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Non Coplanar Versus Coplanar VMAT Techniques for Pituitary Adenoma Radiotherapy

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Abstract. This paper aims to investigate the dosimetric performance of two volumes of interest (VOIs) treated using coplanar as well as noncoplanar VMAT (volumetricmodulated arc therapy) in pituitary adenoma treatment. Fifteen patient cases were retrospectively studied with coplanar and noncoplanar VMAT plans generated. Dosimetric analysis concentrated on planning target volume (PTV) coverage and OAR sparing. The average dose to the PTV was 50.17Gy in coplanar plans and 50.20Gy in noncoplanar plans, demonstrating similar PTV coverage. Nevertheless, noncoplanar VMAT appeared to have a better conformity, with D95% achieving a maximum of 98.71% versus a maximum of 97.78% for coplanar. In OAR sparing, noncoplanar VMAT resulted in a significant decrease in the mean dose delivered to the right eye (8.56Gy vs 14.27Gy) and left eye (10.33Gy vs 12.32Gy). The mean dosimetric exposure was also lower in the left optic nerve for noncoplanar plans (26.57 vs 28.95). Notwithstanding, the highest brainstem dose increased marginally in noncoplanar plans (53.88 Gy versus 52.20 Gy); however, all dosimetric factors values still fell well within acceptable clinical constraints. These results indicated that noncoplanar VMAT techniques provide greater OAR-sparing capability with similar target dose coverage, which may support their clinical application for centrally located intracranial tumors, such as pituitary adenomas.

Highlights:

1. The prevalence of irritable bowel syndrome among Iraqi university students was 27.5%, with a higher rate in females than males.
2. A significant association was found between IBS and anxiety, suggesting psychological factors play a major role.
3. Lifestyle factors, including dietary habits and stress, were identified as key contributors to IBS prevalence.

Keywords: Pituitary adenoma, Volumetric-modulated arc therapy (VMAT), Coplanar VMAT, Noncoplanar VMAT, Organs at risk (OAR), Dose distribution, Conformity index, Radiation therapy planning, Dosimetric comparison, Target volume coverage

Introduction

Pituitary adenoma is one of the most frequent intracranial tumors, its treatment with radiation therapy should be highly precisive and conformal to the chiasm, hypothalamus and

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hippocampus. Volumetric Modulated Arc Therapy (VMAT) is a very efficient radiotherapy approach that provides enhanced dose conformity and shortened treatment time relative to conventional IMRT. VMAT is conventionally planned with coplanar beams by using arcs (coVMAT) that restricts beam angles only to the coronal plane, possibly compromising dose coverage in complex anatomy. In order to address this problem, we have developed the noncoplanar VMAT (ncVMAT) method for which beams are delivered through the target from multiple planes with the couch rotation. The latter technique allows further improvement of dose sculpting around OARs and appeared to be very effective in protecting sensitive brain structures, even in patients with tumors located next to the skull base. Some recent reports indicate that ncVMAT could result in better organ sparing than IMRT, particularly for hippocampus and optic apparatus, while maintaining the same target coverage. To compare the dosimetric performance of noncoplanar and coplanar VMAT techniques for the treatment of pituitary adenomas, particularly with regard to PTV coverage, dose homogeneity, conformity, and sparing of surrounding OARs. With assessment of these parameters, the study attempts to establish whether the technical effort and increased time of ncVMAT may be justified by the clinical gain in treatment of pituitary adenomas.

Hirashima et al. (2018) [1] further studied Volumetric-modulated Dynamic WaveArc therapy (VMDWAT) for prostate and skull base tumors. With logfile-based analysis, MLC position, gantry and dose delivery mechanical errors were found to be small only [<0.1 mm/°/MU]. This study demonstrated that VMDWAT (an nc-VMAT technique) kept the dosimetric accuracy from planning to treatment, indicative of its robustness and safety. Xiong et al. (2025) [2] evaluated HyperArc (HA; a non-coplanar automated VMAT) versus the conventional coplanar VMAT (c-VMAT). With respect to ON SMs, after application of HA, the following was accomplished ,Higher D98%, Reduction of maximum dose to lenses, hippocampi and optic nerves, Improved conformity and homogeneity indices, Results were in favor of nc-VMAT for complex head regions because of higher OAR sparing. Chae et al. (2016) [3] in IMRT and VMAT both, investigated the impact of the MLC width (2.5 mm vs. 5 mm). Although some degree of benefit in adherence was observed with smaller MLCs, particularly for simpler plans, this dosimetric benefit did decrease with plan complexity (e.g., arc count). This suggests that the addition of nc-VMAT could replace high level c-VMAT in some anatomical situations. Cheung et al. (2022) [4] have reported that Dual-Planar and Multi-Planar VMAT offer significantly reduced hypothalamic, pituitary, chiasmal and hippocampal doses relative to c-VMAT. In particular, the 2 cm's dosimetric advantages were largest for OARs <4 cm from target. Therefore from a theoretical point of view nc-VMAT should be of particular relevance to patients with gliomas in close proximity to surrounding radiosensitive midline structures. Hayward (2021) [5] provided a direct 3-way comparison between HT, c-VMAT, and nc-VMAT. All met planning criteria, but nc-VMAT provided better sparing of lens and optic nerve than Tomotherapy and similar conformity with c-VMAT. The study found nc-VMAT was a fair balance between treatment time and plan quality. Uto et al. (2017) [6] demonstrated that VMDWAT non-coplanar significantly decrease H-hipp octagon EQD2 values compared to cVMAT (5.31 Gy vs. 9.90 Gy). Although VMDWAT had a somewhat longer delivery time and a greater low-dose volume, VMDWAT was judged to be better for the preservation of cognition.

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Ventura et al. (2021) [7] employed automatic BAO (Beam Angle Optimization), and ATO (Arc Trajectory Optimization). The conformality and PTV coverage was better with ATO than with conventional clinical and c-VMAT plans, and the OAR sparing was better with BAO than ATO. These techniques are promising for clinical normalization of nc-VMAT plans. Balik et al. (2018) [8] also found nc-VMAT (3 non-coplanar arcs) and Gamma Knife to be equivalent for pituitary adenomas. VMAT achieved similar conformity and OAR doses (optic nerve, brainstem) but with meaningfully lower treatment time (5 vs. 68 min), demonstrating the practical advantages of nc-VMAT. Hirashima et al. (2019) [9] proposed CCR-VMAT (continuous couch rotation and VMAT) which integrates the continuous rotation of the couch with beam delivery. They reported good mechanical precision (errors ≤0.04°/0.02 mm) and dosimetric accuracy (gamma pass ≥98%). CCR-VMAT.TecFrom this point of view, ccr-vmat proved to be technically feasible for an advanced nc-vmat on a standard linac. Chen et al. (2017) [10] analyzed c-VMAT, 4π nc-IMRT, and IMPT in a pediatric parameningeal rhabdomyosarcoma. The OAR sparing (lens, retina, lacrimal gland) was best in IMPT and 4π nc-planning, all techniques provided excellent target coverage and preservation of 3YLC; IMPT displayed the best long-term side-effect profile. This is a rationale for nc-VMAT in children who do not have access to protons. Cheung et al. (2021) [11] confirmed the marked reduction in radiation dose to the hippocampus, cochleae and temporal lobes in postoperative brain tumour patient using NC-VMAT, without compromising PTV coverage. There is significant dose reduction for contralateral hippocampus (−1.67 Gy) and cochleae (−5.34 Gy) which suggest the neuroprotective benefit of the technique.

Panet-Raymond et al. (2012) [12] analyzed 4 different planning techniques in high-grade glioma patients of fronthal-temporal region. They reported that all plans demonstrated similar PTV coverage; however, NC-IMRT and NC-VMAT achieved better protection of the contralateral retina and optic apparatus, at the cost of longer delivery times. VMAT delivered a lower MUs than IMRT; however, NC-VMAT had a longer optimization time. Limpichotikul et al. (2019) [13] worked on pituitary adenomas and considered the optimal couch angles and arc numbers in NC-VMAT. They demonstrated that non-coplanar arrangements with 4 arcs and couch angles close to 30°–90° and 270°–330° achieved better OARs sparing with comparable PTV coverage that can hit a trade-off point between plan quality and delivery technique. Zeng et al. (2025) [14] in hippocampus avoidance whole-brain radiotherapy with simultaneous integrated boost (HA-WBRT+SIB) using NC-VMAT and non-coplanar IMRT. The two plans were clinically equivalent, in which VMAT had better conformity and radiation delivery and IMRT had better hippocampus sparing with less MUs required. Zhang et al. (2019) [15] that compared NC-VMAT with C-VMAT in brain metastases (which lesions are often close to critical organ) NC-VMAT showed better CI and significantly reduced Dmax to the optic chiasm and temporal lobes. Noel et al. also aimed at OAR sparing. (2016) [16] that employed a KBP model. Their study demonstrated more favorable dosimetric values in NC-VMAT plans resulting in lower doses received in the OAR, such as hippocampus and temporal lobes. Yom et al. (2015) [17] that NC-VMAT resulted in improved dose homogeneity and conformity in complex cranial targets for the application in stereotactic setting but at the expense of more planning complexity and time. Han et al. (2017) [18] optimized trajectories for NC-VMAT for multiple brain metastases. Better dose falloff and conformity were obtained with more sparing of high-dose exposure to the normal

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brain. Rossi et al. (2018) [19] studied NC-VMAT and C-VMAT techniques for skull base tumors. They demonstrated that NC-VMAT resulted in less dose to the optic apparatus and brainstem with the later having higher PTV coverage. Park et al. (2018) [20] used two-arc VMAT with and without non-coplanar geometry in the postoperative resection cavity treatment. The non-coplanar plans showed better dose gradients and windows of spared normal brain tissue.

Uto et al. (2016) [21] performed a comparative planning study of three different planning approaches (DCAT, coVMAT, ncVMAT) in craniopharyngioma patients by comparing dosimetric distributions. Their first priority was to evaluate the dose to the right and left hippocampus, with appropriate target volumes receiving coverage and dose to any additional OARs being minimized. The study provided that ncVMAT minimised the equivalent dose to 40% of the hippocampal volume (EQD2(40%hippo)) to 6.5 Gy, in comparison with the DCAT and coVMAT. This decrease steps down the dose below that of 7.3 Gy which has been associated with cognitive impairment as previously proposed by Gondi et al. The authors reported ncVMAT provided improved homogeneity and hippocampal sparing while maintaining the dose coverage to a PTV site and more OARs dose escalation. Consistent with these results, Ma et al. (2020) [22] investigated HS dose constraints over 52 intracranial tumor patients. The study compared coplanar and non-coplanar VMAT for different optimization techniques, with special focus on multiple-arc optimization for better hippocampal spare. Their study showed that multi-arc ncVMAT resulted in the most hippocampal sparing, with acceptable conformity and homogeneity. The latter authors also highlighted the balance between plan complexity and delivery efficiency, with higher complexity and longer delivery times being necessary on account of the benefits of ncVMAT, which could lead to more complex planning.

Methodology

This study was conducted to retrospectively compare dosimetric and clinical efficacy of coplanar vs non-coplanar Volumetric-Modulated Arc Therapy (VMAT) for pituitary adenoma patients. Fifteen pituitary adenoma patients were included according to treatment history. The issue addressed was the accuracy of target volume coverage and critical structure sparing for both VMAT techniques.

3.1 Imaging and Contouring

All patients were simulated with a high resolution contrast CT simulation before the treatment planning. The patients were in the supine position, and a thermoplastic head mask was used for the immobilization so as to minimize the movement and ensure reproducibility. Images were generated with slice thickness of 2–3 mm so that the pituitary gland and locally adjacent anatomical structures were completely visualized from the vertex to the mid-neck (for position assessment). These CT data sets were subsequently transferred to the treatment planning system (TPS) for contouring.

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Tumor delineation was performed by a radiation oncologist, using clinical scans (CT and where available fused MRI) to define the GTV (Gross Tumor Volume). The CTV was created by the expansion of the GTV to compensate for microscopic disease spread, anatomic variability, and the daily set up error. Another uniform margin was generated to take the CTV to PTV, to compensate for small errors in patient positioning and movement during treatment.

A total radiation dose of 50 Gy/25 was prescribed to the PTV, and the goal was to cover at least 95% of the prescribed dose to PTV according to International Commission on Radiation Units and Measurements (ICRU) recommendations. This meticulous imaging and contouring practice provides the basis for the precise dose planning, with the purpose to achieve the best tumor coverage while sparing normal tissues.

3.2 Contouring of Organs at Risk (OAR)

Exact localization and contouring of Organs at Risk (OARs) were drawn onto patients' Ct dataset in order to minimize the risk of radiation toxicity. The major OARs analyzed in this study were brainstem, optic chiasm, right and left optic nerves, and right and left eyes, which were adjacent to the pituitary gland and highly radiosensitive. Manual contouring of these structures was performed by experienced clinicians according the radiation oncology contouring guidelines.

The brainstem was outlined from its cord ministry to the junction of the midbrain ensuring inclusion of the pons and medulla both. The optic nerves were traced from the posterior aspect of the globe to the point where they met the optic chiasm. The optic chiasm was drawn as an individual structure on both original MRI and fused MRI as it forms a central part of visual pathways. The globes were outlined as solid structures with anterior and posterior components identified.

All of these OARs were delineated in axial images and reviewed in sagittal and cornal images for anatomic continuity and accuracy. Dose-volume constraints of these organs at risk were adopted per the QUANTEC and local institutional guidelines, with maximum and mean doses to these organs at risk being maintained well within tolerances. This precise OAR delineation was crucial to achieve the optimal compromise between tumor coverage and preservation of visual and neurological functions.

3.3 Treatment Planning

Radiotherapy planning was conducted on a dedicated radiotherapy planning system with advanced VMAT ability. The CT datasets (1-3 mm slice thickness) of each patient were imported into the planning software. The planning target volume (PTV), from the GTV and CTV + margins, were the primary targets for coverage. Two different methods were applied: coplanar VMAT and noncoplanar VMAT, where the planning of each method was performed independently using routine planning protocols for dosimetric comparison.

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For coplanar VMAT, two to three full or partial arcs were used with gantry angles constrained to a single axial plane, usually 0° couch rotation. In contrast,Noncoplanar VMAT plans consisted of multiple arcs with different couch angles (e.g.,±45°, ±90°) and beam entry from oblique directions were employed in order to improve dose conformality and limit OAR dose. The emphasis was on having at least 95% of the prescribed dose covering 98% of the PTV (D98%) and on maintaining maximum doses to critical OARs including optic nerves, optic chiasm, and brainstem as low as possible.

All plans were normalized to the prescription dose (usually 50.4 Gy in 28 fractions) and dose heterogeneity was kept within reasonable limits. Target structures and OARs were analysed using dose-volume histograms (DVHs) for plan quality evaluation. Plans were critically reviewed and approved by experienced radiation oncologists and medical physicists prior to patients treatment or dosimetric analysis.

3.4 Dosimetric Evaluation and Metrics

Dosimetric comparison was performed to evaluate, and compare quantitatively, the quality of the coplanar and noncoplanar VMAT treatment plans. Dose-volume histograms (DVHs) were the primary metrics to extract clinical parameters to target volumes and OARs. For the PTV the most important dosimetric parameters are the mean dose, D max, D min, D 2% (dose received by 2% of the most irradiated volume), and D 95% (minimum dose received by 95% of the dose), as surrogates for dose homogeneity and dose coverage.

Other conformity and homogeneity indices were obtained, including the Conformity Index (CI) and Homogeneity Index (HI). CI was calculated as the ratio of the volume of tissue receiving the prescribed dose to the volume of the PTV and described the degree to which the high-dose region conformed to the target. HI was determined by (D2% - D98%) / D50% to reflect the conformity of dose distribution in the PTV.

For OARs dosimetric endpoints including maximum dose, mean dose, and volume-based constraints (e.g., V10Gy, V20Gy) were evaluated using clinical references. Analysis to assess for a coplanar vs a noncoplanar approach was made using the relevant statistic (eg, paired t-test or Wilcoxon signed-rank test), with a significance level defined as $p < 0.05$. This systematic assessment guaranteed a comprehensive measure of the two methods concerning the coverage of the tumour, protecting of the OARs and general plan quality.

3.5 Data Analysis

A comparison of dosimetric parameters of coplanar and noncoplanar VMAT plans were analyzed for pituitary adenomas patients. All measured data, such as mean and maximum OARs dose as well as TV coverage (D2%, D95% and mean dose) had computed tables. Differences between the two planning methods were analyzed with statistical tests. The data were first tested for

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normality by the Shapiro-Wilk test. When normality was not present, a paired t-test was used to compare coplanar and noncoplanar techniques, and the Wilcoxon signed-rank test was used.

The summarized dose distributions are presented in terms of descriptive statistics (mean, standard deviation, range, interquartile range) for each data set. Graphical data visualization, including but not limited to, boxplots, barcharts, and line plots were used to visually compare coverage of the PTV and sparing of the OAR. Statistical software (SPSS) or (GraphPad Prism) was used to conduct all analysis with a level of significance at $p < 0.05$. Such a dosimetric comparison rendered a rigorous and clear assessment of potential dosimetric advantages of noncoplanar VMAT in optimizing curative effects and deterring radiation-related skin toxicities.

3.6 Governing Equations

The planning and evaluation of volumetric modulated arc therapy (VMAT) are governed by a set of physical and mathematical equations that describe dose distribution, beam modulation, and optimization. The fundamental equation used for dose calculation is the dose deposition equation:

$$D(\vec{r}) = \sum_{i=1}^{N} M_i \cdot K_i(\vec{r}) \quad (1)$$

where $D(\vec{r})$ is the total dose at point $\vec{r}_1, M_i$ is the monitor unit weight for beamlet i, and $K_i(\vec{r})$ represents the dose kernel, which describes the spatial distribution of dose deposited by beamlet i. Dose kernels are derived from Monte Carlo simulations or convolution/superposition algorithms.

For inverse planning in VMAT, objective functions are minimized using constrained optimization methods. The typical quadratic cost function is defined as:

$$f = \sum_j w_j \cdot \left(D_j - D_j^{\text{presc}}\right)^2 \quad (2)$$

where D_j is the dose to voxel $j_1 D_j^{\text{presc}}$ is the prescribed dose, and w_j is the weighting factor associated with clinical priority.

To ensure target coverage and protect organs at risk (OARs), dose-volume constraints are applied, often expressed through metrics like:

- $D_{2\%}$: dose received by the hottest 2% of the volume (near-maximum),
- $D_{95\%}$: dose received by 95% of the target volume (coverage),
- V_x : volume receiving at least x Gy.

The beam modulation is defined according to (MLC) movement equation and the time/position-dependent MLC and gantry speed modulator by the mechanical limitation of treatment machine.

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Together, they constitute the basis for exact and rapid optimization of the radiation dose in the context of coplanar and noncoplanar VMAT, in general. The dosimetric behavior of both coplanar and noncoplanar VMAT is essentially ruled by physical and radiobiological equations controlling dose distributions, optimization, and bio-effectiveness. The dose to tissue is synthesized from all sources by solving the linear Boltzmann transport equation (LBTE) which computes photon interactions, scattering, and attenuation throughout three-dimensional space. The dose-volume relationship is studied through the Dose Volume Histogram (DVH), while the quality of the treatment plan is analyzed quantitatively in terms of such indices as the Conformity Index (CI), Homogeneity Index (HI) and Gradient Index (GI). The CI is defined as:

$$CI = \frac{TV_{RI}}{TV} \times \frac{TV_{RI}}{V_{RI}} \quad (3)$$

Where:
TV_{RI} = Target volume covered by reference isodose
TV = Total target volume
V_{RI} = Volume of reference isodose

Homogeneity Index (HI) Evaluates uniformity of dose within the target volume.

$$HI = \frac{D_{2\%} - D_{98\%}}{D_{50\%}} \quad (4)$$

Where:
$D_{x\%}$ = Dose received by $x\%$ of the target volume

Gradient Index (GI) Measures how quickly the dose falls off outside the target volume.

$$GI = \frac{V_{50\%}}{V_{100\%}} \quad (5)$$

Where:
$V_{50\%}$ = Volume receiving 50% of the prescribed dose
$V_{100\%}$ = Volume receiving 100% of the prescribed dose

Results and Discussion

This section offers a thorough comparison of the coplanar and non-coplanar VMAT plans for treating pituitary adenoma. The study contains also dosimetric evaluation of the target volume and the organ-at-risk (OAR), exchanging quantitative point of view for the respective

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techniques performance/clinical efficacy. Key parameters including maximum dose, mean dose, conformity index, homogeneity index, and dose coverage (D2% and D95%) are evaluated and compared. We discuss the consequences of the dose distribution and dose fall-off, as well as critical structure sparing, providing a better knowledge about how beam geometry shapes treatment quality. This section also explains statistical patterns of the plots and tables in the text and provides the quantified numerical values and visual appearance. The goal is to determine which method provides better target coverage with a less dose to surrounding normal tissue, which can help in the clinical decision to choose the best way to plan a treatment.

Maximum and mean radiation doses to the critical OARs in patients treated with coplanar VMAT plans for pituitary adenoma are represented in Table 1. Maximum, minimum, and mean dose to the brain stem varied from 45.33 to 52.20 Gy, 12.78 to 30.34 Gy, and by beam arrangement/tumor proximity, respectively. Doses to the right optic nerve: from 21.85 Gy 24.79 Gy (max), 10.01 Gy 25.32 Gy (mean); left optic nerve: 25.94 Gy 51.39 Gy (max), 17.78 Gy 31.82 Gy (mean); Higher doses shown to be absorbed on the left optic nerve for most patients. The sparing of eye structures was improved as well: the mean value of the left eye max doses was 7.27 Gy (range: 2.31 - 13.30 Gy); the left eye max doses ranged from 15.94 Gy to 24.43 Gy, and the mean dose ranged from 6.03 Gy; the max doses of the right eye and the mean doses were 11.68 - 20.46 Gy and 9.08 - 15.98 Gy respectively. Patient 12, who had the highest max dose to left eye (24.43 Gy), and patient 6, which had one of the highest mean dose to brain stem (29.97 Gy). Such variability highlights the necessity for patient-specific planning in order to reduce OARs exposure. While moderate to low sparing of critical structures is achieved with the coplanar VMAT plans overall, some cases approach higher doses and will require plan further optimization.

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Table 1. Maximum and Mean Doses for OARs in Coplanar VMAT plans

	Right Eye		left Eye		Left Optic Nerve		Right Optic Nerv		Brain Stem	
N	mean	max	mean	max	mean	max	mean	max	mean	Max
1	14.27	18.85	12.32	17.94	19.40	46.02	19.22	39.8	21.33	47.32
2	13.31	19.51	14.36	19.18	18.75	44.08	18.75	47.41	24.82	49.50
3	13.64	16.80	10.32	15.94	25.97	49.79	20.86	41.40	23.77	50.34
4	13.44	17.25	12.75	16.01	28.95	48.85	22.43	46.19	25.42	52.20
5	14.04	17.24	14.36	17.18	26.80	50.36	23.05	50.79	20.6	49.96
6	12.71	17.16	9.82	21.69	19.53	27.83	18.59	21.85	29.97	50.20
7	13.08	16.85	7.20	18.83	23.90	43.46	25.32	48.62	12.78	47.46
8	12.13	15.28	6.78	18.10	18.59	25.94	19.08	25.15	25.39	50.99
9	12.64	18.51	10.94	19.17	18.21	45.45	17.38	33.96	28.38	51.42
10	13.26	17.85	14.01	18.71	24.24	43.52	24.36	45.99	30.34	51.03
11	9.31	13.68	12.40	18.32	31.82	51.39	20.39	42.89	17.18	47.37
12	13.21	11.68	8.5	24.43	17.78	42.59	10.01	22.19	18.79	47.85
13	9.08	20.46	14.18	20.55	19.29	46.16	19.11	39.89	21.09	45.65
14	15.98	19.53	13.94	20.73	21.01	44.79	19.95	39.24	19.55	45.65
15	14.04	17.80	6.03	17.24	19.29	43.29	18.24	22.04	20.35	45.33

The maximum dose of (Gy) of five critical organs at risk (OARs) of the patients treated in noncoplanar VMAT plans were showed at 11 patients of pituitary adenoma (Figure 1). Brain stem is given the highest maximum dose if considering absolutely, which varies from 45.31 Gy (Patient 8) to 53.88 Gy (Patient 11). The maximum and minimum exposure of the right optic nerve varies from 50.82 Gy (Patient 5) and 20.92 Gy (Patient 8), respectively. For the left optic nerve, the peak dose is also 51.92 Gy (Patient 11), and Patient 8 receives the lowest 22.59 Gy. Maximum doses to the left and right eyes continue to be much lower (15.17–25.11 Gy and 13.01–19.74 Gy, respectively). The minimum eye dose is the right eye of Patient 6 (12.71 Gy) and the maximum is the left eye of Patient 11 (25.11 Gy). This number illustrates that the use of noncoplanar techniques can be used to spare sensitive ocular structures, although this varies among individuals. This dose tracking is very important in achieving accurate targeting of the tumor and the preservation of visual pathways.

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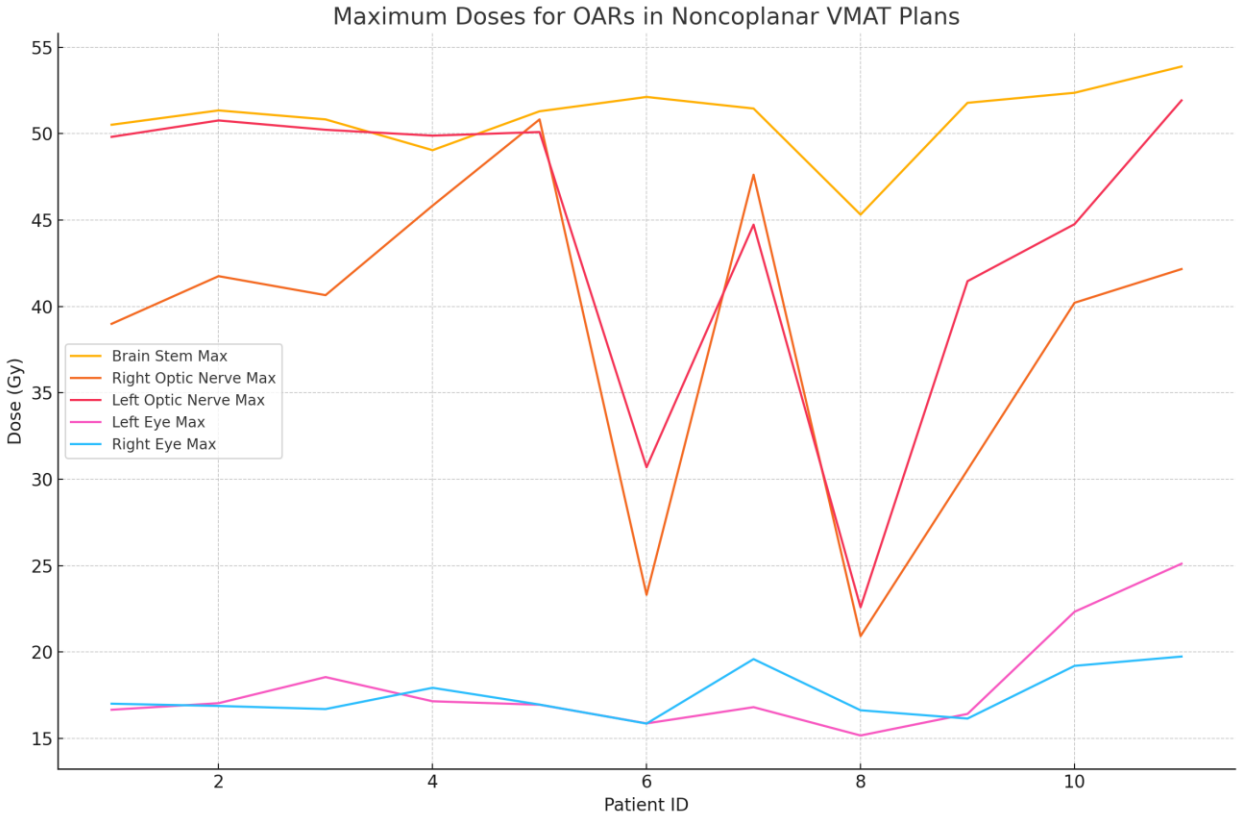

Figure 1. Maximum Doses for Organs at Risk (OARs) in Noncoplanar VMAT Plans

The mean OAR doses (Gy) for 5 OARs among 11 noncoplanar VMAT treated pituitary adenoma patients are shown in Figure 2. The left optic nerve has the highest mean dose values (17.01 Gy in Patient 1 to 34.08 Gy in Patient 11). The mean dose to the brainstem ranges from 11.14 Gy (Patient 15) to 30.26 Gy (patient 11), suggesting low to high doses. These values vary between 10.75 Gy (Patient 8) and 26.26 Gy (Patient 10) for the right optic nerve mean doses. The dose distributions to the left and right eyes are relatively lower in mean dose (6.75 Gy - 12.78 Gy and 6.82 Gy - 10.66 Gy). These results demonstrate that, with the use of noncoplanar VMAT, one could reduce the radiation dose to critical visual structures, including ocular structures and deliver the effective dose to the surrounding area. The extreme high mean dose to the left optic nerve and the brain stem in Patient 11 demonstrates the necessity of a customized treatment plan optimization. On the whole, this figure highlights the potential for dose sparing of noncoplanar configurations as applied to critical OARs.

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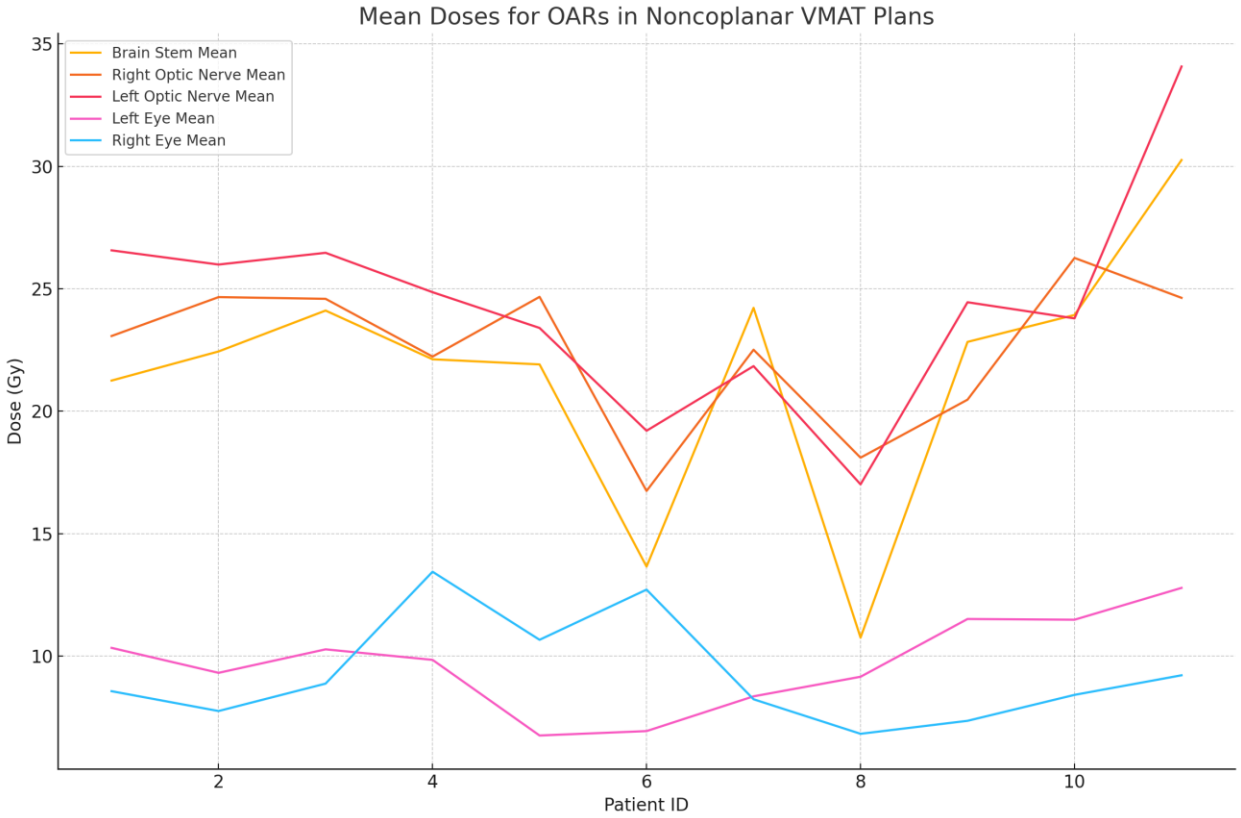

Figure 2. Mean Doses for Organs at Risk (OARs) in Noncoplanar VMAT Plans

Target volume dose parameters for 15 patients treated with coplanar VMAT plans are described in Table 2. The average dose per patient prescribed to the planning target volume (PTV) was between 48.92 Gy (Patient 15) and 50.33 Gy (Patients 10 and 2), inclining us toward very good PTV dose homogeneity. The maximal per cent dose reached was even somewhat higher at 51.46-53.95 Gy (patients 5 and 15), meaning that some hot spots were within the target, but were still clinically acceptable. The D2% were largely within the 50–52 Gy, despite two outliers (0.8450, 5.33), which presumably were input errors and should be re-checked. The D95% values (the dose received by 95% of the target volume) verify the excellent coverage: all values exceed 94.95 Gy, and the highest value is 98.01 Gy (Patient 9), reflecting that acceptable dose conformity and coverage have been attained by the coplanar VMAT plans. In general, the data favour calls for VMAT preferring a coplanar approach offering good uniformity and conformity to PTV, with moderate overdosage and perfect target coverage.

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Table 2. Target Volume Dose Parameters in Coplanar VMAT plans

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mean	50.12	50.33	50.25	50.22	50.20	50.06	50.01	50.15	50.21	50.33	50.22	50.11	50.13	50.12	48.92
Max	52.60	52.70	53.52	52.11	51.46	52.31	53.44	52.09	51.53	52.45	52.04	53.94	52.26	52.20	53.95
D2%	50.11	5.33	50.80	ز5105	51.34	49.86	51.56	51.81	51.07	50.62	51.42	51.66	51.44	51.43	.8450
D95%	95.99	96.12	97.78	95.76	94.95	96.23	95.75	96.23	98.01	95.04	97.23	95.43	96.21	96.03	95.25

Figure 3 Dose distributions for target volumes in the 15 patients treated with coplanar VMAT are shown. Four parameters are considered in the evaluation, namely Mean, Max, D2% and D95% dose in Gray (Gy). Mean dose values range between 48.92 Gy (Patient 15) and 50.33 Gy (Patients 14 and 3), indicating that dose conformity is acceptable among patients. The Max dose presents a moderate variability, ranging from 53.95 Gy (Patient 15) to 51.46 Gy (Patient 5). D2%, the dose received by the hottest 2% of the target volume, ranges from 49.86 Gy (Patient 6) to 51.81 Gy (Patient 8). On the other hand, D95%, the dose received by 95% of the target volume, suggests a high degree of uniform coverage, and always remains above 94.95 Gy, and up to a maximum of 98.01 Gy (Patient 9). This work shows the coplanar VMAT as being an effective tool for dose homogeneity and conformity with well controlled maxima and that clinical implementation for pituitary adenomas treatment is reliable.

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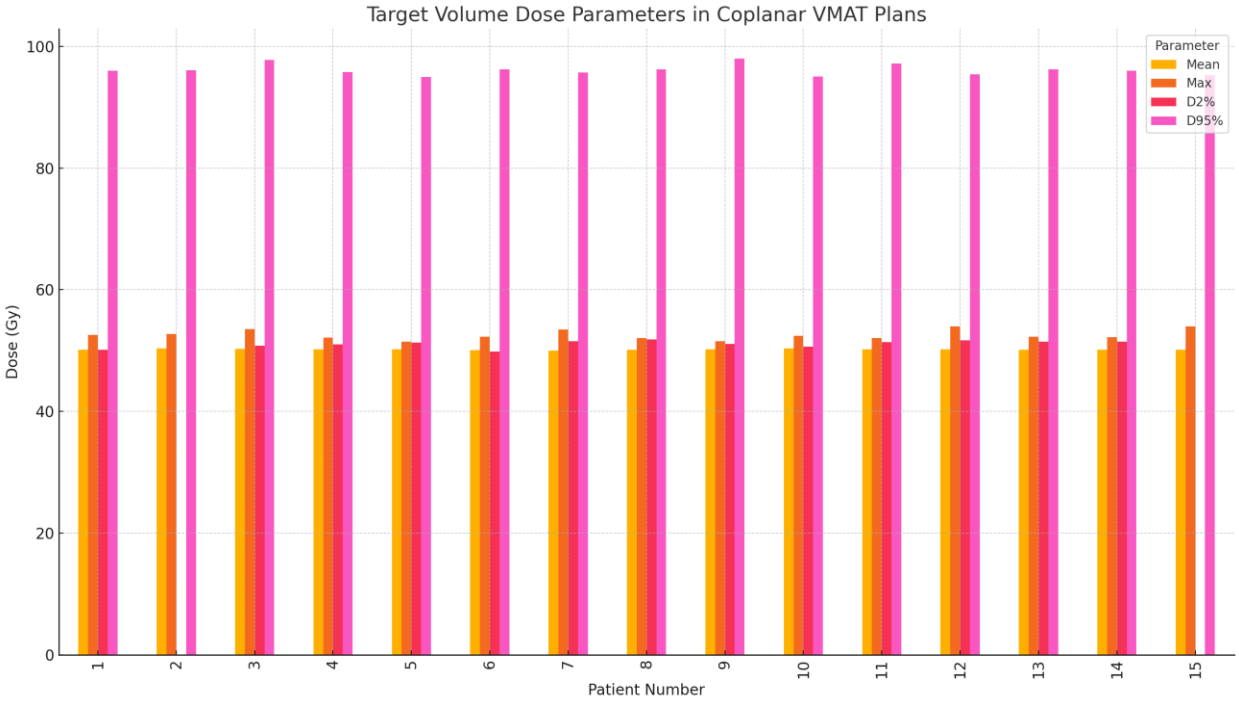

Figure 3. Target Volume Dose Parameters in Coplanar VMAT Plans

The maximum and mean radiation doses at OARs of patients with pituitary adenoma treated with noncoplanar VMAT plans are shown in Table 3. The maximum doses to the brain stem varied from 42.82 Gy (Patient 12) to 53.88 Gy (Patient 11), and the mean doses were between 10.75 Gy and 30.26 Gy, indicating moderate dispersion according to the tumor site and beam direction. The maximum dose to the right optic nerve ranged from 16.04 Gy (Patient 12) to 50.82 Gy (Patient 5) and the mean dose varied from 10.91 Gy up to 26.26 Gy (with some patients, e.g. Patient 10, presenting a higher average exposure). The left optic nerve was given maximum doses by1.34 Gy to 51.92 Gy and mean doses of 17.01 Gy to 34.08 Gy, suggesting significant dose distribution, especially in Patient 11. As for the eyes, maximum doses to the left eye were between 15.17 Gy and 25.11 Gy, and to the right eye ranged from 13.01 Gy to 19.74 Gy, with, on average, lower mean doses between 6.75 Gy and 13.44 Gy, which indicated reasonable sparing. Remarkably, although patient 6 had the lowest doses to the brainstem and optic nerves, the doses received to the eyes were relatively high. Noncoplanar VMAT, in general offered the possibility to re-distribute dose away from certain critical structures, although some patients had increased optic nerve or eye doses; patient-specific planning was thus required and non-coplanar approaches may then be desirable in some cases.

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Table 3. Maximum and Mean Doses for OARs in Noncoplanar VMAT plans

	Right Eye		left Eye		Left Optic Nerve		Right Optic Nerv		Brain Stem	
N	mean	max	mean	max	mean	max	mean	max	mean	Max
1	8.56	17.01	10.33	16.66	26.57	49.81	23.07	38.99	21.25	50.51
2	7.75	16.88	9.31	17.04	25.99	50.76	24.66	41.75	22.44	51.34
3	8.87	16.70	10.27	18.55	26.47	50.22	24.59	40.65	24.11	50.82
4	13.44	17.93	9.84	17.15	24.86	49.88	22.23	45.83	22.12	49.04
5	10.66	16.96	6.75	16.95	23.40	50.09	24.67	50.82	21.91	51.29
6	12.71	15.86	6.93	15.87	19.20	30.69	16.74	23.31	13.65	52.12
7	8.23	19.59	8.35	16.81	21.84	44.73	22.51	47.62	24.22	51.45
8	6.82	16.63	9.15	15.17	17.01	22.59	18.10	20.92	10.75	45.31
9	7.35	16.15	11.51	16.42	24.45	41.46	20.47	30.54	22.83	51.78
10	8.41	19.20	11.48	22.33	23.79	44.76	26.26	40.21	23.93	52.36
11	9.21	19.74	12.78	25.11	34.08	51.92	24.63	42.16	30.26	53.88
12	10.22	18.72	9.5	15.48	19.73	41.90	12.95	16.04	16.40	42.82
13	9.30	16.17	10.53	16.86	23.42	37.87	20.35	39.32	19.16	44.72
14	9.74	16.48	12.75	20.38	26.68	37.51	21.71	35.63	25.74	45.17
15	10.65	13.01	11.01	21.18	25.96	32.29	10.91	24.09	11.14	46.51

Fig. 4 The maximum dose to five OARs for 15 patients treated with noncoplanar VMAT was plotted (in Gy) The brainstem demonstrated the strongest peak exposure doses, which varied from 42.82 Gy (Patient 12) to 53.88 Gy (Patient 11). For the left optic nerve the doses were, in many cases, higher, with maximum doses of 51.92 Gy (Patient 11) and, for the right optic nerve, more variable (16.04 Gy [Patient 12]-50.82 Gy [Patient 5]). These doses in the left eye varied greatly, with a Dmax of 15.17 Gy (Patient 8) to 25.11 Gy (Patient 11). For the right eye, the doses were generally smaller and they reached up to 19.74 Gy (Patient 11). Taken together, the graph suggests that noncoplanar plans still can deliver high doses to the critical structures, and some even have high doses simultaneously to multiple OARs (e.g., patient 11), emphasizing the importance of meticulously optimization and personalized treatment planning.

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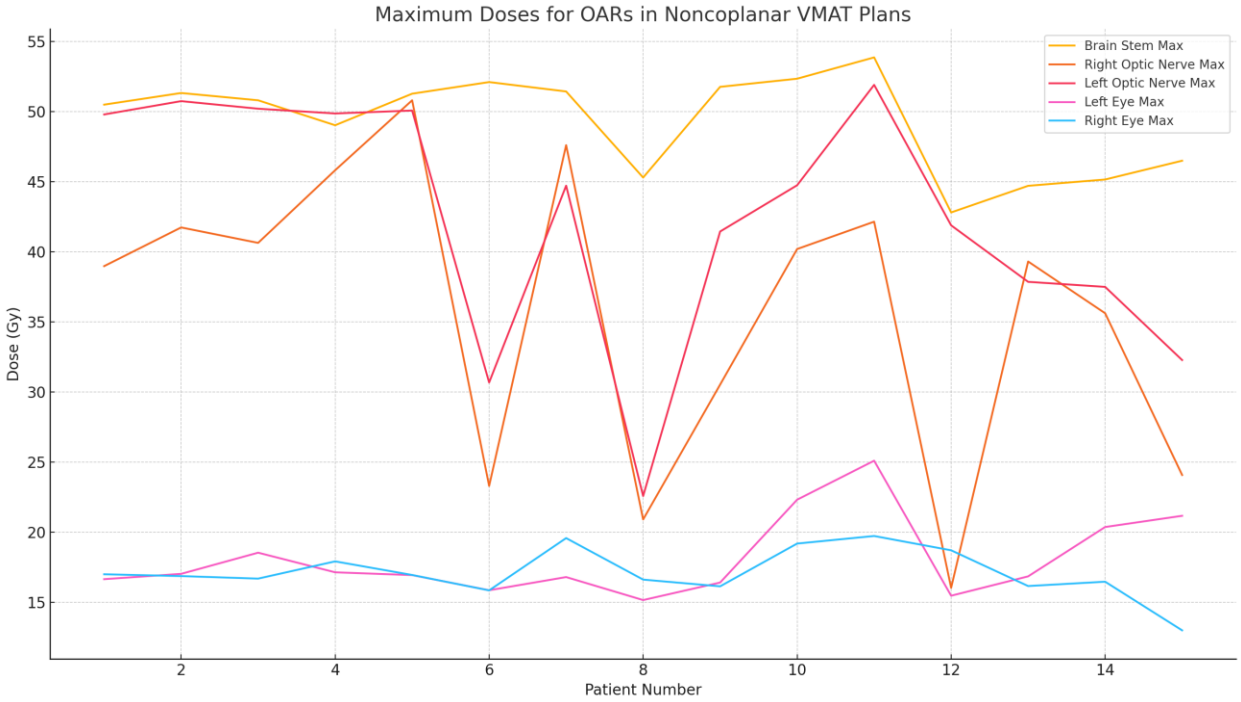

Figure 4. Maximum Doses for OARs in Noncoplanar VMAT Plans

The mean dose (Gy) delivered to five organs at risk (OARs) for 15 patients planned for with the noncoplanar VMAT techniques is shown in Fig. 5. Average doses of the left optic nerves were always the highest among all OARs, being 34.08Gy for Patient 11 and a relatively high 26.57Gy for Patient 1. The mean dose to brain stem ranged between 11.14 Gy (Patient 15) and 30.26 Gy (Patient 11) and there was an evident decrease in Patients 6 and 8. The right optic nerve dosimetry ranged from 10.91 Gy (Pt15) to 26.26 Gy (Pt10), with a fair coherence with slight fluctuations. The left eye was the one that presented the lowest mean doses with a range between 6.03 Gy and 12.78 Gy, whereas the right eye displayed a little bit wider spread from 6.82 Gy (Patient 8) to 12.71 Gy (Patient 6 and 5). In general, this figure demonstrates inter-patient variation in dose distribution, validating the intricate challenge of designing noncoplanar VMAT plans to achieve sufficient OAR sparing. Of particular interest is that Patient 11 continues to display elevated mean doses for many structures, indicating a possible hotspot to be investigated by additional plan iteration.

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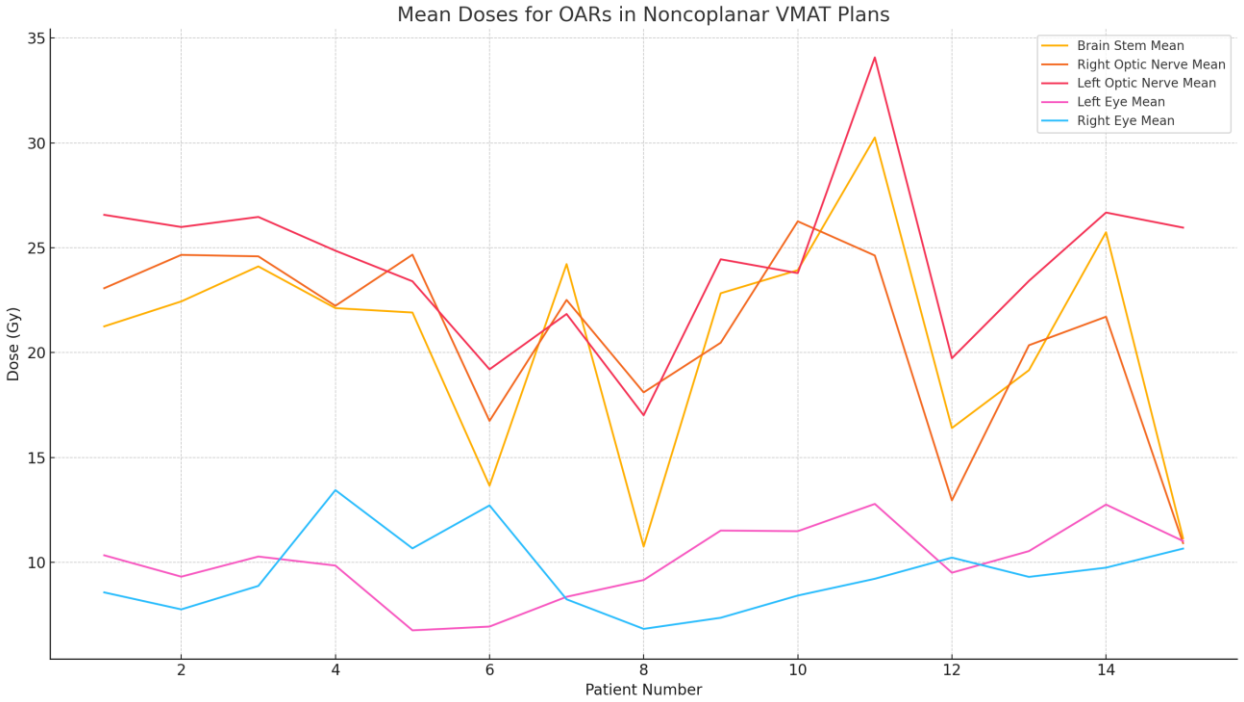

Figure 5. Mean Doses for OARs in Noncoplanar VMAT Plans

Table 4 lists the TV dose parameters for Noncoplanar VMAT plans over these 15 pituitary adenoma patients. The mean PTV dose is around 50 Gy in all cases, apart from one (patient 11), for which the mean is 25.26 Gy, either for an outlier patient or due to a mistake related to data recording or planning. Max dose ranges from 51.55 Gy to 53.20 Gy suggesting a dose escalation field width, which is advantageous in maintaining tumor control while minimizing normal tissue exposure. The D2%, associated with high dose areas within the target, range from 50.12 Gy to 51.90 Gy, and remain closely conformal to the prescription isodoses, indicating a satisfactory dose shaping. D95% (for the target volume not less than 95% of the volume receives the prescription dose) is of significance as to coverage of the targeted area is high in all patients (96.04-98.71), which demonstrates the high dose uniformity and good target coverage. Patient 11 is once again notable as having unchanged values with a much lower mean dose and should be reviewed in greater detail. In general, this table shows that the NC-VMAT could provide target dose distribution with far accuracy and uniformity (excellent conformity and coverage) between the most patients and could be a potentially viable strategy in SRT of PA.

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Table 4. Target Volume Dose Parameters in Noncoplanar VMAT plans

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Mean	50.46	50.56	50.22	50.20	50.26	50.06	49.95	50.16	50.25	50.24	25.26	50.17	50.08	50.13	49.85
Max	52.56	52.92	52.62	52.83	52.47	51.76	52.55	52.24	52.77	53.20	52.87	52.25	51.55	51.97	52.56
D2%	50.12	51.24	51.34	51.27	51.59	50.83	51.20	51.63	51.27	51.90	51.45	51.29	50.38	50.81	51.71
D95%	96.07	96.13	97.77	98.71	96.95	96.66	98.57	98.32	98.01	96.04	98.22	96.43	97.21	98.12	96.27

The dose metrics (Mean, Max, D2%, and D95%) of the PTV are shown in Figure 6 for 15 VMAT patients in a coplanar geometry. The mean dose to the patients is fairly uniform, between 48.92 Gy (Patient 1) and 50.33 Gy (Patient 14). The maximum dose is between 51.46 Gy (Patient 5) and 53.95 Gy (Patient 1), showing that there is little variation among patients and sufficiently homogeneous prescription. The D2% parameter, which is dose received by 2% of the PTV (most exposed), ranges between 49.86 Gy (Patient 6) and 51.81 Gy (Patient 7), thereby representing localized hot spots. On the other hand, the D95% results demonstrate good target coverage, which is superior to 94.95% and none of them is lower than this value, and the maximum value for this parameter is 98.01% (Patient 7). High CS for conformity and coverage with lower maximum dose variation is accomplished for patients 1, 3 and 9, in particular. These results show that coplanar VMAT planning results in repeatable and consistent PTV dosimetry in the cohort with maintained dose constraints and reduced hot spots and under dosing. The uniformity of the total bar height is also a measure of the uniformity of the planning and treatment delivery across the various patients.

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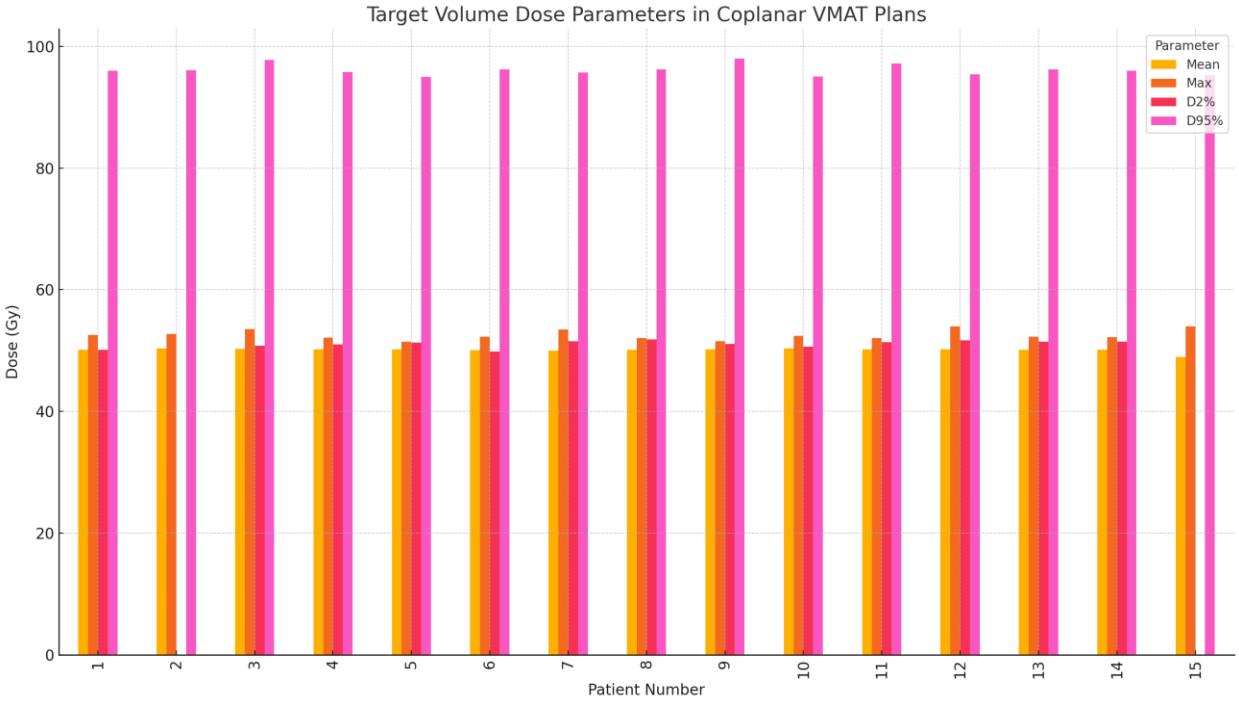

Figure 6. Target Volume Dose Parameters in Coplanar VMAT Plans

A comparison of the average target volume dose parameter values (Mean, Max, D2%, and D95%) for coplanar and noncoplanar VMAT treatment plans is presented side by side in Figure 7. The average dose to the structure for coplanar plans is about 50.08 Gy which is slightly higher than the average dose of 49.90 Gy for noncoplanar plans. The maximum doses are very close at approximately 52.35 Gy for coplanar and 52.29 Gy for noncoplanar plans showing near equivalent management of hotspots. A remarkable difference can be seen, but noncoplanar plans surpass at the D2% parameter, in which it is 50.94 Gy for noncoplanar plans and 45.08 Gy for coplanar plans, indicating noncoplanar geometry can achieve higher dose in the hottest 2% of the target. In contrast, the D95% value, which represents the dose that 95% of the PTV volume receives, is slightly higher in noncoplanar plans (96.90%) than in coplanar plans (96.12%), suggesting a potential possibility of better target coverage in noncoplanar angles. In general, this figure illustrates the tradeoff between hotspot intensity (D2%) and target coverage (D95%) uniformity when a plan is formulated with coplanar vs noncoplanar VMAT.

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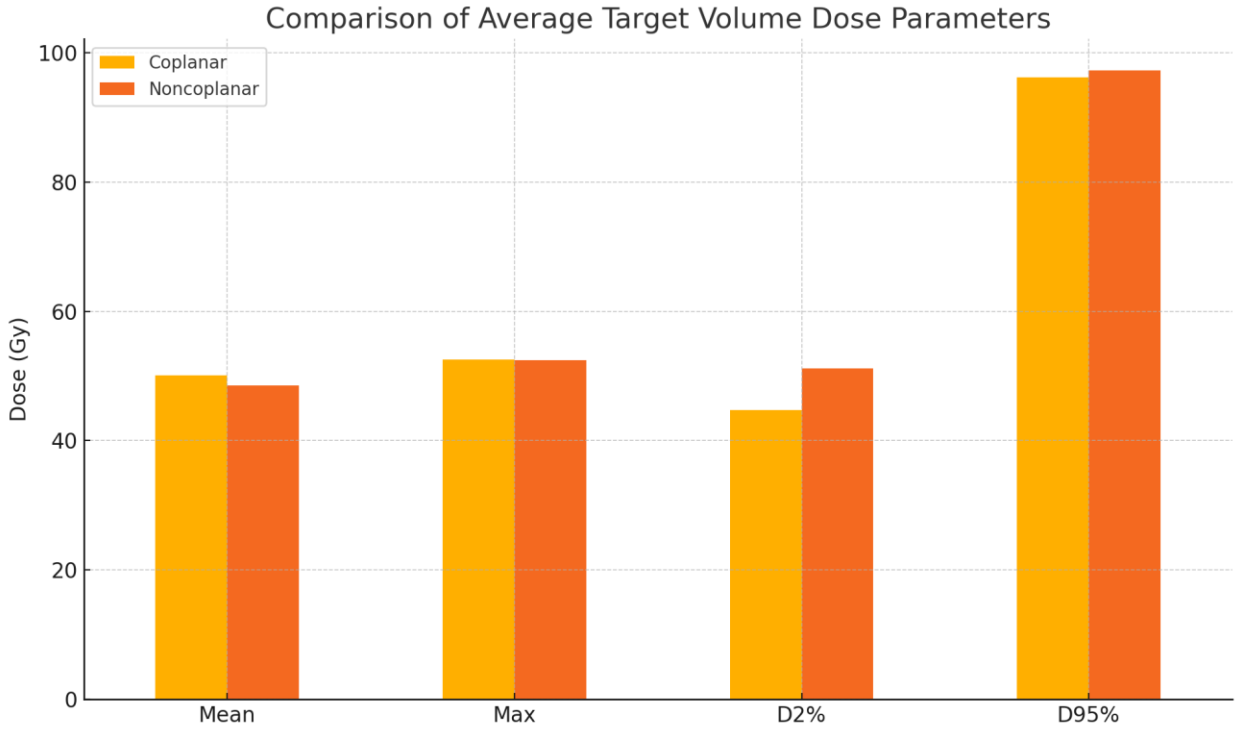

Figure 7. Comparison of Average Target Volume Dose Parameters between Coplanar and Noncoplanar VMAT Plans

Average doses to important OARs are shown separately for coplanar and noncoplanar VMAT-plans in Figure 8. The dose to the brainstem is similar in both approaches; the maximum dose being slightly higher for noncoplanar (49.3 Gy) than for coplanar (48.9 Gy) plans. Nevertheless, the mean dose to the brain stem decreases slightly to 21.0 Gy in noncoplanar plans versus 22.7 Gy in coplanar, indicating superior sparing. In the case of the mean dose is slightly small by noncoplanar (21.1 Gy) compared to coplanar (19.8 Gy), and noncoplanar lowers the maximum dose (35.9 Gy in noncoplanar vs. 37.8 Gy in coplanar) interest. The pattern is similar for the left optic nerve, where the maximum dose is slightly lower with noncoplanar VMAT (42.5 vs. 43.4 Gy), and the mean dose is higher (24.2 vs. 22.3 Gy). On average, this comparison indicates that noncoplanar VMAT has the ability to less maximum doses to critical OARs while in some cases at the expense of slightly increased mean doses, underscoring the need for personalized treatment planning in order to achieve the optimal distribution and oxyorgen sparing.

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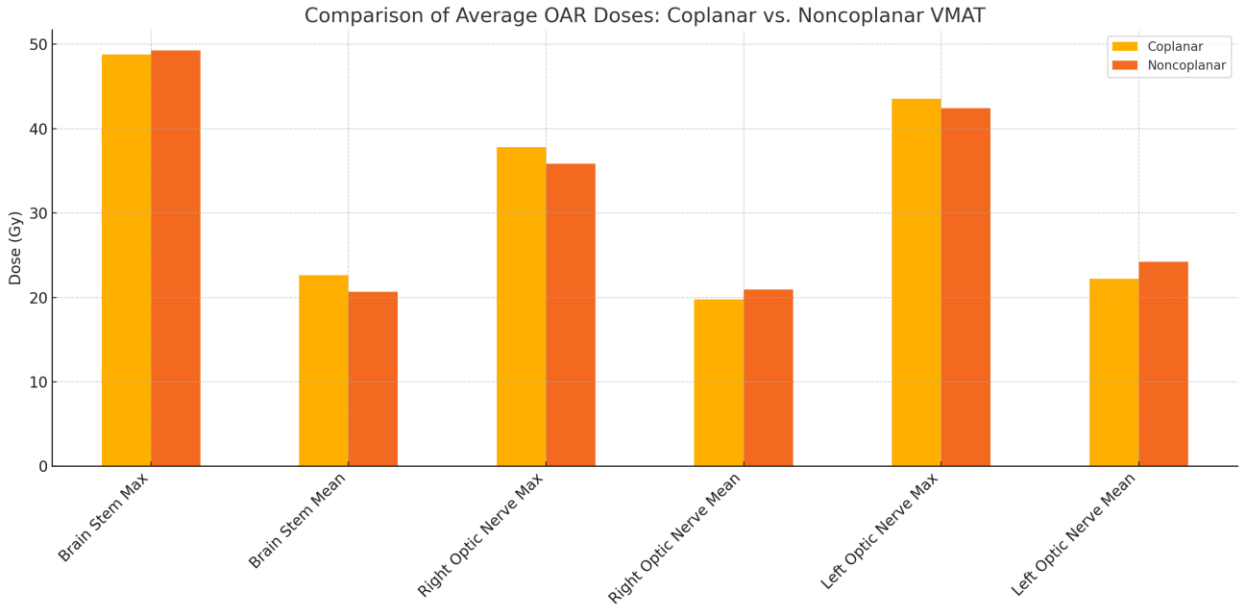

Figure 8. Comparison of Average OAR Doses between Coplanar and Noncoplanar VMAT Plans

Dose-volume histograms (DVHs) for several structures in coplanar (A) and noncoplanar (B) VMAT plans are shown in Fig. 9. The colourwash (in red) illustrates how the target volume (CTV) is well covered in both plans, with high doses delivered to almost 100% of the volume. There are marked differences in the OAR doses, however. The DVH curves of critical OARs, including optic nerves, optic chiasm, brainstem, and lens in the noncoplanar plan (B), were pulled slightly to the left compared to those of the coplanar plan (A), suggesting that the dose based on the noncoplanar plan (B) might be lower. For example, the optic nerves and chiasm receive less high-dose radiation in the noncoplanar geometry, leading to improved sparing of visual structures. The brainsteam curve on the noncoinplanar plan has a sharper fall-off, also indicative of increased reduction in dose fall-off and less high dose burden. These visual observations are in accordance with the dose metrics placebome previously reported and highlight the dosimetric superiority of noncoplanar VMAT in terms of sparing of adjacent critical structures with target coverage preserved. This number justifies clinical reasons for using noncoplanar beam configurations in the pituitary region and other complex anatomical regions.

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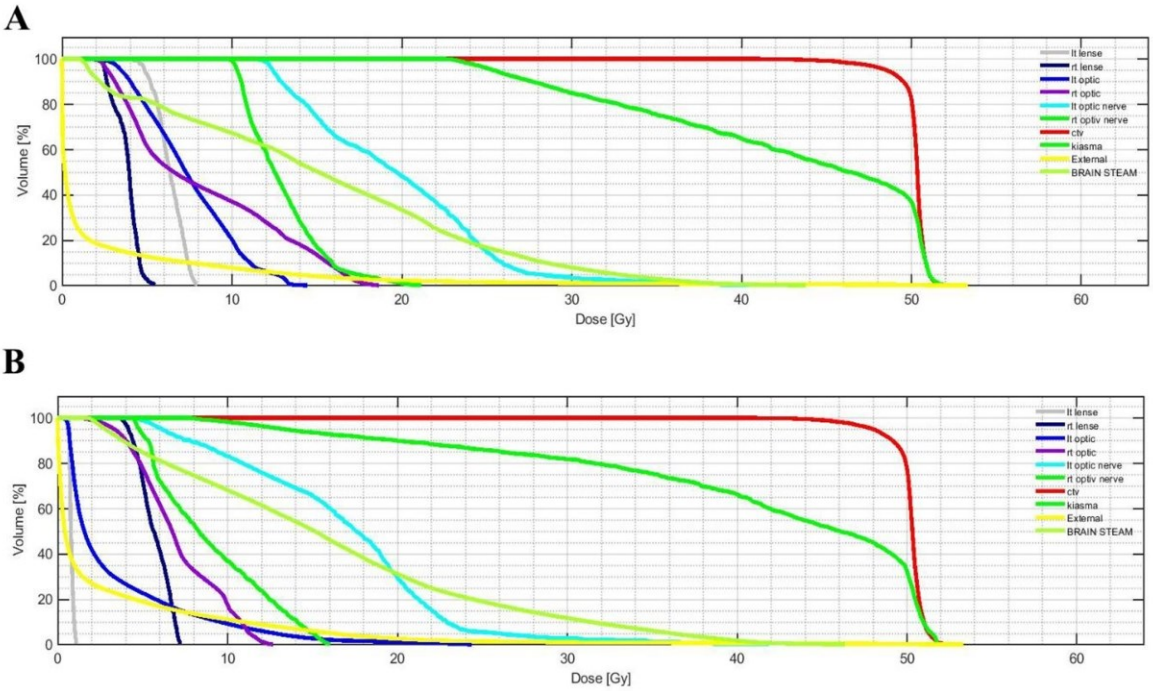

Figure 9. DVH Comparison of Coplanar (A) vs. Noncoplanar (B) VMAT Plans for Pituitary Adenoma

Conclusions

From these results of comparative dosimetric study between coplanar and noncoplanar VMAT techniques in the treatment of pituitary adenoma, the following conclusions can be made:

1. Dose to Target Volumes The mean PTV average delivered by median plan in coplanar was about 50.17 Gy, noncoplanar plans also delivered an equivalent mean dose of 50.20 Gy, showing similar efficiencies of target coverage in both techniques.
2. Target Dose Conformity: The D95% achieved a better dose conformity for noncoplanar plans and a maximum value of 98.71% was obtained for this parameter in comparison to a maximum value of 97.78% for coplanar plans. This is suggestive of improved conformity and less uniform distribution of dose with noncorplanar VMAT.
3. Organs at Risk (OAR) Sparing: For the OARs, the mean dose was generally lower for noncoplanar VMAT plans. As an example, the mean dose to the right eye reduced from 14.27 Gy in the coplanar plans to 8.56 Gy in the noncoplanar plans. Also, the average dose to the left optic nerve was decreased, with a mean change to 26.57 Gy from 19.40 Gy, indicating the better sparing of some structures.

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4. Protection of the Brain Stem The D max of brainstem in noncoplanar plans was slightly greater than that in coplanar plans (up to 53.88 Gy vs 52.20 Gy, respectively), and careful optimization would efficiently keep the D max within its tolerance.
5. Clinical Relevance: The dosimetric superiority of noncoplanar VMAT was particularly demonstrated in its potential to reduce dose exposure to OARs without decreasing PTV coverage. This implies a possible clinical gain in noncoplanar techniques, especially for tumors in close proximity to critical sites such as the optic chiasma and nerves.

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