan. Low-dose exposure to normal tissue was estimated using V5%, V10%, and V20%. Moreover, different levels of doses in critical organs such as brainstem, spinal cord, optic nerves, eyes, lenses, cochleae, and parotid glands were recorded as well.

Effectiveness was evaluated through monitor units, reference point, beam set-up, among others. Statistical analyses were performed through the use of paired comparisons between VMAT and IMRT. Continuous variables were represented using mean ± SD. Significance was considered when $p < 0.05$.

2.1 Patient selection and contouring

The study is a dosimetric comprehensive and comparative retrospective study that used treatment planning data from 2023 to 2026; a total of 43 patients with brain tumors were included in the study, with each patient receiving separate VMAT and IMRT

plans for comparison and dosimetric analysis based on the same CT simulation data target volumes, prescribed doses, and OAR constraints that allow the direct comparison between the paired plans.

The study involved dose schedules of 60 Gy, 66 Gy, and 70 Gy based on institutional protocol. To eliminate variations in the planning, the planning for both arms was performed according to the same criteria. This implies that variations in doses could only be attributed to the delivery method since the anatomy among all patients was the same.

The paired planning design would serve to be an excellent test of the target dose coverage, conformity, homogeneity, and sparing of OARs.

2.1.1 Inclusion and Exclusion Criteria

The patients eligible for inclusion criteria are those with brain tumor diseases, those who underwent CT simulation and planning radiotherapy in Baquba Teaching Hospital, and those with data sets for analysis purposes. Patients with appropriate target volume and OAR contouring were considered for this study.

On the other hand, the patients excluded from this study were those with inadequate treatment planning data sets; those with inappropriate target volume and OAR contouring, and those with insufficient treatment planning imaging.

2.1.2 Patient Positioning and CT Simulation

The Subjects were made to undergo the procedure of CT scan using a specialized CT machine used for radiological planning. Patient positioning included making the subject lie in the supine position where the head of the patient was fixed using the thermoplastic mask to ensure the immobility of the subject. Images taken at thickness of slice ranging from 1 to 3 mm were obtained in DICOM file format.

2.1.3 Delineation of Target Size and Organs at Risk

Size of GTV was determined using available information from CT simulation; CTV and PTV sizes were computed depending upon the standards followed for treatment. Other organs at risk (OARs) such as eyes, lenses, optic nerves, brain stem, spinal cord, and pituitary glands were considered.

2.2 Radiotherapy Planning System

Treatment plan for all subjects was generated using the eclipse radiotherapy planning system manufactured by Varian Medical Systems, USA. Both treatment techniques followed equal dose constraint optimization parameters.

2.2.1 Volumetric modulated arc therapy (VMAT)

The VMAT is a form of advanced inverse-planned therapy, which involves continuous dose delivery during gantry rotation along with modulation of the MLCs positions, dose rate, and gantry speed. This approach allows for highly conformational distribution of radiation doses within the PTV while ensuring effective treatment delivery and minimizing exposure of surrounding normal tissues to radiation (Rennau and Hildebrandt, 2026).

This current study involved VMAT plans designed through the Varian Eclipse Treatment Planning System, employing 6-MV photon beams. As per the anatomical features of patients, plans were developed through either dual full arcs or partial arcs. In the case of dual-arc VMAT, there was delivery of the first arc in the clockwise (CW) orientation followed by delivery of another arc in counterclockwise (CCW) orientation. Through the employment of arcs in opposing directions, more degree of optimization can be achieved, providing a large number of entrance beams for dose calculations (Choi et al., 2025).

Two rotational arcs were chosen because they were expected to increase the capacity to modulate doses around intricate tumor shapes and allow better balancing of target coverage and organ sparing. In recent studies, dual-arc VMAT plans have proven to provide better tumor conformity and better critical organ sparing with no compromise on target coverage as compared to single arc plans (Choi et al., 2025; Huang et al., 2026).

VMAT was performed using partial arcs for some patients when the target was situated close to critical organs or when specific angles of the gantry would result in unwanted exposure of healthy tissues to radiation. Dose modulation was achieved by limiting beams to specific angles, which facilitated lowering doses delivered to critical organs while ensuring appropriate coverage of planning target volumes. Partial arcs have been shown to allow normal tissue sparing without compromising dosimetry of the plan (Rennau and Hildebrandt, 2026).

Full arc or partial arc selection was customized on the basis of target size, target shape, tumor localization, and adjacency to the neighboring organ(s) at risk. Accordingly, the choice of an optimal arc arrangement depended on the complexity of the anatomical site and the dose requirements and not merely on the prescribed dose level. During the process of optimization, the same target goals and OAR constraints were considered in all patients. The principle underlying VMAT optimization was to achieve high PTV coverage, homogenous and conformal dose distribution, and low doses to surrounding normal tissues whenever possible (Zeng et al., 2025; Choi et al., 2025).

Figure 1 illustrates a typical VMAT plan obtained for one of the patients with a brain tumor. The VMAT plan was created through optimization of two rotating beams delivered clockwise (CW) and counterclockwise (CCW). Isodose lines in Figure 1 illustrate how VMAT allows the achievement of high conformity of target area coverage while delivering appropriate doses to neighboring organs at risk.

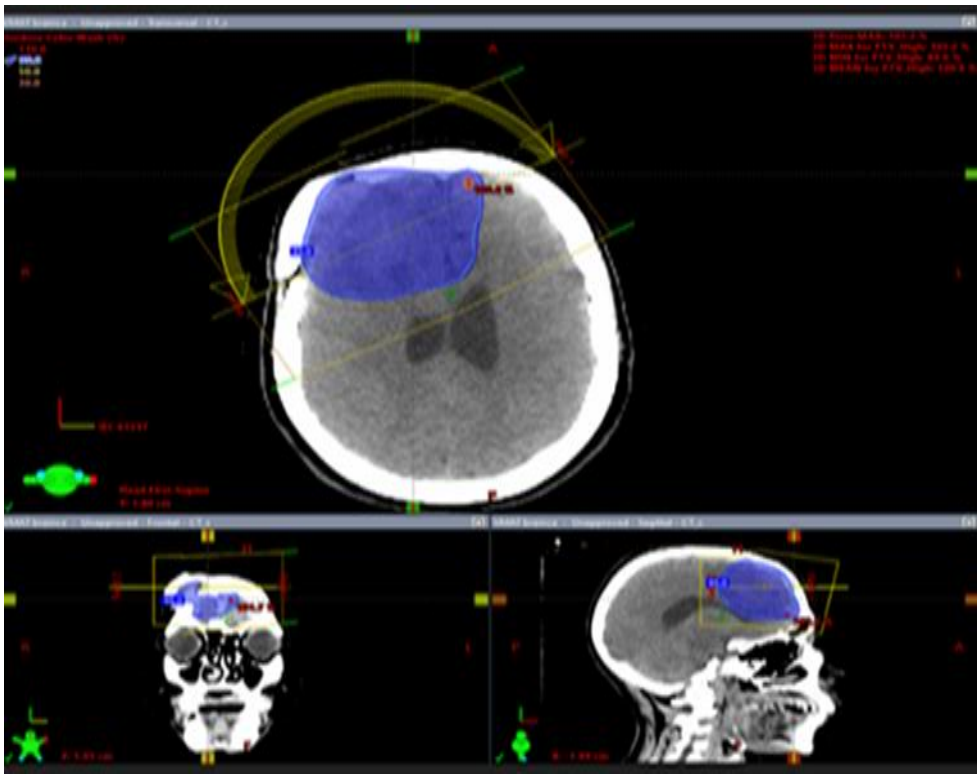

Fig. 1. VMAT radiation treatment plan for a patient with a brain tumor.

2.2.2 Intensity-modulated radiation therapy (IMRT)

Intensity-modulated radiotherapy (IMRT) represents inverse radiotherapy treatment method, based on computerized intensity modulation of photon beams; hence, IMRT allows delivering high dose conformity due to the use of a multileaf collimator (MLC). The use of IMRT is particularly useful in situations when high doses are needed within the planning target volume (PTV), while keeping the adjacent organs at risk (OARs) safe from high doses of radiation. IMRT proves to be extremely efficient for the treatment of brain tumors that occur near neurologically sensitive areas (Freihat et al., 2025).

In the current study, the treatment plan was developed using Varian Eclipse treatment planning system with IMRT technique used in combination with 6-MV photon beams and the step-and-shoot delivery method. Step-and-shoot IMRT implies the use of several independent segments for irradiation. In step-and-shoot IMRT, irradiation is stopped whenever leaves of MLC change their positions until the proper segment geometry is created; after that, the next irradiation begins until all segments with necessary geometry have been delivered (Moyano et al., 2026).

Five to nine beams coplanar fields were utilized depending on the anatomical and dosimetric complexities of the cases. Selection of the beams' number and angles depended upon the tumor volume size, tumor shape, closeness of the target organ to vital organs, and the need for dose modulation to meet treatment planning objectives. The choice of the beams' number was not

determined by the dose prescription itself but by the complexity of target-organ relationship and the needed dose conformity (Jafar and Jia, 2026).

Cases of tumors with large volumes, with irregular shapes, or tumors that were close to radiosensitive structures including brainstem, optic nerves, optic chiasm, cochlea, and lenses needed larger numbers of beams. More beam angles improved the dose conformity, increased dose homogeneity in the PTV region, and provided better sparing of adjacent organs at risk. Small or less complex tumors could be adequately treated by few beams without affecting target coverage and quality of the treatment plans (Freihat et al., 2025).

This method was personalized based on target size, shape, location and proximity to critical structures in order to maximize the treatment efficiency, homogeneity and target conformality while minimizing normal tissue exposure.

The brain tumor case was planned using the Varian Eclipse Treatment Planning System using multiple coplanar step and shoot fields to make sure sufficient target coverage was achieved while keeping doses to surrounding healthy tissues to a minimum.

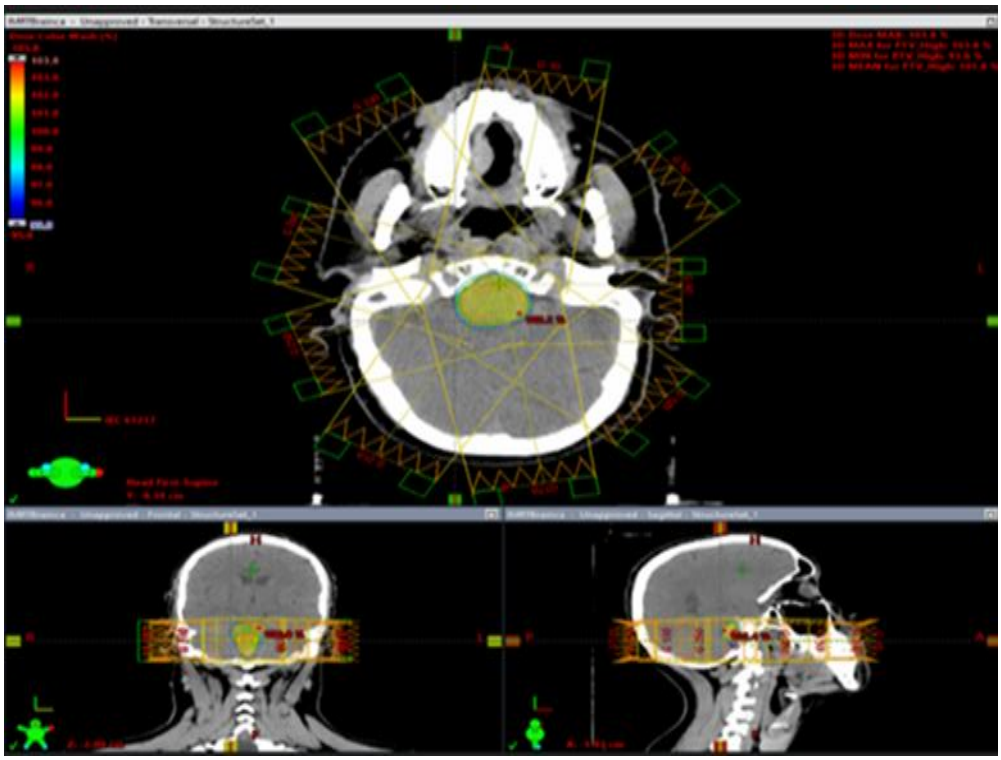

Fig. 2. IMRT radiation treatment plan for a patient with a brain tumor.

2.3 Analytical Methods

Treatment plans were evaluated using dose–volume histogram (DVH)-based metrics. Target coverage was assessed by D2%, D50%, D95%, D98%, Dmax, Dmean, and Dmin. Plan quality was quantified using the Homogeneity Index (HI) and Conformity Index (CI). Low-dose exposure to surrounding normal tissues was evaluated using V5%, V10%, and V20%, while doses to critical organs at risk were also analyzed. These parameters were selected to provide a comprehensive assessment of target coverage, dose distribution, normal tissue sparing, and treatment delivery.

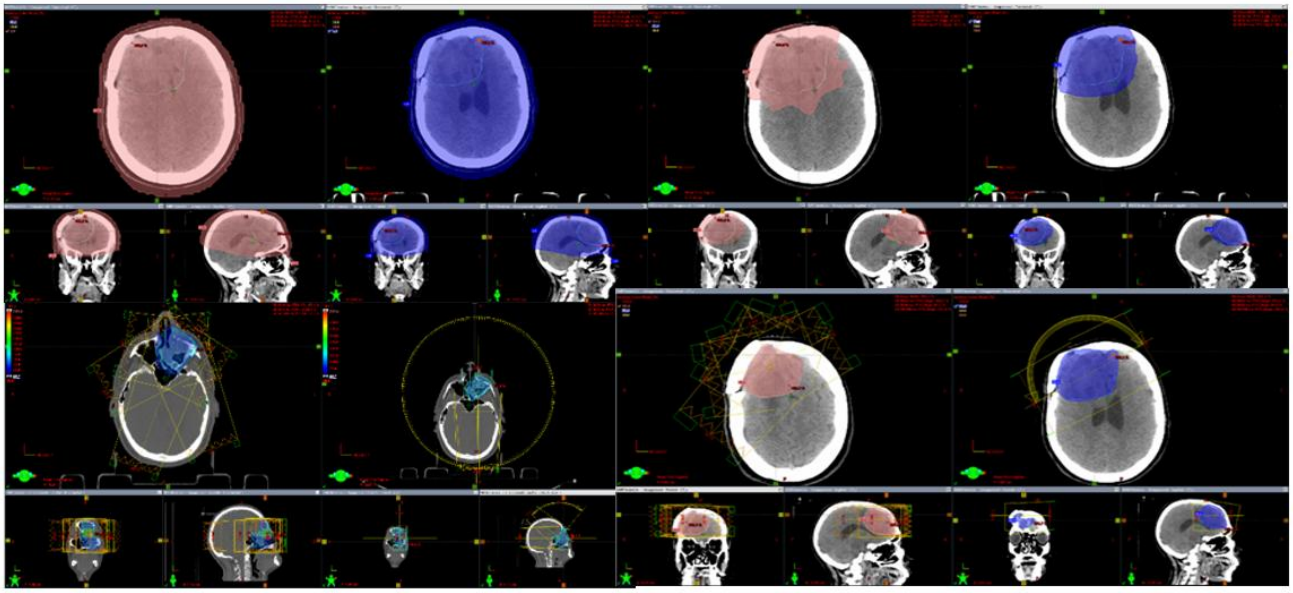

Fig. 3. PTV dose distribution metrics for IMRT and VMAT plans, showing D2%, D50%, D95%, and D98%.

2.5 Statistical Analysis

GraphPad Prism 11.1.0 (GraphPad Software, Boston, MA, USA) was used for statistical analysis. Data are presented as mean ± SD, and normality of the paired differences was tested using the Shapiro Wilk test; a paired t test was used if the paired differences were normally distributed, or the Wilcoxon signed rank test was used for nonnormally distributed paired differences. Cohen's dz effect sizes were calculated for paired comparisons and statistical significance was set at $p < 0.05$.

3. RESULTS AND DISCUSSION

3.1 Preliminary Analysis

A comprehensive and comparative analysis between VMAT and IMRT was carried out to understand their capability of delivering a desirable dose to the tumor targets while minimizing the dose to surrounding healthy tissues during brain tumor radiation therapy. Both of these procedures are extensively utilized in modern radiation treatment; however, an investigation into which one is relatively better is clinically relevant when the following aspects are taken together.

In the present study, treatment plans were generated using identical CT simulation datasets, target volume delineations, and organ-at-risk constraints, allowing a direct comparison of the dosimetric characteristics of each technique. The dose of 60 Gy, 66 Gy, and 70 Gy was included in the calculation of this work; this is a usual dose in cases when brain tumor therapy is needed. The parameters that were evaluated in the dosimetry study include: target volume dose parameters (D2%, D50%, D95%, D98%, Dmax, Dmean, Dmin), homogeneity index, conformity index, low dose volume parameters (V5%, V10%, V20%), and treatment delivery efficiency parameters.

Determination of whether VMAT can give dosimetric and/or delivery benefits relative to IMRT when having similar PTV coverage was the main focus of this assessment. Specifically, target dose distribution, low-dose exposure of the surrounding tissue, effectiveness, and possible medical implications of the difference found between both treatments were of importance here. The results are shown below in the subsequent sections, where first, target coverage and dosimetric qualities are discussed, and secondly, plan quality parameters, normal tissue exposure, sparing of organs at risk, and treatment efficiency are assessed.

Natural Resources for Human Health
eISSN: 2583-1194

Table 1. Comprehensive and comparative analysis of target dose coverage and dosimetric characteristics between VMAT and IMRT treatment plans.

Case	plan	Technology	Fractionation	Hotspot dose ≥ 110%	D2% (Gy)	D50% (Gy)	D95% (Gy)	D98% (Gy)	Dmax (Gy)	Dmean (Gy)	Dmin (Gy)	Dose coverage (%)
1	1.	VMAT	2GY*33	108.66	68.62	66.9	65.02	64.49	71.72	66.81	54.38	100
	2.	IMRT	2GY*33	106.42	68.41	66.33	64.8	64.14	70.24	66.35	52.09	100
2	3.	VMAT	2GY*33	108.42	68.53	66.87	65	64.48	71.56	66.77	54.47	100
	4.	IMRT	2GY*33	107.41	68.82	66.57	65.26	64.8	70.89	66.66	53.03	100
3	5.	VMAT	2GY*33	107.66	68.19	66.72	64.85	64.33	71.06	66.59	54.61	100
	6.	IMRT	2GY*33	107.44	68.88	66.58	65.29	64.86	70.91	66.68	53.34	100
4	7.	VMAT	2GY*33	105.29	67.7	66.04	64.52	63.95	69.49	66.01	59.22	100
	8.	IMRT	2GY*33	104.22	67.41	66.07	64.66	63.89	68.78	66.03	58.8	100
5	9.	VMAT	2GY*33	104.33	67.34	66.1	65.02	64.78	68.86	66.08	61.91	100
	10.	IMRT	2GY*33	104.14	67.3	66.19	65.17	64.96	68.73	66.17	62.16	100
6	11.	VMAT	2GY*33	102.03	65.86	64.86	63.9	63.74	67.31	64.83	61.84	100
	12.	IMRT	2GY*33	102.85	67.14	66.01	64.89	64.71	67.88	65.98	60.61	100
7	13.	VMAT	2GY*33	107.6	68.79	66.82	65.42	65.1	71.01	66.85	60.17	100
	14.	IMRT	2GY*33	105.19	67.98	66.86	65.83	65.62	69.43	66.84	62.79	100
8	15.	VMAT	2GY*33	103.4	67.24	66.01	64.8	64.36	68.3	65.97	60.59	100
	16.	IMRT	2GY*33	102.89	67.22	65.95	64.61	63.99	67.9	65.89	58.96	100
9	17.	VMAT	2GY*33	104.5	67.92	66.68	65.45	65.01	68.99	66.64	61.2	100
	18.	IMRT	2GY*33	103.92	67.9	66.62	65.26	64.64	68.59	66.56	59.56	100
10	19.	VMAT	2GY*33	105.89	67.65	65.11	63.47	63.14	69.89	65.19	57.53	100
	20.	IMRT	2GY*33	102.77	66.77	65.48	64.28	63.89	67.83	65.45	59.07	100
11	21.	VMAT	2.5Gy*28	106.99	71.78	70.9	68.7	68.2	74.81	70.76	56.34	100
	22.	IMRT	2.5Gy*28	106.21	72.91	69.79	67.67	67.15	74.35	69.83	58.04	100
12	23.	VMAT	2.5Gy*28	108.75	73.03	71.29	69.21	68.51	76.12	71.16	56.66	100
	24.	IMRT	2.5Gy*28	105.99	72.9	70.54	68.3	67.77	74.2	70.46	58.8	100
13	25.	VMAT	2.5Gy*28	107.99	72.65	70.87	69.32	68.91	75.59	70.83	59.46	100
	26.	IMRT	2.5Gy*28	106.1	72.57	70.51	68.4	67.9	74.27	70.43	59.18	100

14	27.	VMAT	2.5Gy*28	107.34	71.24	69.53	67.83	67.36	75.14	69.46	58.76	100
	28.	IMRT	2.5Gy*28	105.72	72.5	70.49	68.36	67.84	74.08	70.4	58.7	100
15	29.	VMAT	2.5Gy*28	106.55	72.37	70.61	68.75	68.2	74.58	70.53	59.53	100
	30.	IMRT	2.5Gy*28	106.12	72.44	70.56	68.4	67.91	74.28	70.44	58.08	100
16	31.	VMAT	2.5Gy*28	106.73	72.37	70.75	69	68.49	74.71	70.66	59.48	100
	32.	IMRT	2.5Gy*28	106.51	72.49	70.33	68.2	67.71	74.56	70.25	57.72	100
17	33.	VMAT	2.5Gy*28	106.5	72.61	71.02	69.35	68.85	74.55	70.94	58.16	100
	34.	IMRT	2.5Gy*28	105.33	72.25	70.47	68.32	67.79	73.73	70.35	58.3	100
18	35.	VMAT	2.5Gy*28	108.1	73.92	70.63	68.37	65.17	75.67	70.52	56.61	100
	36.	IMRT	2.5Gy*28	108.9	72.74	69.54	67.38	64.59	76.26	69.47	54.3	100
19	37.	VMAT	2.5Gy*28	107.7	73.07	70.57	68.31	65.56	75.4	70.39	57.61	100
	38.	IMRT	2.5Gy*28	108.2	72.72	70.06	67.79	65.33	75.38	69.96	55.22	100
20	39.	VMAT	2.5Gy*28	105.85	72.03	70.02	68.14	67.24	74.1	69.97	62.26	100
	40.	IMRT	2.5Gy*28	106.09	73.27	71.63	69.4	68.37	74.26	71.52	62.14	100
21	41.	VMAT	2.5Gy*28	107.49	72.86	70.88	69.48	69.21	75.24	70.91	64.56	100
	42.	IMRT	2.5Gy*28	103.96	71.58	70.33	69.18	68.97	72.78	70.3	65.92	100
22	43.	VMAT	2.5Gy*28	104.98	71.52	70.25	69.13	68.92	73.02	70.23	66.02	100
	44.	IMRT	2.5Gy*28	103.33	71.45	70.13	68.91	68.7	72.33	70.1	64.32	100
23	45.	VMAT	2GY*30	108.4	61.71	59.98	57.95	57.4	64.82	59.86	48.73	100
	46.	IMRT	2GY*30	107.64	62.92	60.98	59.08	58.64	64.52	60.88	50.14	100
24	47.	VMAT	2GY*30	107.91	62.07	60.42	58.49	57.97	64.75	60.3	49.96	100
	48.	IMRT	2GY*30	107.41	62.34	59.93	58.14	57.74	64.44	59.89	49.39	100
25	49.	VMAT	2GY*30	107.82	62.01	60.39	58.48	57.98	64.69	60.27	49.93	100
	50.	IMRT	2GY*30	107.21	62.32	60.14	58.39	57.98	64.33	60.07	49.49	100
26	51.	VMAT	2GY*30	106.75	61.4	59.79	57.9	57.42	64.05	59.67	49.44	100
	52.	IMRT	2GY*30	107.38	62.35	60.06	58.36	58.02	64.43	60.03	50.22	100
27	53.	VMAT	2GY*30	107.28	61.7	60.09	58.19	57.69	64.37	59.97	49.68	100
	54.	IMRT	2GY*30	107.88	62.33	60.1	58.29	57.88	64.73	60.04	49.16	100
28	55.	VMAT	2GY*30	103	61.19	60.57	59.53	58.96	61.8	60.48	56.82	100

	56.	IMRT	2GY*30	108	63.54	62.23	59.67	58.37	64.8	62.01	51.27	100
29	57.	VMAT	2GY*30	107.2	62.76	61.71	60.21	58.62	64.32	61.54	53.89	100
	58.	IMRT	2GY*30	108.4	62.79	61.1	58.88	57.24	65.08	60.94	49.02	100
30	59.	VMAT	2GY*30	107.9	62.8	60.21	59.12	57.37	64.78	60.36	52.06	100
	60.	IMRT	2GY*30	108.3	62.46	60.96	59.4	58.42	64.98	60.84	50.06	100
31	61.	VMAT	2GY*30	104.75	61.4	60.09	58.85	58.41	62.85	60.06	54.95	100
	62.	IMRT	2GY*30	104.01	61.21	60.05	58.88	58.28	62.41	60.01	53.88	100
32	63.	VMAT	2GY*30	105.06	61.08	60.1	59.16	58.98	62.68	60.08	56.35	100
	64.	IMRT	2GY*30	103.85	61.31	60.23	59.2	58.98	62.31	60.2	55.46	100
33	65.	VMAT	2GY*30	105.61	61.4	60.17	59.05	58.69	63.36	60.14	55.21	100
	66.	IMRT	2GY*30	103.84	61.41	60.1	58.9	58.32	62.3	60.07	53.71	100
34	67.	VMAT	2GY*30	102	59.3	58.35	57.44	57.26	60.85	58.33	54.7	100
	68.	IMRT	2GY*30	103.51	61.09	60.15	59.16	59.06	62.11	60.11	56.04	100
35	69.	VMAT	2GY*33	106.61	67.99	66.28	64.23	63.64	70.36	66.16	53.03	100
	70.	IMRT	2GY*33	106.87	68.26	66.13	64.53	63.86	70.54	66.12	51.7	100
36	71.	VMAT	2GY*30	105.85	61.6	60.4	58.74	58.15	63.51	60.28	54.75	100
	72.	IMRT	2GY*30	106.51	61.57	60.17	58.84	58.31	63.9	60.13	54.97	100
37	73.	VMAT	2GY*33	107.89	67.45	62.43	56.85	55.16	71.21	62.19	39.1	100
	74.	IMRT	2GY*33	107.81	67.93	62.11	57.23	55.6	71.16	62.32	36.42	100
38	75.	VMAT	2GY*30	101.11	59.35	58.75	57.75	57.19	59.95	58.67	55.11	100
	76.	IMRT	2GY*30	104.74	61.64	60.36	57.88	56.61	62.86	60.15	49.74	100
39	77.	VMAT	2GY*33	103.98	66.87	65.11	63.09	60.69	68.63	64.9	54.08	100
	78.	IMRT	2GY*33	104.55	66.07	64.62	62.81	61.09	69	64.46	51.05	100
40	79.	VMAT	2GY*33	105.29	67.7	66.04	64.52	63.95	69.49	66.01	59.22	100
	80.	IMRT	2GY*33	104.22	67.41	66.07	64.66	63.89	68.78	66.03	58.8	100
41	81.	VMAT	2GY*30	104.75	61.4	60.09	58.85	58.41	62.85	60.06	54.95	100
	82.	IMRT	2GY*30	104.01	61.21	60.05	58.88	58.28	62.41	60.01	53.88	100
42	83.	VMAT	2GY*30	108.42	61.27	59.36	57.62	56.82	65.05	59.3	38.886	100
	84.	IMRT	2GY*30	107.84	62.42	60.31	58,28	57.47	64.7	60.24	36.16	100
43	85.	VMAT	2GY*33	108.53	68.33	66.4	64.57	63.3	71.4	66.28	46.36	100
	86.	IMRT	2GY*33	108.57	67.35	64.97	63.22	62.31	71.65	64.92	47.76	100

Results demonstrated broadly similar dose distributions with VMAT and IMRT for Hotspot dose Dmax, Dmin, Dmean, D2, D50, D95 and D98, with no meaningful difference between techniques, and areas receiving doses of at least 110 percent were restricted to within the therapeutic target volume.

In order to give a thorough analysis of treatment plan efficiency, a further analysis of the treatment plans has been done considering various dosimetric qualities and delivery efficiencies of these two techniques. Alongside target dose volume histograms, factors such as D95%, homogeneity index (HI), conformity index (CI), number of beams, and monitor units (MU) were used to evaluate the capacity of both the methods in effectively treating the targets efficiently. This is crucial owing to the importance that can be attributed to the efficacy of these methods. Thus, it becomes appropriate in comparing the two treatments.

Table 2. Comparative analysis of dose coverage (D95%), plan quality (HI and CI), beam arrangement, and treatment delivery for VMAT and IMRT.

Case	plan	Technology	D95%	HI	CI	Arc/Fields	Reference Points (MU)
1	1.	VMAT	99.81	0.061	1.04	2 full	649
	2.	IMRT	99.76	0.064	1.09	5 fields	1349
2	3.	VMAT	99.82	0.060	1.40	2 full	651
	4.	IMRT	99.96	0.060	1.41	5 fields	1323
3	5.	VMAT	99.8	0.057	1.17	2 full	652.3
	6.	IMRT	99.97	0.060	1.27	5 fields	1466
4	7.	VMAT	99.8	0.056	1.07	2 half	426.1
	8.	IMRT	99.72	0.053	1.06	7 fields	696
5	9.	VMAT	100	0.038	1.15	2 half	431.9
	10.	IMRT	99.99	0.035	1.15	7 fields	726
6	11.	VMAT	99.9	0.032	1.15	2 half	423.5
	12.	IMRT	99.99	0.036	1.12	7 fields	747
7	13.	VMAT	99.98	0.055	1.17	2 half	437.7
	14.	IMRT	100	0.035	1.18	7 fields	733.3
8	15.	VMAT	99.95	0.043	1.09	2 half	432.2
	16.	IMRT	99.76	0.048	1.07	7 fields	732
9	17.	VMAT	99.9	0.043	1.12	2 half	436.6
	18.	IMRT	99.93	0.048	1.109	7 fields	739.4
10	19.	VMAT	99.21	0.069	1.04	2 half	408.4
	20.	IMRT	99.78	0.043	1.07	7 fields	755
11	21.	VMAT	99.47	0.050	1.05	2 full	531.5
	22.	IMRT	99.48	0.082	1.02	5 fields	1548.5
12	23.	VMAT	99.55	0.063	1.26	2 full	555.8
	24.	IMRT	99.89	0.072	1.14	5 fields	1600

13	25.	VMAT	99.85	0.052	1.38	2 full	581.3
	26.	IMRT	99.96	0.066	1.177	5 fields	1710
14	27.	VMAT	99.5	0.055	1.42	2 full	593
	28.	IMRT	99.95	0.066	1.16	5 fields	1703
15	29.	VMAT	99.61	0.059	1.31	2 full	597.5
	30.	IMRT	99.94	0.064	1.42	5 fields	1666
16	31.	VMAT	99.69	0.054	1.27	2 full	626.1
	32.	IMRT	99.9	0.067	1.15	5 fields	1586
17	33.	VMAT	99.78	0.052	1.19	2 full	575.3
	34.	IMRT	99.93	0.063	1.16	5 fields	1692
18	35.	VMAT	97.19	0.123	1.30	2 full	534
	36.	IMRT	96.25	0.117	1.27	9 fields	1520.8
19	37.	VMAT	97.43	0.106	1.32	2 full	697.4
	38.	IMRT	96.9	0.105	1.32	9 fields	1607
20	39.	VMAT	99.21	0.039	1.03	2 half	571.6
	40.	IMRT	99.82	0.068	1.08	7 fields	853.1
21	41.	VMAT	99.99	0.051	1.24	2 half	523.4
	42.	IMRT	99.99	0.037	1.16	7 fields	915
22	43.	VMAT	100	0.037	1.18	2 half	516.2
	44.	IMRT	99.99	0.039	1.12	7 fields	916
23	45.	VMAT	98.97	0.071	1.19	2 full	590
	46.	IMRT	99.93	0.070	1.22	7 fields	1699
24	47.	VMAT	99.59	0.067	1.37	2 full	597.1
	48.	IMRT	99.65	0.076	1.30	7 fields	1638.1
25	49.	VMAT	99.61	0.066	1.37	2 full	598.9
	50.	IMRT	99.8	0.072	1.34	7 fields	1649
26	51.	VMAT	99.07	0.066	1.28	2 full	593
	52.	IMRT	99.87	0.072	1.10	7 fields	1670.2
27	53.	VMAT	99.42	0.066	1.08	2 full	596
	54.	IMRT	99.74	0.074	1.08	7 fields	1635.8
28	55.	VMAT	100	0.036	1.12	2 full	422.4
	56.	IMRT	99.36	0.083	1.22	9 fields	668
29	57.	VMAT	99.31	0.067	1.29	2 full	456.8
	58.	IMRT	98.27	0.091	1.19	9 fields	745.5

30	59.	VMAT	98.33	0.090	1.15	2 full	440
	60.	IMRT	99.28	0.066	1.27	9 fields	923.7
31	61.	VMAT	99.91	0.049	1.19	2 half	429.6
	62.	IMRT	99.85	0.048	1.07	7 fields	696
32	63.	VMAT	100	0.034	1.21	2 half	402.5
	64.	IMRT	99.99	0.038	1.13	7 fields	751
33	65.	VMAT	99.98	0.045	1.14	2 half	402.6
	66.	IMRT	99.83	0.051	1.07	7 fields	741
34	67.	VMAT	99.42	0.034	1.10	2 half	390.8
	68.	IMRT	100	0.033	1.15	7 fields	773
35	69.	VMAT	99.48	0.065	1.10	2 full	642.9
	70.	IMRT	99.6	0.066	1.28	5 field	1311
36	71.	VMAT	99.75	0.057	1.14	2 half	424.5
	72.	IMRT	99.83	0.054	1.16	7 field	883
37	73.	VMAT	96.85	0.196	0.71	2 half	442.1
	74.	IMRT	97.57	0.198	0.70	7 fields	1201
38	75.	VMAT	98.6	0.036	1.14	2 full	409.7
	76.	IMRT	97.3	0.083	1.09	9 fields	648
39	77.	VMAT	95.99	0.094	1.08	2 full	485.9
	78.	IMRT	95.32	0.077	1.09	9 fields	987.3
40	79.	VMAT	99.8	0.056	1.07	2 full	426.1
	80.	IMRT	99.72	0.053	1.06	7 fields	696
41	81.	VMAT	99.91	0.049	1.08	2 half	429.6
	82.	IMRT	99.85	0.048	1.07	7 fields	696
42	83.	VMAT	97.6	0.074	1.05	2 half	606
	84.	IMRT	98.75	0.082	1.04	7 fields	1222
43	85.	VMAT	98.48	0.075	1.18	2 half	521.3
	86.	IMRT	97.11	0.077	1.01	9 fields	1383

Table 3 gives an outline of the comparison between VMAT and IMRT treatment plans regarding the target dose coverage, plan quality, and efficiency in the delivery of treatments. It was shown that both VMAT and IMRT had high levels of dose coverage since the values of D95% exceeded the clinical standard at all prescribed doses. There were no significant differences between the values of D95% for VMAT and IMRT, meaning that both methods ensured the delivery of adequate radiation dose to the PTV.

Similar to that, the Homogeneity Index (HI) and Conformity Index (CI) exhibited very similar values for the two planning methods. The results indicate that both methods were able to generate homogenous dose distribution inside the target volume, achieving high conformity between the isodose distribution of the prescribed dose and the PTV. HI and CI results were identical, implying that the rotational treatment technique employed in VMAT does not adversely affect homogeneity and conformity compared to fixed fields IMRT.

However, in terms of delivery efficiencies, despite having similar coverage and quality parameters, notable disparities were noted between the two modalities. The VMAT treatment plans were delivered with two full and partial arcs, while the IMRT treatment was delivered with five to nine coplanar fields with the use of step-and-shoot technology. Despite making use of lesser numbers of beams compared to IMRT, VMAT was able to deliver comparable dosimetric results.

Among the most important results of the current study, it can be mentioned that a significant reduction of Monitor Units (MU) and delivery reference points was recorded in VMAT treatment planning. Thus, the average reference point was about 500 MU in VMAT versus about 1324 MU in IMRT. This decrease resulted from the difference in dosing principles used by these two methods. So, during the process of beam on-off cycles in IMRT, the radiation dose is delivered using several segmented fields, which requires several times starting and stopping the beam and results in an increase in monitor units needed for delivering the dose.

Notably, the noted decrease in MU does not have any negative impact on the adequacy of target dose coverage, conformality, homogeneity, or hotspot control. The values for D95%, HI, and CI remained consistent despite the significant drop in MU. Such results imply that plan quality depends on the optimization technique and dosimetric profile used and is unrelated to the actual number of MUs delivered.

From the perspective of clinical practice, several benefits might arise due to the decreased MU needs that are characteristic of VMAT. The less complex delivery of treatment often implies a shortened duration of each session, decreased risks of any movements made by patients during the procedure, higher comfort levels of patients, and higher efficiency of treatment delivery. All these aspects are especially important for brain radiotherapy, since the precise immobilization and reproducibility of treatment is crucial for achieving positive results.

In general, the findings of the study show that despite having no statistically significant differences in terms of the accuracy and quality of plans, VMAT still proved to be more effective in delivering treatment due to fewer numbers of arcs and lower MU needs.

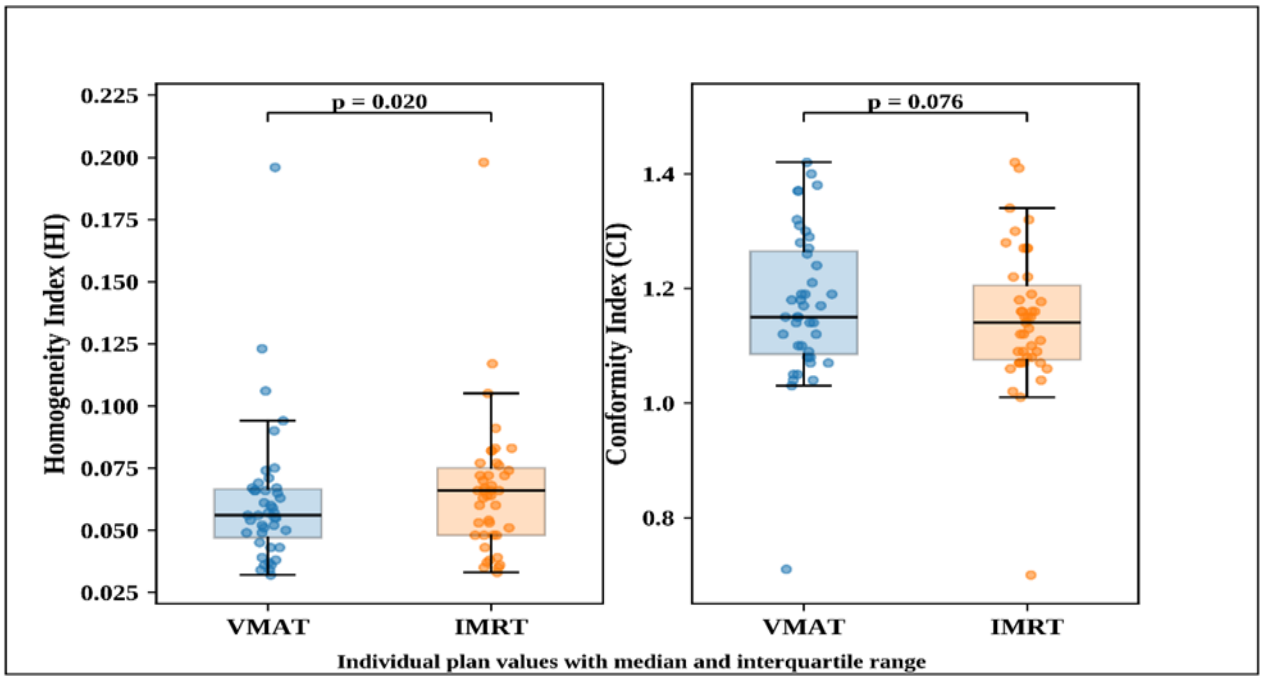

Fig. 4. Distribution comparison of Homogeneity Index (HI) and Conformity Index (CI) between VMAT and IMRT.

VMAT produced a slightly lower Homogeneity Index than IMRT (0.062 ± 0.028 vs 0.066 ± 0.028; p = 0.020), while the Conformity Index was similar between techniques (1.172 ± 0.130 vs 1.148 ± 0.122; p = 0.076). These differences are small and broadly similar plan quality exists, although VMAT shows a slight edge in homogeneity in the paired data.

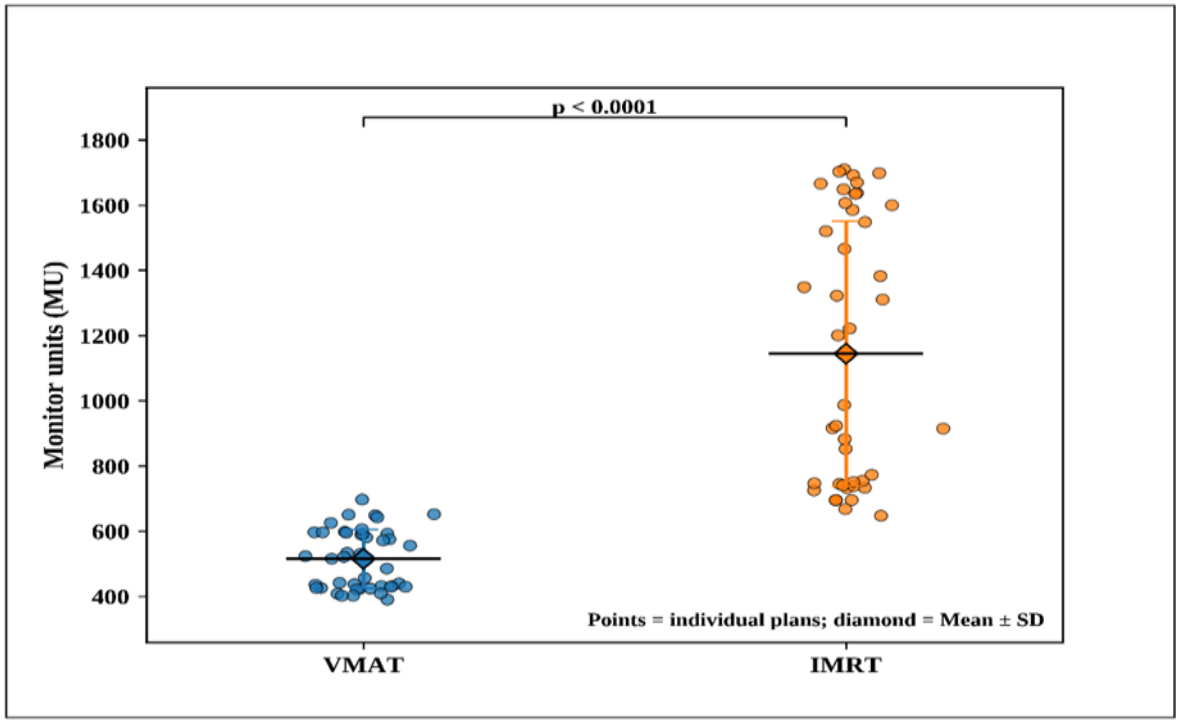

Fig. 5. Column scatter plot comparing monitor units for VMAT and IMRT with Mean ± SD.

VMAT required substantially fewer monitor units than IMRT (515.34 ± 90.49 MU vs 1144.23 ± 406.25 MU). The paired difference was highly significant (p<0.0001, Wilcoxon signed-rank test); it showed a significant delivery-efficiency advantage for VMAT with similar target coverage.

To give a more thorough assessment of the dose distribution not only inside but also outside the PTV, a volumetric dose analysis was conducted according to the criteria for low-dose irradiation. The parameters V5%, V10%, and V20% were analyzed to evaluate the magnitude of the radiation exposure from low- and intermediate doses applied to normal tissues around the target volume. The significance of these parameters lies in their ability to show the amount of dose spreading beyond the treatment target, thus providing additional information on normal tissue protection. Although ensuring complete coverage of the target is considered a priority when planning radiotherapy, sparing normal tissues of excessive radiation at lower doses is also highly desirable. This is why the assessment of V5%, V10%, and V20% provides useful information concerning the effectiveness of dose distribution in VMAT and IMRT. The comparison results are shown in Table 3.

Table 3. Comparative analysis of low- and intermediate-dose exposure indicators (V5%, V10%, and V20%) in VMAT and IMRT.

Case	plan	Technology	V(5%)	V(10%)	V(20%)
1	1.	VMAT	54.11	44.93	31.67
	2.	IMRT	57.62	52.9	42.09
2	3.	VMAT	54.08	44.88	31.64
	4.	IMRT	57.57	52.6	41.95
3	5.	VMAT	54.03	44.82	31.59

	6.	IMRT	57.87	52.72	42.1
4	7.	VMAT	34.56	29.19	18.52
	8.	IMRT	34.47	28.37	19.43
5	9.	VMAT	34.85	29.7	18.8
	10.	IMRT	34.63	28.83	19.97
6	11.	VMAT	34.83	29.74	18.93
	12.	IMRT	34.64	28.82	19.82
7	13.	VMAT	34.84	29.76	18.94
	14.	IMRT	34.67	28.95	20.12
8	15.	VMAT	34.56	29.33	18.46
	16.	IMRT	34.56	28.58	19.49
9	17.	VMAT	34.61	29.46	18.62
	18.	IMRT	34.61	28.72	19.62
10	19.	VMAT	34.11	28.91	18.05
	20.	IMRT	34.35	28.28	19.35
11	21.	VMAT	55.8	46.06	32.45
	22.	IMRT	56.25	49.23	36.35
12	23.	VMAT	55.28	45.29	32.32
	24.	IMRT	56.21	49.39	36.44
13	25.	VMAT	56	47.32	34.22
	26.	IMRT	56.6	50.25	37.33
14	27.	VMAT	55.77	47.25	33.81
	28.	IMRT	56.76	50.54	37.54
15	29.	VMAT	55.25	46.89	33.81
	30.	IMRT	57.1	51.75	38.35
16	31.	VMAT	55.57	47.08	33.81
	32.	IMRT	56.98	51.42	38.1
17	33.	VMAT	55.91	46.3	33.58
	34.	IMRT	56.92	51.21	38
18	35.	VMAT	29.5	25.19	13.69
	36.	IMRT	27.59	22.64	15.48
19	37.	VMAT	29.47	24.96	14.11
	38.	IMRT	27.95	22.95	15.45
20	39.	VMAT	34.19	28.89	17.78

	40.	IMRT	34.01	28.1	19.09
21	41.	VMAT	35.05	29.93	19.34
	42.	IMRT	34.41	28.68	19.75
22	43.	VMAT	34.76	29.47	18.9
	44.	IMRT	34.39	28.54	19.57
23	45.	VMAT	54.22	45.82	33.84
	46.	IMRT	57.15	49.44	37.58
24	47.	VMAT	54.24	45.95	33.97
	48.	IMRT	57.36	49.1	36.88
25	49.	VMAT	54.25	45.93	33.95
	50.	IMRT	57.7	50.63	37.07
26	51.	VMAT	54.16	45.77	33.8
	52.	IMRT	57.43	49.84	36.99
27	53.	VMAT	54.21	45.85	33.88
	54.	IMRT	57.3	49.72	36.85
28	55.	VMAT	30.08	26.04	14.19
	56.	IMRT	28.4	22.49	14.31
29	57.	VMAT	29.4	25.27	13.87
	58.	IMRT	28.2	22.39	14.26
30	59.	VMAT	29.48	25.52	14.46
	60.	IMRT	28.21	22.62	14.33
31	61.	VMAT	34.52	29.36	18.51
	62.	IMRT	34.62	28.57	19.6
32	63.	VMAT	35.06	29.95	19.43
	64.	IMRT	34.37	28.62	19.69
33	65.	VMAT	34.83	29.6	19.05
	66.	IMRT	34.33	28.35	19.33
34	67.	VMAT	34.89	29.62	19.06
	68.	IMRT	34.55	28.78	19.81
35	69.	VMAT	54.22	45.22	33.84
	70.	IMRT	57.64	52.98	42.16
36	71.	VMAT	19.03	15.48	9.58
	72.	IMRT	19.89	16.09	9.23
37	73.	VMAT	27.36	22.31	14.05

	74.	IMRT	28.68	24.18	14.71
38	75.	VMAT	29.93	25.77	13.5
	76.	IMRT	28.21	22.17	13.73
39	77.	VMAT	29.18	24.93	12.83
	78.	IMRT	27.53	22.42	14.51
40	79.	VMAT	34.56	29.19	18.52
	80.	IMRT	34.47	28.37	19.43
41	81.	VMAT	34.52	29.36	18.51
	82.	IMRT	34.62	28.57	19.6
42	83.	VMAT	37.86	32.63	27.47
	84.	IMRT	36.79	32.34	26.88
43	85.	VMAT	38.42	33.46	28.35
	86.	IMRT	37.35	33.38	27.9

The following Table 4 shows the comprehensive and comparative values of V5%, V10%, and V20% for both VMAT and IMRT treatments in terms of low-dose irradiations. It can be observed from the results shown above that the V5%, V10%, and V20% values showed an increase for IMRT compared to VMAT at all prescription doses. This indicated that in IMRT treatment, a large amount of normal tissue got exposed to low and intermediate levels of radiation.

The primary reason behind this higher dose exposure of normal tissue in IMRT can be attributed to the employment of several static fields for dose application in IMRT treatment, leading to increased exposure of dose outside the PTV. In the case of VMAT, the rotational technique allowed dose shaping within the target volume efficiently.

The notable decrease in V5%, V10%, and V20% with the use of VMAT, however, was not related to any decrease in target irradiation. According to D2%, D50%, D95%, D98%, HI, and CI outcomes, VMAT and IMRT provided equally excellent target coverage, which was above 99%. Thus, discrepancies presented in Table 4 can be viewed from the angle of dosimetry efficiency, but not from that of target irradiation capability.

Overall, both approaches proved to be efficient for fulfilling the main purpose of radiation therapy in terms of target coverage. Nonetheless, VMAT proved to have a better low-dose distribution as evidenced by V5%, V10%, and V20% results.

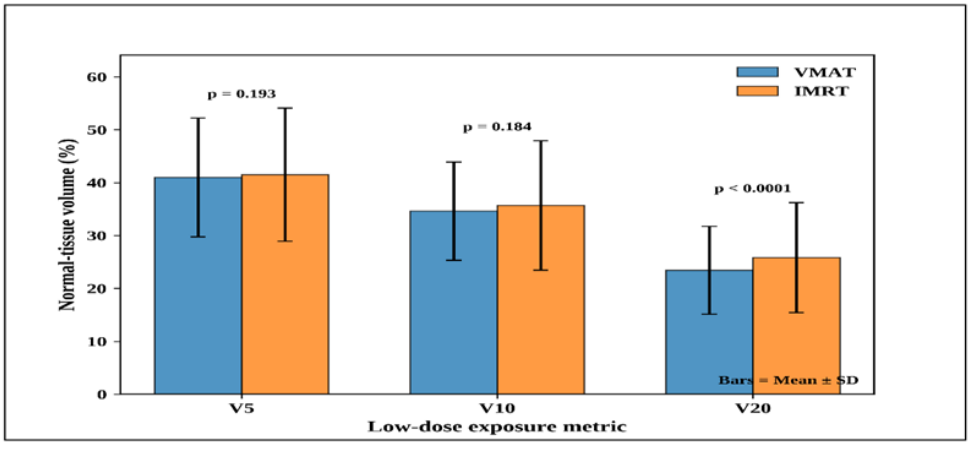

Fig. 6. Grouped mean ± SD comparison of low-dose exposure parameters V5, V10, and V20.

IMRT showed higher mean low-dose exposure than VMAT at all three evaluated thresholds: V5 (41.51% vs 40.97%), V10 (35.69% vs 34.61%), and V20 (25.82% vs 23.43%). The paired recalculation is the one with the clearest separation, at V20 ($p<0.0001$), while the paired recalculation at V5 and V10 did not reach statistical significance ($p = 0.193$ and $p = 0.184$, respectively). The total trend is in favour of VMAT to reduce the low to intermediate dose spread, especially V20.

Other than ensuring that the target area is optimally covered in the planning target volume (PTV), new radiotherapy methods have been devised to ensure that radiation dose is minimized for adjacent normal structures known as organs at risk (OAR). As such, a complete dosimetric analysis of important structures, including the brainstem, cochleae, eyes, lenses, optic nerves, parotid glands, and spinal cords, was done. This choice was based on the clinical importance of these organs and their likelihood of developing radiation-related problems. The purpose of this test was to see if similar radiation doses could be provided while keeping within allowable dose constraints. The OAR dosimetric analysis results for VMAT and IMRT radiotherapy treatments are shown in Table 4.

Table 4. Dosimetry Analysis for VMAT and IMRT Organs-at-Risk

Plan	Technology	Brain Stem	Cochlea L	Cochlea R	Eye L	Eye R	Lens L	Lens R	Optic Nerve L	Optic Nerve R	Parotid L	Parotid R	Spinal Cord
	VMAT	21.44	12.2	7.4	2.83	2.35	1.64	1.62	5.04	5.73	2.47	2.03	19.97
	IMRT	24.57	12.96	10.01	4.22	4.14	3.32	3.25	5.66	10.39	5.74	4.83	24.32
	VMAT	21.41	12.14	7,36	2.82	2.35	1.8	1.77	4.98	5.73	2.47	2.01	19.99
	IMRT	24.52	13.03	9.85	4.15	4.05	3.64	3.27	5.64	8.68	5.69	4.9	24.43
	VMAT	21.32	12.19	7.41	2.85	2.35	1.77	1.73	4.85	5.74	2.45	2	19.95
	IMRT	24.97	13.02	13	4.32	4.03	3.67	3.26	5.54	8.88	5.64	4.9	24.81
	VMAT	2.06	0.64	0.65	2.49	3.04	1.52	1.44	1.62	2.1	0.21	0.22	0.34
	IMRT	1.95	0.68	0.63	2.41	2.76	1.51	1.36	1.67	1.97	0.21	0.23	0.36
	VMAT	2.12	0.66	0.66	2.55	3.19	1.6	1.5	1.74	2.2	0.23	0.23	0.35
	IMRT	2.02	0.7	0.65	2.48	2.8	1.55	1.39	1.72	2.02	0.24	0.22	0.36
	VMAT	2.14	0.67	0.67	2.57	3.15	1.61	1.5	1.77	2.18	0.21	0.22	0.36
	IMRT	2.01	0.69	0.65	2.51	2.79	1.55	1.37	1.71	2.01	0.23	0.25	0.35
	VMAT	2.13	0.68	0.66	2.63	3.23	1.62	1.51	1.73	2.21	0.22	0.23	0.37
	IMRT	2.04	0.71	0.67	2.51	2.83	1.57	1.41	1.74	2.03	0.23	0.24	0.37
	VMAT	2.07	0.64	0.65	2.54	3.1	1.56	1.45	1.67	2.14	0.21	0.23	0.31
	IMRT	1.97	0.68	0.64	2.53	2.77	1.54	1.35	1.68	1.98	0.22	0.22	0.32
	VMAT	2.1	0.65	0.66	2.57	3.13	1.58	1.47	1.69	2.16	0.21	0.24	0.36
	IMRT	1.99	0.69	0.65	2.56	2.8	1.56	1.36	1.7	2	0.23	0.22	0.37
	VMAT	1.99	0.62	0.63	2.21	2.93	1.46	1.4	1.62	2.02	0.2	0.22	0.33

20.	IMRT	1.96	0.67	0.64	2.57	2.73	1.55	1.33	1.66	1.97	0.22	0.23	0.35
21.	VMAT	30.43	8.96	9.9	5.72	5.13	5.6	5.5	7.48	7.48	2.62	4.1	20.99
22.	IMRT	25.33	8.75	10.15	4.16	5.09	2.44	2.9	5.11	11.22	4.7	4.37	22.96
23.	VMAT	32.41	10.35	12.5	7.4	6.96	6.4	5.3	7.4	6.96	2.29	2.93	24.87
24.	IMRT	25.74	8.79	10.2	3.88	5.45	2.42	2.95	5.21	11.22	4.76	4.49	23.18
25.	VMAT	36.13	8.5	10.47	7.23	4.23	3.01	2.5	8.77	8.01	3.15	3.65	29.04
26.	IMRT	27.35	10.28	12.57	5.35	6.67	2.63	3.22	5.72	11.77	4.72	4.65	23.21
27.	VMAT	32.22	11.77	13.1	6.99	4.43	5.3	4.7	9.66	7.61	2.94	2.87	24.47
28.	IMRT	28.27	10.82	13.23	5.81	7.31	2.77	3.32	5.95	11.45	4.79	4.58	23.35
29.	VMAT	31.54	11.75	12.6	7.23	4.78	6.4	4.2	9.48	8.27	3.01	3.54	11.26
30.	IMRT	30.75	13.13	16.28	7.77	9.85	3.84	4.05	8.76	20.6	4.77	4.61	23.08
31.	VMAT	31.89	11.76	13.1	7.03	3.92	6.4	4	9.14	6.91	2.96	3.04	24.58
32.	IMRT	30.44	13.26	15.77	8.06	8.78	3.68	4.04	9.16	11.9	4.6	4.59	22.89
33.	VMAT	35.04	13.4	12.7	6.32	4.14	5.6	4.3	8.35	7.06	2.84	3.63	25.71
34.	IMRT	29.53	12.63	15.25	7.3	7.59	3.15	3.59	7.46	10.44	4.79	4.67	24.06
35.	VMAT	54.2	33.99	36.83	1	1.02	0.59	0.58	1.03	1.11	7.07	8.81	8.07
36.	IMRT	54.1	29.25	26.61	1.1	1.13	0.62	0.63	1.09	1.17	7.87	5.81	6.65
37.	VMAT	54.6	34.18	37.29	0.9	1.03	0.59	0.6	1.05	1.14	6.19	9.24	8.79
38.	IMRT	54	31.62	29:57:00	1.09	1.08	0.61	0.6	1.09	1.16	7.71	7.01	6.7
39.	VMAT	2.11	0.65	0.66	2.34	2.93	1.56	1.43	1.62	2.06	0.21	0.23	0.35
40.	IMRT	2.03	0.71	0.67	2.46	2.75	1.59	1.39	1.74	2.03	0.23	0.24	0.36
41.	VMAT	2.31	0.74	0.72	2.8	3.54	1.75	1.63	1.87	2.4	0.24	0.25	0.38
42.	IMRT	2.12	0.73	0.69	2.56	2.87	1.65	1.45	1.81	2.11	0.24	0.23	0.38
43.	VMAT	2.26	0.72	0.7	2.78	3.43	1.72	1.58	1.83	2.34	0.24	0.24	0.37
44.	IMRT	2.1	0.72	0.69	2.6	2.88	1.64	1.43	1.79	2.09	0.24	0.25	0.37
45.	VMAT	21.48	13.89	9.1	2.83	2.11	1.6	1.29	5.41	3.42	2.29	2.38	20.55
46.	IMRT	25	13.44	14.55	3.6	3.31	2.97	2.66	9.01	5.9	4.96	3.97	18.05
47.	VMAT	21.62	13.91	9.05	2.88	2.13	2.07	1.64	5.6	3.45	2.29	2.36	20.19

48.	IMRT	25.97	13.1	14.38	4.48	3.35	3.24	2.88	9.22	5.63	4.76	3.86	17.49
49.	VMAT	21.61	13.91	8.94	2.85	2.13	2.06	1.62	5.64	3.44	2.28	2.35	20.22
50.	IMRT	26.94	14.89	15.52	6.23	5.38	4.57	4.38	12.87	10.3	4.79	3.88	17.59
51.	VMAT	21.4	13.77	8.85	2.82	2.11	2.04	1.61	5.58	3.41	2.26	2.33	20.02
52.	IMRT	24.5	14.23	15.79	4.54	3.49	3.46	2.81	9.35	5.81	4.78	3.88	17.72
53.	VMAT	21.5	13.84	8.89	2.83	2.12	2.04	1.62	5.61	3.43	2.27	2.34	20.12
54.	IMRT	24.25	14.72	14.03	4.7	3.58	3.26	2.98	9.33	5.71	4.8	3.77	17.45
55.	VMAT	54	32.52	35.25	0.84	0.88	0.51	0.52	0.91	0.99	5.33	8.08	7.72
56.	IMRT	52.55	25.94	24.57	0.81	0.87	0.46	0.47	0.84	0.9	4.74	6.57	6.1
57.	VMAT	52.92	28.8	34.18	0.86	0.87	0.51	0.52	0.89	0.97	5.59	7.81	6.43
58.	IMRT	50.44	25.72	24.26	0.83	0.88	0.47	0.48	0.85	0.9	4.73	6.7	5.76
59.	VMAT	52.05	28.87	34.93	0.87	0.9	0.53	0.54	0.91	1	5.59	7.78	6.12
60.	IMRT	53.6	27.22	24.31	0.88	0.93	0.49	0.5	0.9	0.97	4.76	6.59	6.04
61.	VMAT	1.88	0.58	0.6	2.24	2.85	1.38	1.29	1.48	1.9	0.19	0.2	0.31
62.	IMRT	1.8	0.62	0.58	2.23	2.56	1.38	1.25	1.54	1.81	0.2	0.21	0.32
63.	VMAT	2.03	0.63	0.62	2.55	3.09	1.52	1.4	1.62	2.06	0.21	0.22	0.33
64.	IMRT	1.81	0.63	0.59	2.18	2.43	1.4	1.22	1.54	1.79	0.2	0.21	0.32
65.	VMAT	1.96	0.61	0.6	2.48	3.02	1.47	1.36	1.56	2.01	0.2	0.21	0.31
66.	IMRT	1.77	0.61	0.58	2.21	2.45	1.38	1.21	1.51	1.77	0.2	0.21	0.32
67.	VMAT	1.97	0.62	0.6	2.47	3	1.47	1.36	1.57	2	0.2	0.21	0.32
68.	IMRT	1.82	0.63	0.59	2.24	2.49	1.42	1.25	1.56	1.82	0.21	0.2	0.32
69.	VMAT	21.28	12.48	12.12	2.67	2.32	2.12	2.11	7.54	5.43	2.44	2.02	20
70.	IMRT	24.9	13.07	12.98	4.27	4.12	4.06	4.32	9.23	7.15	5.71	4.92	24.86
71.	VMAT	4.54	3.47	2.72	4.16	3.83	1.41	1.72	1.19	1.19	0.21	0.24	5.56
72.	IMRT	6.73	5.83	5.52	5.25	4.62	1.36	1.57	1.16	1.27	0.31	0.34	5.87
73.	VMAT	7.65	5.84	3.87	2.35	2.25	1.14	0.87	2.21	1.92	18.9	5.99	33.86
74.	IMRT	13.72	11.25	13.68	2.81	2.3	1.31	0.96	2.43	2.12	19.94	9.72	39:55:00
75.	VMAT	54.87	31.54	34.19	0.82	0.86	0.5	0.51	0.88	0.96	5.17	7.84	7.49

76.	IMRT	50.98	25.16	23.83	0.79	0.85	0.45	0.46	0.82	0.87	4.6	6.37	5.91
77.	VMAT	54.93	27.2	31.14	0.91	0.93	0.55	0.54	0.93	1.02	5.23	6.83	6.69
78.	IMRT	54.93	27.29	24.88	0.95	0.98	0.53	0.54	0.96	1.03	5.8	6.5	6.27
79.	VMAT	2.06	0.65	0.66	2.49	3.04	1.52	1.44	1.62	2.1	0.21	0.22	0.34
80.	IMRT	1.95	0.63	0.62	2.41	2.76	1.51	1.36	1.67	1.97	0.22	0.23	0.35
81.	VMAT	1.88	0.59	0.62	2.24	2.85	1.38	1.29	1.48	1.9	0.19	0.2	0.31
82.	IMRT	1.8	0.63	0.59	2.23	2.56	1.38	1.25	1.54	1.81	0.19	0.2	0.32
83.	VMAT	50.97	4.44	6.03	12.34	12.9	4.91	3.94	29.99	13.85	1.31	1.3	1.71
84.	IMRT	51.97	4.56	6.45	13.01	12.6	5.21	4.01	30.01	14.21	1.37	1.7	1.75
85.	VMAT	31.02	8.84	9.21	5.5	5.7	5.2	3.94	7.65	7.63	2.72	2.73	20.2

It was showed that both VMAT and IMRT could effectively maintain the radiation dose for all organs at risk within clinical acceptable levels. None of the organs exceeded the set planning criteria, which indicated that both treatments were effective in delivering adequate irradiation to the targeted areas while minimizing risks to the surrounding normal tissues. It can be concluded that the treatment plans developed in this study were indeed satisfactory from a clinical perspective.

In regards to the dose sparing to two of the most important and dose limiting structures during brain radiotherapy, namely brain stem and spinal cord, the results indicated that both methods yielded satisfactory sparing. The same is true for the optic nerves, eyeballs, and lenses. This indicates that both planning methods are able to deliver doses while minimizing risks to vision structures, even though their anatomical location places them close to the tumor site. It should also be noted that the cochlea and the parotid glands also received satisfactory doses.

While there were minor discrepancies between plans generated by VMAT and IMRT for individual patients, no pattern of consistent superiority could be established in favor of either one over the other in protecting critical organs. These discrepancies can be explained by the anatomical variability, target shape, and positional correlation between the PTV and surrounding structures in the planning process, not inherent inadequacy of any specific treatment-planning technique.

The ability of both VMAT and IMRT plans to produce treatment plans where the target area is properly exposed to radiation while OARs were protected. Thus, the adequacy of target radiation combined with low OAR doses proves the efficacy of the two planning methods in producing optimal results. Consequently, the findings demonstrate similar abilities of VMAT and IMRT to preserve normal tissues during radiotherapy.

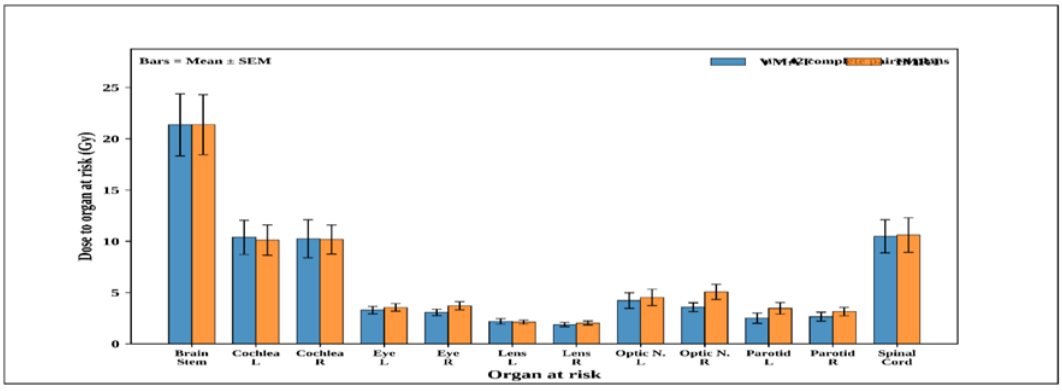

Fig. 7. Clustered vertical bar comparison of organ-at-risk doses between VMAT and IMRT (Mean ± SEM).

Most dose differences between the OARs were near the zero, showing no consistent overall advantages of either technique. The biggest reductions with VMAT were seen for the right ON, right parotid and left parotid, but the differences for the brainstem, cochleae, eyes lenses and left ON and spinal cord were generally small.

In order to augment the numerical analysis with graphs, D2%, D50%, D95%, and D98% values were plotted graphically, providing a visual presentation of differences in target dose distribution among VMAT and IMRT patients. It is generally acknowledged that these indices play an important role as critical metrics of target coverage and dose uniformity, reflecting on both high-dose areas and PTV coverage. Visual presentation allows gaining additional insight into comparing the two techniques in question, as well as showing the differences between individual patients included in the study group. The comprehensive and comparative distribution of these dosimetric indices is illustrated below in the figures.

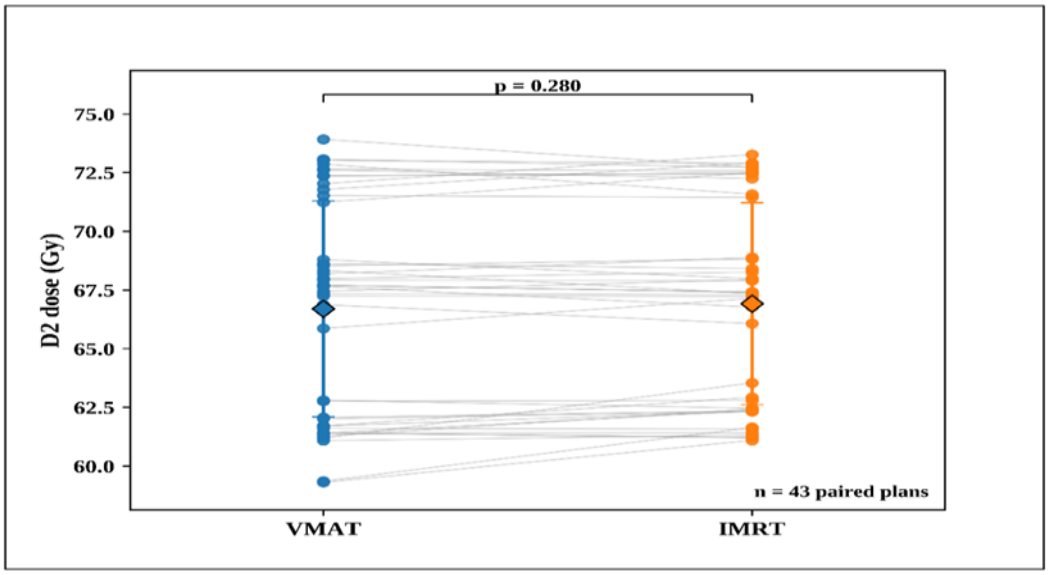

Fig. 8. Paired before-after plot of D2% values for VMAT and IMRT treatment plans.

It was observed that the paired comparison revealed very similar D2 value for VMAT and IMRT (66.70 ± 4.60 Gy vs 66.92 ± 4.30 Gy, respectively). This difference was not statistically significant (p = 0.280, Wilcoxon signed rank test), and so the target-dose performance of this index was comparable between the two techniques.

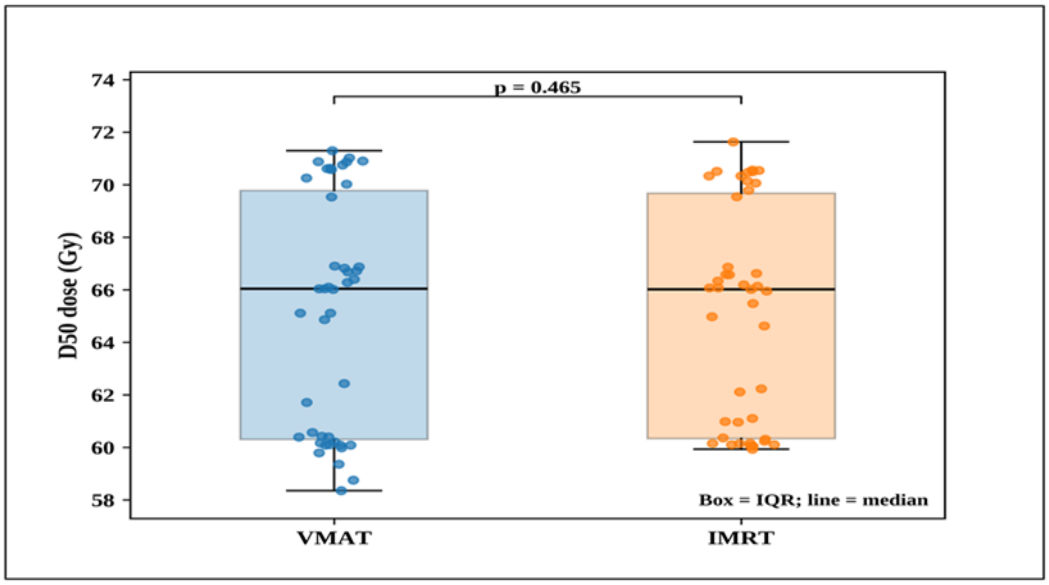

Fig. 9. Box-and-whisker distribution of D50% values for VMAT and IMRT treatment plans.

Very similar D50 values for VMAT as compared to IMRT (65.03 ± 4.40 Gy vs 65.07 ± 4.13 Gy, respectively) were obtained during the paired comparison. There was no significant difference (p = 0.465; Wilcoxon signed-rank test) between the two techniques, suggesting that the target-dose performance of this index is similar between the two.

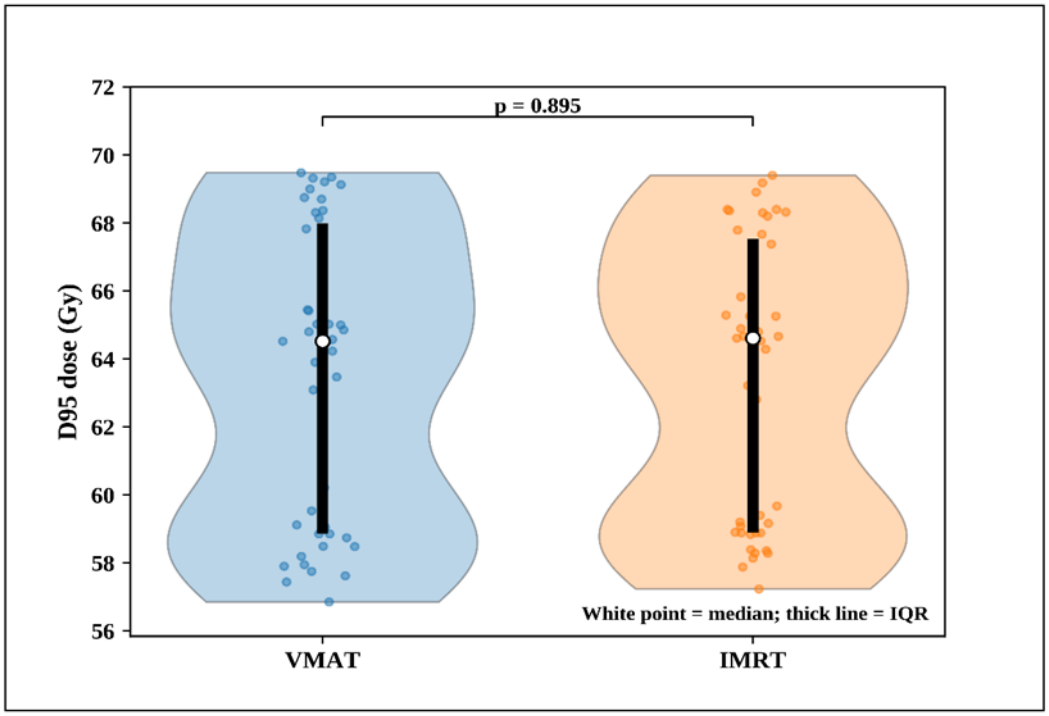

Fig. 10. Violin distribution plot of D95% values for VMAT and IMRT treatment plans.

The paired comparison showed a very similar D95 value of 63.34 ± 4.37 Gy for VMAT and 63.33 ± 4.13 Gy for IMRT with p = 0.895 indicating that the target dose coverage was similar between the two techniques for D95.

Fig. 11. Violin distribution plot of D98% values for VMAT and IMRT treatment plans.

The paired comparison revealed almost the same D98 values of VMAT and IMRT (62.61 ± 4.37 Gy and 62.60 ± 4.18 Gy, respectively). This difference was not statistically significant (p = 0.968; paired t-test), which shows that there is no statistically significant difference between the target-dose performance of this index for the two techniques.

3.2 Discussion

Paired statistical analyses were performed for the dosimetric parameters D2 D50 D95 D98 MU V5 V10 and V20 After evaluation of the normality of the paired difference, the statistical test was chosen according to the Cohen's dz for paired design was used to estimate the effect sizes.

Table 5. Comparative analysis of target coverage, low-dose irradiation, and delivery characteristics of VMAT and IMRT treatment plans.

Parameter	VMAT Mean±SD (GY)	IMRT Mean±SD (GY)	p-value	Cohen's dz	Effect
D2	66.70 ± 4.60	66.92 ± 4.30	0.280	-0.262	Small
D50	65.03 ± 4.40	65.07 ± 4.13	0.465	-0.052	Negligible
D95	63.34 ± 4.37	63.33 ± 4.13	0.895	0.020	Negligible
D98	62.61 ± 4.37	62.60 ± 4.18	0.968	0.006	Negligible
MU	515.34 ± 90.49	1144.23 ± 406.25	<0.0001	-1.884	Large

V5%	40.97 ± 11.24	41.51 ± 12.59	0.193	-0.320	Small
V10%	34.61 ± 9.28	35.69 ± 12.22	0.184	-0.323	Small
V20%	23.43 ± 8.29	25.82 ± 10.41	<0.0001	-0.839	Large

No statistically significant differences were found for D2 D50 D95 and D98 The paired effect size was small for D2 and negligible for D50 D95 and D98 indicating that target dose coverage was highly comparable between VMAT and IMRT.

Higher mean values were obtained for IMRT for V5 V10 and V20, but the paired differences for V5 and V10 were not significant; V20 was statistically significant ($p < 0.0001$) which was indicative of a definite decrease in intermediate dose spread with VMAT.

It is possible to explain the decrease in V5%, V10%, and V20% with VMAT based on the properties of rotational delivery. By continuously varying the gantry angle, dose rate, and multileaf collimator positions during treatment delivery, VMAT delivered very conformal radiation doses, minimizing unnecessary radiation dose to surrounding areas outside the treatment volume. As a result, VMAT could deliver comparable target coverage while lowering low-dose radiation exposure to nearby healthy tissue.

This represents a large paired effect size with a highly significant paired difference ($p< 0.0001$) showing a strong delivery efficiency advantage for VMAT (mean 515.34 ± 90.49 MU) compared to IMRT (mean 1144.23 ± 406.25 MU).

Clinically the much reduced monitor unit requirement with VMAT suggests greater delivery efficiency Target dose indices were similar between techniques, whereas V20 was significantly lower with VMAT, and V5 and V10 showed significant but non significant trends in favor of VMAT. The main advantage observed with VMAT was delivery efficiency and reduced intermediate dose exposure rather than superior target coverage.

4. CONCLUSION

Based on the findings of the current study, it is possible to state that the utilization of Volumetric Modulated Arc Therapy (VMAT) and Intensity-Modulated Radiation Therapy (IMRT) is a very efficient way to treat brain tumors by using radiotherapy, since both types of treatments are able to provide highly acceptable treatment plans with excellent coverage of target volumes and proper protection of organs-at-risk.

From the perspective of statistical evaluation, it is important to note that no statistically significant difference was found between VMAT and IMRT in terms of the main indicators of target coverage, including D2%, D50%, D95% and D98%. Likewise, when comparing the levels of conformity and homogeneity between the two approaches, only minor differences were observed.

Although both techniques demonstrated similar target coverage and plan quality characteristics, VMAT was able to deliver the plan with significantly fewer monitor units and a significantly lower V20 and numerically lower but not statistically significant V5 and V10.

Finally, VMAT and IMRT exhibited broadly similar dosimetric performance for target dose delivery and OAR sparing, with the primary difference being that related to treatment delivery and low dose exposure. Both techniques are suitable for brain tumor radiotherapy and VMAT also demonstrated lower monitor unit requirements and a more favorable low dose distribution in the evaluated parameters.

To conclude, the selection of either VMAT or IMRT for the planning process is best determined based on the above criteria and not by preconceived notions of significant disparity in terms of tumor coverage, as neither technique outperformed the other in achieving optimal radiotherapy treatment plans.

ABBREVIATIONS

D2%	dose received by 2% of the PTV	RT	Radiation therapy
D50%	dose received by 50% of the PTV	VMAT	volumetric modulated arc radiotherapy
D95%	dose received by 95% of the PTV	IMRT	Intensity-modulated radiotherapy

D98%	dose received by 98% of the PTV	V95cm³	volume of the planning target volume receiving at least 95% of the prescribed dose
Dmax (Gy)	maximum dose within the evaluated volume	V5%	body volume receiving ≥5% of the prescribed dose
Dmean (Gy)	mean dose within the evaluated volume	V10%	body volume receiving ≥10% of the prescribed dose
Dmin (Gy):	minimum dose within the evaluated volume	V20%	body volume receiving ≥20% of the prescribed dose.
OARs	organs at risk	MU	monitor units

AUTHOR CONTRIBUTIONS

Abbood Abbas Abbood: Writing—Review & Editing, Methodology, Data Curation, Formal Analysis

Ahmad Lutfi Yusoff: Supervision, Writing—Review & Editing.

Norazlina Binti Mat Nawi: Methodology.

Hayday Hamza Alabedi: Data Curation, Formal Analysis.

Ibrahim H. Alnidawi: Conceptualization, Investigation.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

STATEMENT OF ETHICS

This retrospective study was approved by the Jawatankuasa Etika Penyelidikan Manusia USM (JEPeM) (Approval No. USM/JEPeM/KK/25070657). The study also received approval from the Ministry of Health of Iraq, Diyala Health Directorate, Training and Human Development Center, Research Management Unit (Ref. No. 24316; Date: 10 July 2025).

FUNDING

None declared.

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