

Dosimetric Impact of Collimator Angle and Arc Number on Target Dosimetry and Organ-at-Risk Sparing in Volumetric Modulated Arc Therapy for Thyroid-Associated Ophthalmopathy

KANG ZHANG

Department of Oncology, Southwest Hospital, Third Military Medical University (Army Medical University)

JINGCONG CHEN

Department of Oncology, Southwest Hospital, Third Military Medical University (Army Medical University)

YUHAN CHEN

Department of Oncology, Southwest Hospital, Third Military Medical University (Army Medical University)

LU ZOU

Department of Oncology, The People's Hospital of RongChang District ChongQing

ZHE WANG

Department of Oncology, Southwest Hospital, Third Military Medical University (Army Medical University)

FENGWEI RAN

ranfengwei@tmmu.edu.cn

Department of Oncology, Southwest Hospital, Third Military Medical University (Army Medical University)

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Abstract

Purpose

To evaluate the effects of arc number and collimator angle on target dosimetry, organ-at-risk (OAR) sparing, and plan complexity in volumetric modulated arc therapy (VMAT) for thyroid-associated ophthalmopathy (TAO), and to identify a preferred planning configuration.

Methods and Materials:

Following institutional review board approval, 24 patients with TAO were retrospectively included. For each patient, 16 VMAT plans were generated using two arc configurations (2Arc and 4Arc) and eight collimator angle combinations (C0-0H to C90-270H), resulting in 384 plans. All plans prescribed 20 Gy in 10 fractions and were normalized so that at least 95% of CTV1 was covered by the prescription dose. Differences among the 8 collimator angles were evaluated separately within the 2Arc and 4Arc configurations using the Friedman test with Nemenyi post hoc comparisons, with Kendall's W as the overall effect size. For the 2Arc-vs-4Arc comparison, Wilcoxon signed-rank tests were performed at each collimator angle level (8 angle groups $\times$ 20 metrics = 160 tests), with Benjamini-Hochberg correction applied within each angle family ($m = 20$ per family), and effect size r was computed.

Results

Across collimator angle configurations, 4Arc plans showed better target dosimetric performance than 2Arc plans, with an 11.1% reduction in homogeneity index, a 2.2% increase in conformity index, a 0.3% increase in CTV1 D98, and a 1.0% decrease in CTV1 Dmax. The gradient index increased slightly by 1.1%. Meanwhile, 4Arc plans increased total leaf travel by 94% and MUs by 2%, without significant changes in MCSv. Among OARs, aggregate maximum doses to the brainstem (-2.2%), left (-0.9%) and right (-1.1%) eyes, bilateral optic nerves (-0.9% each), optic chiasm (-1.2%), pituitary (-1.9%), and lenses (left -2.9% , right -3.6%) all decreased; the right hippocampus was the only parameter showing no significant difference at any angle. However, under the study's own per-angle Benjamini-Hochberg framework, these OAR differences reached statistical significance mainly in the small-angle range (0° – 45° ; optic chiasm, pituitary, and lenses were each significant only at 0° , and the eyes at 3/8 angles) and thus represent descriptive aggregate differences rather than per-angle inferential conclusions. Kendall's W was generally higher for 4Arc than for 2Arc, indicating clearer dose differentiation across collimator angles: from 0° to 60° , the homogeneity index improved from 0.218 to 0.055 and the conformity index from 0.589 to 0.898; from 0° to 75° , lens Dmax decreased by up to 59%.

Conclusions

Four-arc VMAT showed improved target dosimetric performance and lower doses to most OARs compared with 2Arc VMAT in TAO radiotherapy planning. Considering both arc number and collimator angle configuration, the 4Arc_C60-300H configuration provided the best balance between target dosimetry and OAR sparing. When OAR sparing was prioritized, the 4Arc_C75-285H configuration showed the lowest composite OAR-sparing score, with similar scores at 68° and 90° . The 0° and 15° collimator angles should be avoided on target-quality and OAR-Dmax grounds, although their smaller low-dose bath may be weighed in specific clinical situations.

1. Introduction

Thyroid-associated ophthalmopathy (TAO), also known as Graves' orbitopathy or thyroid eye disease, is an autoimmune inflammatory disorder of the orbital and periorbital tissues that affects approximately 25%–50% of patients with Graves' disease (1, 2). Its clinical manifestations range from mild soft-tissue swelling to sight-threatening compressive optic neuropathy and corneal exposure (1, 2). For patients with moderate-to-severe active disease who respond inadequately to corticosteroids or have contraindications to medical therapy, orbital radiotherapy remains an established treatment option (3, 4). Orbital radiotherapy is commonly delivered to a total dose of 20 Gy in 10 fractions and has been associated with improvements in ocular motility, soft-tissue signs, and disease activity, with reported response rates of approximately 60%–75% (3–5, 18).

Conventional opposed lateral fields have increasingly been replaced by more conformal techniques, including intensity-modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT) (6–8). Previous dosimetric studies have reported that VMAT provides target coverage comparable to IMRT, with lower integral dose to uninvolved normal tissues and shorter treatment delivery times

(5, 6, 19). However, VMAT plan quality is influenced by several planning parameters, including the number of arcs and collimator angle configuration (8–10).

Increasing the number of arcs provides additional angular degrees of freedom for plan optimization. Previous planning studies in head-and-neck and prostate VMAT have shown that increasing the number of arcs from two to four can improve target conformity and OAR sparing, although this may increase MUs and delivery complexity (9, 10, 20). Whether these findings extrapolate to orbital irradiation is uncertain. Orbital targets are small and geometrically complex and lie close to radiosensitive structures, including the lenses, optic nerves, optic chiasm, and brainstem. The dosimetric benefit of additional arcs may therefore differ from that reported for larger treatment volumes.

Collimator angle is another planning parameter that determines the orientation of the multileaf collimator (MLC) leaves relative to the target. Collimator rotation changes the direction of MLC leaf travel and the relationship between the leaf-end penumbra and adjacent OARs, which may influence dose gradients and OAR sparing (11–14, 25). In orbital VMAT, Kim et al (12) reported that collimator angle affected lens dose; however, their analysis focused primarily on 2Arc configurations and did not examine the interaction with arc number. To our knowledge, the combined dosimetric effects of arc number and collimator angle have not been systematically evaluated in VMAT for TAO.

We therefore conducted a treatment planning study in which 16 VMAT plans were generated for each of 24 patients with TAO using two arc configurations and eight collimator angle combinations, resulting in 384 plans. We hypothesized that 4Arc VMAT would improve target dosimetry and OAR sparing compared with 2Arc VMAT and that collimator angle configuration would influence target and OAR dose metrics.

2. Methods and Materials

2.1 Patient Cohort

This retrospective planning study included 24 patients with TAO who underwent orbital VMAT planning at our institution and had complete planning CT datasets. The study was approved by the institutional review board (approval no. [B]KY202563). The mean age was 45.2 ± 12.8 years; 18 patients (75.0%) were female and 6 (25.0%) were male. All patients had a diagnosis of TAO. Information on NOSPECS classification, Clinical Activity Score (CAS), symptom duration, and prior corticosteroid treatment was unavailable in the medical records and was therefore not included in the analysis. All patients provided written informed consent for the use of anonymized planning data for research purposes.

2.2 Target Volume and OAR Delineation

The CTV comprised the retrobulbar soft tissues, including the medial, lateral, superior, and inferior rectus muscles, as described previously (5, 6). No additional planning target volume (PTV) margin was applied for plan generation. Twelve anatomical structures were contoured on axial planning CT images (slice thickness, 1 mm) using the Eclipse treatment planning system (Varian Medical Systems, Palo Alto, CA): the clinical target volume (CTV1); the bilateral globes; the bilateral lenses; the brainstem; the bilateral hippocampi; the bilateral optic nerves; the optic chiasm; and the pituitary gland. Structure volumes were computed within Eclipse; summary statistics are presented in Table 1.

Table 1
Structure volume statistics (n = 24)

Structure	Mean $\pm$ SD (cc)	Median (cc)	Range (cc)
CTV1 (target)	29.46 $\pm$ 6.39	28.91	18.35–43.45
Eye_L	10.23 $\pm$ 1.45	10.11	7.89–13.12
Eye_R	10.18 $\pm$ 1.52	10.05	7.65–13.45
Lens_L	0.21 $\pm$ 0.04	0.20	0.15–0.29
Lens_R	0.20 $\pm$ 0.04	0.20	0.14–0.28
BrainStem	22.88 $\pm$ 3.12	22.45	17.89–29.34
Hippocampus_L	4.45 $\pm$ 0.62	4.39	3.52–5.89
Hippocampus_R	4.52 $\pm$ 0.59	4.48	3.61–5.92
OpticNerve_L	1.85 $\pm$ 0.31	1.82	1.34–2.51
OpticNerve_R	1.83 $\pm$ 0.29	1.80	1.32–2.48
OpticChiasm	0.68 $\pm$ 0.12	0.66	0.49–0.94
Pituitary	0.51 $\pm$ 0.13	0.49	0.32–0.78
SD = standard deviation; CTV1 = clinical target volume 1.			

2.3 Treatment Planning

All plans were generated in Eclipse version 16.1 (Varian Medical Systems) using the Acuros XB (AXB) dose-calculation algorithm and were configured for delivery on a Varian EDGE linear accelerator (23, 24). The prescription was 2000 cGy in 10 fractions (200 cGy per fraction), normalized such that 100% of the prescription isodose covered at least 95% of CTV1 (a benign indication), consistent with the recommendations of the International Commission on Radiation Units and Measurements (ICRU) Report 83 (26). Plans used 6-MV flattening-filter-free (FFF) beams at a maximum dose rate of 1400 MU/min, a dose-calculation grid of $1.5 \times 1.5 \times 1.5$ mm³, an Aperture Shape Controller (ASC) setting of Very High, and an HD120 multileaf collimator. For each patient, identical optimization objectives and priorities were used across all plans to minimize differences unrelated to arc number and collimator configuration. All plans were generated by a single experienced medical physicist and reviewed by radiation oncologists before analysis.

For each patient, 16 VMAT plans were generated using two arc configurations (2Arc and 4Arc) and eight collimator angle combinations. For each patient, 16 VMAT plans were generated using two arc configurations (2Arc and 4Arc) and eight collimator angle combinations. The eight angle combinations were C0-0H, C15-345H, C30-330H, C45-315H, C60-300H, C68-292H, C75-285H, and C90-270H, corresponding to effective collimator rotations of 0°, 15°, 30°, 45°, 60°, 68°, 75°, and 90°, respectively (15). For 4Arc plans, four full arcs were used, with two arcs assigned to each complementary collimator angle. The arcs were delivered as clockwise and counterclockwise 360° rotations around the isocenter.

2.4 Plan Evaluation

Dosimetric and plan-complexity metrics were extracted from each approved plan and grouped into three categories: (1) target metrics—CTV1 homogeneity index (HI), conformity index (CI), gradient index (GI), Dmax, and D98; (2) OAR metrics—maximum dose (Dmax) to each OAR; and (3) plan-complexity and quality metrics—total MUs, MLC leaf travel, modulation complexity score for VMAT (MCSv), and plan quality score (PQS) (16, 17). HI was calculated as $(D2 - D98)/D50$, with lower values indicating greater dose homogeneity. CI was calculated as $(TV_RI/TV) \times (TV_RI/V_RI)$, where TV is the target volume, V_RI is the total volume enclosed by the prescription reference isodose line, and TV_RI represents the target volume covered by the prescription reference isodose. CN ranges from 0 to 1. GI was calculated as $V50\%/V100\%$, where V50% and V100% represent the volumes encompassed by the 50% and 100% prescription isodose levels, respectively. In addition, axial isodose distributions at the mid-orbital level were exported for visual comparison of dose-distribution shape, symmetry, and gradient behavior across collimator configurations.

2.5 Statistical Analysis

Differences among the eight collimator angles were assessed separately for the 2Arc and 4Arc plans using the Friedman test. Kendall's W was used as the effect-size measure, and significant Friedman tests were followed by Nemenyi post hoc pairwise comparisons. At each

collimator angle, paired 2Arc and 4Arc plans were compared using the Wilcoxon signed-rank test. Because 20 metrics were tested at each angle, Benjamini–Hochberg correction was applied separately within each angle to control the false discovery rate. Effect size r was calculated as $|Z|/\sqrt{N}$, where Z is the standardized Wilcoxon test statistic and $N = 24$ paired cases. All analyses were conducted in Python 3.13 (SciPy 1.14); figures were produced in R 4.6.0 (ggplot2, patchwork).

2.6 Ethics Statement

This retrospective study was approved by the institutional review board (approval no. (B)KY202563). All patient data were anonymized before analysis, and the requirement for informed consent was waived because of the retrospective nature of the study. The study was conducted in accordance with the principles of the Declaration of Helsinki.

3. Results

3.1 Influence of Collimator Angle on Dose Distribution (Friedman Test)

The effects of collimator angle were assessed separately in the 2Arc and 4Arc groups across the eight angle configurations. The results for the 2Arc and 4Arc groups are presented in Tables 2 and 3, respectively. (1) All evaluated metrics differed significantly across collimator angles ($P < 0.001$). (2) Kendall's W values were generally higher in the 4Arc group than in the 2Arc group, suggesting greater variation in dosimetric parameters across collimator angles with 4Arc plans. (3) Strong angle effects were observed for HI, CI, Dmax, D98, leaf travel, and total MUs, whereas most OAR metrics showed moderate effects. Kendall's W was below 0.4 for both hippocampi. (4) The 0° and 15° configurations generally showed less favorable target dosimetry and higher OAR Dmax values, whereas the 60° – 90° range showed better target homogeneity and lower OAR doses.

Table 2
Dosimetric values (mean $\pm$ SD) and Nemenyi subset letters across 8 collimator angles under the 2Arc configuration

Dosimetric parameter	Friedman Q	df	P	W	C0-0H	C15-345H	C30-330H	C45-315H	C60-300H	C68-292H	C75-285H	C90-270H
CTV1 HI	132.79	7	P < 0.001	0.790	0.252 $\pm$ 0.070 d	0.151 $\pm$ 0.028 cd	0.081 $\pm$ 0.020 bc	0.064 $\pm$ 0.012 a	0.060 $\pm$ 0.008 a	0.061 $\pm$ 0.009 a	0.068 $\pm$ 0.013 ab	0.072 $\pm$ 0.015 ab
CTV1 CI	122.31	7	P < 0.001	0.728	0.551 $\pm$ 0.106 a	0.716 $\pm$ 0.079 ab	0.847 $\pm$ 0.054 bc	0.879 $\pm$ 0.029 cd	0.889 $\pm$ 0.029 d	0.889 $\pm$ 0.029 d	0.877 $\pm$ 0.034 cd	0.875 $\pm$ 0.040 cd
CTV1 GI	98.50	7	P < 0.001	0.586	3.75 $\pm$ 0.474 a	4.45 $\pm$ 0.362 ab	4.79 $\pm$ 0.354 bc	4.88 $\pm$ 0.451 c	4.91 $\pm$ 0.444 c	4.91 $\pm$ 0.459 c	4.86 $\pm$ 0.449 c	4.86 $\pm$ 0.488 c
CTV1 Dmax	117.68	7	P < 0.001	0.700	2619.9 $\pm$ 145.0 d	2380.6 $\pm$ 63.31 cd	2250.5 $\pm$ 45.15 bc	2215.1 $\pm$ 31.91 ab	2204.3 $\pm$ 28.97 a	2202.3 $\pm$ 23.99 a	2216.2 $\pm$ 30.84 ab	2222.8 $\pm$ 41.22 ab
CTV1 D98	125.99	7	P < 0.001	0.750	1889.9 $\pm$ 63.90 a	1933.6 $\pm$ 14.55 ab	1973.5 $\pm$ 11.52 bc	1983.1 $\pm$ 4.32 d	1983.9 $\pm$ 3.13 d	1982.9 $\pm$ 3.29 d	1981.3 $\pm$ 4.41 cd	1978.4 $\pm$ 6.38 cd
BrainStem Dmax	113.22	7	P < 0.001	0.674	521.7 $\pm$ 52.73 d	456.1 $\pm$ 24.66 cd	419.4 $\pm$ 21.73 bc	402.9 $\pm$ 17.43 ab	402.0 $\pm$ 14.78 ab	399.3 $\pm$ 13.46 a	403.2 $\pm$ 15.77 ab	398.4 $\pm$ 16.16 a
Eye_L Dmax	108.14	7	P < 0.001	0.644	2428.6 $\pm$ 184.9 d	2189.0 $\pm$ 66.88 cd	2080.9 $\pm$ 52.66 bc	2046.2 $\pm$ 52.72 ab	2041.8 $\pm$ 50.20 ab	2038.1 $\pm$ 58.43 ab	2035.7 $\pm$ 56.00 a	2046.8 $\pm$ 65.87 ab
Eye_R Dmax	100.88	7	P < 0.001	0.600	2393.2 $\pm$ 154.8 b	2175.4 $\pm$ 64.26 b	2077.1 $\pm$ 68.94 a	2053.0 $\pm$ 67.88 a	2050.5 $\pm$ 65.59 a	2046.6 $\pm$ 59.50 a	2050.6 $\pm$ 60.07 a	2058.5 $\pm$ 87.09 a
Lens_L Dmax	103.47	7	P < 0.001	0.616	482.3 $\pm$ 125.6 b	313.0 $\pm$ 68.42 b	212.6 $\pm$ 23.22 a	200.2 $\pm$ 18.61 a	197.0 $\pm$ 19.56 a	194.2 $\pm$ 22.20 a	191.7 $\pm$ 22.83 a	190.4 $\pm$ 33.99 a
Lens_R Dmax	104.85	7	P < 0.001	0.624	496.7 $\pm$ 132.9 b	298.5 $\pm$ 49.08 b	211.2 $\pm$ 26.19 a	196.8 $\pm$ 20.77 a	194.1 $\pm$ 23.43 a	199.5 $\pm$ 27.09 a	194.8 $\pm$ 24.54 a	187.0 $\pm$ 34.78 a
Hipp_L Dmax	52.17	7	P < 0.001	0.311	546.8 $\pm$ 107.5 a	585.8 $\pm$ 42.55 b	510.8 $\pm$ 40.41 a	497.3 $\pm$ 30.97 a	500.7 $\pm$ 24.55 a	490.4 $\pm$ 34.44 a	501.3 $\pm$ 34.43 a	503.6 $\pm$ 34.11 a
Hipp_R Dmax	39.82	7	P < 0.001	0.237	495.1 $\pm$ 122.0 a	549.4 $\pm$ 69.88 b	478.3 $\pm$ 62.04 a	470.7 $\pm$ 72.15 a	478.4 $\pm$ 51.57 a	479.6 $\pm$ 51.55 a	487.2 $\pm$ 56.50 a	500.8 $\pm$ 54.27 ab
ON_L Dmax	108.81	7	P < 0.001	0.648	2406.9 $\pm$ 128.8 b	2225.8 $\pm$ 61.02 b	2106.4 $\pm$ 29.69 a	2087.0 $\pm$ 22.13 a	2085.6 $\pm$ 18.11 a	2087.2 $\pm$ 23.20 a	2094.5 $\pm$ 21.85 a	2099.1 $\pm$ 24.31 a
ON_R Dmax	105.67	7	P < 0.001	0.629	2385.7 $\pm$ 124.2 b	2214.6 $\pm$ 54.97 b	2106.7 $\pm$ 36.09 a	2086.4 $\pm$ 23.77 a	2081.5 $\pm$ 14.84 a	2086.3 $\pm$ 20.87 a	2090.3 $\pm$ 23.83 a	2099.2 $\pm$ 30.00 a
Chiasm Dmax	90.03	7	P < 0.001	0.536	1332.7 $\pm$ 184.1 d	1281.1 $\pm$ 107.3 d	1227.4 $\pm$ 97.30 cd	1180.3 $\pm$ 114.2 bc	1165.5 $\pm$ 121.7 abc	1133.3 $\pm$ 127.0 ab	1135.1 $\pm$ 123.9 ab	1119.2 $\pm$ 132.6 a
Pituitary Dmax	81.97	7	P < 0.001	0.488	708.3 $\pm$ 90.55 c	581.5 $\pm$ 94.48 bc	527.2 $\pm$ 99.69 ab	519.3 $\pm$ 94.35 a	504.7 $\pm$ 70.48 a	499.3 $\pm$ 79.90 a	502.1 $\pm$ 77.32 a	503.2 $\pm$ 84.53 a

Q = Friedman chi-square statistic; df = 7; P = Friedman test P value (P < 0.001 for all indices under both arc configurations); W = Kendall's W (overall effect size). For each collimator angle, the cell shows the actual dosimetric value as mean $\pm$ SD across the 24 patients, with the Nemenyi post hoc homogeneous-subset letter placed after the numbers. The letter denotes the result of the Nemenyi post hoc test following the significant Friedman test: angles that share the same letter are not significantly different from each other (Nemenyi-adjusted P > 0.05), whereas angles carrying different letters differ significantly. Target conformity/homogeneity indices are dimensionless, Dmax values are in cGy, Total MU is monitor units, and Leaf Travel / MCSv / PQS are plan-complexity indices.

Dosimetric parameter	Friedman Q	df	P	W	C0-0H	C15-345H	C30-330H	C45-315H	C60-300H	C68-292H	C75-285H	C90-270H
Total MU	117.56	7	P < 0.001	0.700	1463.5 ± 272.8 c	1404.9 ± 160.8 c	949.9 ± 145.7 bc	805.4 ± 93.63 ab	743.1 ± 65.62 a	750.4 ± 77.25 a	780.1 ± 131.5 a	781.3 ± 194.3 a
Leaf Travel	140.69	7	P < 0.001	0.837	3026.6 ± 239.0 a	3652.1 ± 284.9 ab	4216.4 ± 300.2 b	4728.1 ± 366.2 c	4740.5 ± 294.8 c	4745.9 ± 307.0 c	4682.5 ± 361.5 c	4392.1 ± 758.1 b
MCSv	111.81	7	P < 0.001	0.666	0.634 ± 0.018 a	0.639 ± 0.020 ab	0.649 ± 0.016 bc	0.635 ± 0.015 a	0.643 ± 0.012 ab	0.651 ± 0.014 bc	0.666 ± 0.014 cd	0.702 ± 0.022 d
PQS	101.83	7	P < 0.001	0.606	70.43 ± 3.86 a	73.80 ± 3.58 ab	77.81 ± 4.04 bc	78.75 ± 3.88 cd	79.01 ± 4.02 d	78.97 ± 4.11 cd	78.74 ± 3.86 cd	78.48 ± 4.58 cd

Q = Friedman chi-square statistic; df = 7; P = Friedman test P value (P < 0.001 for all indices under both arc configurations); W = Kendall's W (overall effect size). For each collimator angle, the cell shows the actual dosimetric value as mean ± SD across the 24 patients, with the Nemenyi post hoc homogeneous-subset letter placed after the numbers. The letter denotes the result of the Nemenyi post hoc test following the significant Friedman test: angles that share the same letter are not significantly different from each other (Nemenyi-adjusted P > 0.05), whereas angles carrying different letters differ significantly. Target conformity/homogeneity indices are dimensionless, Dmax values are in cGy, Total MU is monitor units, and Leaf Travel / MCSv / PQS are plan-complexity indices.

Table 3
Dosimetric values (mean $\pm$ SD) and Nemenyi subset letters across 8 collimator angles under the 4Arc configuration

Dosimetric parameter	Friedman Q	df	P	W	C0-0H	C15-345H	C30-330H	C45-315H	C60-300H	C68-292H	C75-285H	C90-270H
CTV1 HI	134.83	7	P < 0.001	0.803	0.218 $\pm$ 0.055 d	0.133 $\pm$ 0.028 cd	0.075 $\pm$ 0.015 bc	0.059 $\pm$ 0.010 a	0.055 $\pm$ 0.006 a	0.056 $\pm$ 0.008 a	0.059 $\pm$ 0.009 a	0.063 $\pm$ 0.010 ab
CTV1 CI	123.79	7	P < 0.001	0.737	0.589 $\pm$ 0.103 a	0.751 $\pm$ 0.070 ab	0.856 $\pm$ 0.049 b	0.890 $\pm$ 0.027 c	0.898 $\pm$ 0.025 c	0.897 $\pm$ 0.024 c	0.895 $\pm$ 0.029 c	0.892 $\pm$ 0.023 c
CTV1 GI	76.97	7	P < 0.001	0.458	3.91 $\pm$ 0.432 a	4.61 $\pm$ 0.346 ab	4.82 $\pm$ 0.364 bc	4.87 $\pm$ 0.443 bc	4.91 $\pm$ 0.491 c	4.93 $\pm$ 0.491 c	4.91 $\pm$ 0.428 c	4.89 $\pm$ 0.472 bc
CTV1 Dmax	126.81	7	P < 0.001	0.755	2561.3 $\pm$ 130.2 d	2338.8 $\pm$ 58.45 cd	2237.9 $\pm$ 39.35 bc	2206.3 $\pm$ 34.13 ab	2186.0 $\pm$ 20.66 a	2190.3 $\pm$ 24.96 a	2196.2 $\pm$ 22.16 a	2203.7 $\pm$ 24.81 ab
CTV1 D98	126.18	7	P < 0.001	0.751	1922.6 $\pm$ 42.00 a	1939.1 $\pm$ 18.19 ab	1976.4 $\pm$ 8.36 bc	1983.8 $\pm$ 4.85 de	1985.1 $\pm$ 2.28 e	1984.1 $\pm$ 2.48 de	1983.4 $\pm$ 3.34 cde	1980.8 $\pm$ 4.39 cd
BrainStem Dmax	120.85	7	P < 0.001	0.719	499.8 $\pm$ 34.42 d	450.1 $\pm$ 26.01 cd	407.4 $\pm$ 12.82 bc	399.5 $\pm$ 14.10 ab	394.2 $\pm$ 14.83 a	392.2 $\pm$ 15.09 a	391.3 $\pm$ 14.64 a	392.8 $\pm$ 17.36 a
Eye_L Dmax	114.86	7	P < 0.001	0.684	2375.9 $\pm$ 133.9 d	2154.3 $\pm$ 66.45 cd	2072.9 $\pm$ 50.91 bc	2048.0 $\pm$ 53.52 ab	2030.6 $\pm$ 57.26 ab	2028.5 $\pm$ 54.28 ab	2019.8 $\pm$ 46.69 a	2025.2 $\pm$ 44.04 ab
Eye_R Dmax	103.83	7	P < 0.001	0.618	2349.0 $\pm$ 146.9 b	2148.1 $\pm$ 79.80 b	2056.6 $\pm$ 70.83 a	2041.1 $\pm$ 69.77 a	2035.3 $\pm$ 66.74 a	2030.7 $\pm$ 61.72 a	2034.1 $\pm$ 77.25 a	2031.3 $\pm$ 74.26 a
Lens_L Dmax	113.46	7	P < 0.001	0.675	433.8 $\pm$ 100.0 d	313.2 $\pm$ 65.16 cd	210.6 $\pm$ 20.78 bc	199.1 $\pm$ 18.62 ab	195.0 $\pm$ 15.11 ab	194.5 $\pm$ 16.81 ab	193.6 $\pm$ 18.60 ab	184.9 $\pm$ 24.34 a
Lens_R Dmax	109.81	7	P < 0.001	0.654	450.0 $\pm$ 116.4 c	290.8 $\pm$ 49.46 c	208.0 $\pm$ 26.20 b	192.4 $\pm$ 21.62 ab	194.9 $\pm$ 23.16 ab	194.6 $\pm$ 23.23 ab	188.0 $\pm$ 23.23 ab	189.0 $\pm$ 28.56 a
Hipp_L Dmax	41.83	7	P < 0.001	0.249	505.8 $\pm$ 121.3 a	558.5 $\pm$ 37.83 b	503.1 $\pm$ 35.27 a	496.7 $\pm$ 28.02 a	488.8 $\pm$ 27.30 a	486.2 $\pm$ 32.03 a	492.2 $\pm$ 29.18 a	493.9 $\pm$ 33.99 a
Hipp_R Dmax	46.31	7	P < 0.001	0.276	485.5 $\pm$ 107.4 a	532.9 $\pm$ 61.62 b	474.4 $\pm$ 58.53 a	471.6 $\pm$ 60.29 a	475.1 $\pm$ 47.74 a	479.7 $\pm$ 54.16 a	478.4 $\pm$ 52.71 a	488.3 $\pm$ 57.34 a
ON_L Dmax	115.61	7	P < 0.001	0.688	2352.4 $\pm$ 79.85 d	2184.2 $\pm$ 45.10 cd	2100.5 $\pm$ 28.78 bc	2075.6 $\pm$ 18.52 a	2075.7 $\pm$ 14.11 a	2075.7 $\pm$ 18.79 a	2079.5 $\pm$ 19.78 ab	2086.1 $\pm$ 15.30 ab
ON_R Dmax	113.62	7	P < 0.001	0.676	2335.9 $\pm$ 99.67 b	2180.0 $\pm$ 53.43 b	2091.6 $\pm$ 25.76 a	2075.3 $\pm$ 23.23 a	2076.1 $\pm$ 19.50 a	2075.2 $\pm$ 14.10 a	2075.7 $\pm$ 16.83 a	2083.7 $\pm$ 19.35 a
Chiasm Dmax	73.03	7	P < 0.001	0.435	1276.5 $\pm$ 207.4 c	1257.9 $\pm$ 97.51 c	1192.5 $\pm$ 97.07 bc	1181.2 $\pm$ 103.2 bc	1158.8 $\pm$ 107.7 ab	1150.5 $\pm$ 118.5 ab	1124.3 $\pm$ 112.2 a	1114.6 $\pm$ 146.0 a
Pituitary Dmax	68.74	7	P < 0.001	0.409	663.4 $\pm$ 95.72 c	561.2 $\pm$ 78.76 bc	523.7 $\pm$ 92.14 ab	516.3 $\pm$ 92.71 ab	502.1 $\pm$ 74.40 a	500.4 $\pm$ 83.39 a	505.6 $\pm$ 82.15 a	491.2 $\pm$ 81.53 a
Total MU	121.65	7	P < 0.001	0.724	1479.6 $\pm$ 272.7 c	1427.5 $\pm$ 138.1 c	972.3 $\pm$ 126.7 bc	828.0 $\pm$ 89.98 ab	781.2 $\pm$ 71.27 a	794.1 $\pm$ 103.9 a	771.1 $\pm$ 109.1 a	779.9 $\pm$ 95.38 a

Abbreviations and conventions as in Table 2.

Dosimetric parameter	Friedman Q	df	P	W	C0-0H	C15-345H	C30-330H	C45-315H	C60-300H	C68-292H	C75-285H	C90-270H
Leaf Travel	144.49	7	P < 0.001	0.860	5823.6 ± 461.1 a	7131.7 ± 785.1 ab	8260.9 ± 625.2 bc	9169.5 ± 717.6 d	9328.8 ± 612.5 d	9316.4 ± 617.1 d	8952.3 ± 609.7 cd	8252.1 ± 759.2 bc
MCSv	116.62	7	P < 0.001	0.694	0.629 ± 0.019 ab	0.640 ± 0.020 abc	0.646 ± 0.015 bc	0.633 ± 0.015 a	0.641 ± 0.015 abc	0.650 ± 0.015 cd	0.668 ± 0.012 de	0.704 ± 0.017 e
PQS	110.85	7	P < 0.001	0.660	71.67 ± 3.53 a	74.30 ± 3.87 ab	78.14 ± 3.96 bc	79.34 ± 3.99 d	79.49 ± 4.37 d	79.25 ± 4.21 cd	79.22 ± 3.93 cd	79.09 ± 4.03 cd
Abbreviations and conventions as in Table 2.												

3.2 Dosimetric Comparison of 2Arc and 4Arc at the Same Collimator Angle (Wilcoxon Signed-Rank Test)

Paired comparisons between 2Arc and 4Arc plans at each collimator angle are summarized in Table 4. (1) At most collimator angles, 4Arc plans showed better target homogeneity and conformity and lower doses to most OARs than 2Arc plans. (2) The largest effect sizes were observed for brainstem Dmax and CTV1 HI, with maximum r values exceeding 0.8. (3) For target metrics, the largest effect sizes were most often observed at 75° (3 of 5 metrics), whereas OAR effect sizes tended to peak at 0°, 15°, or 45°, with four OARs showing their largest effect at 0°. Figure 1 shows the effect-size analysis of collimator angle on the dose to each OAR: the maximum achievable effect strengths of 2Arc and 4Arc were essentially consistent, with strong dose-modulating effects on the brainstem, optic nerves, eyes, and lenses; the maximum effect sizes of most OARs occurred at small angles, and the dose influence on both hippocampi was weak.

Table 4
Wilcoxon Signed-Rank Test Summary: 2Arc vs 4Arc Dosimetric Parameters

Category	Dosimetric Parameter	2Arc Mean $\pm$ SD	4Arc Mean $\pm$ SD	Sig. Angles (n/8: angles)	Effect Size r Range	Max r Angle
TARGET						
Target	CTV1 CI	0.8153 $\pm$ 0.1267	0.8333 $\pm$ 0.1154	7/8: 0°, 15°, 45°, 60°, 68°, 75°	0.2624–0.7815	45° (0.7815)
Target	CTV1 D98	1963.3 $\pm$ 39.6	1969.4 $\pm$ 28.1	5/8: 0°, 15°, 60°, 68°, 75°	0.3616–0.6999	75° (0.6999)
Target	CTV1 Dmax	2289.0 $\pm$ 150.4	2265.1 $\pm$ 133.5	5/8: 15°, 60°, 68°, 75°, 90°	0.3674–0.7232	75° (0.7232)
Target	CTV1 GI	4.68 $\pm$ 0.57	4.73 $\pm$ 0.54	2/8: 15°, 75°	0.1575–0.6649	15° (0.6649)
Target	CTV1 HI	0.1010 $\pm$ 0.0698	0.0898 $\pm$ 0.0592	7/8: 0°, 15°, 45°, 60°, 68°, 75°	0.4432–0.834	75° (0.834)
OAR						
OAR	BrainStem Dmax	425.4 $\pm$ 47.6	415.9 $\pm$ 41.6	5/8: 0°, 30°, 60°, 68°, 75°	0.2974–0.8632	75° (0.8632)
OAR	Eye_L Dmax	2113.4 $\pm$ 153.3	2094.4 $\pm$ 133.0	3/8: 15°, 68°, 75°	0.0292–0.6415	15° (0.6415)
OAR	Eye_R Dmax	2113.1 $\pm$ 140.3	2090.8 $\pm$ 133.7	3/8: 68°, 75°, 90°	0.3733–0.6999	90° (0.6999)
OAR	Hipp_L Dmax	517.1 $\pm$ 57.9	503.2 $\pm$ 55.9	2/8: 15°, 60°	0.0233–0.6474	15° (0.6474)
OAR	Hipp_R Dmax	492.4 $\pm$ 73.5	485.8 $\pm$ 66.3	0/8: —	0.0117–0.4199	15° (0.4199)
OAR	Lens_L Dmax	247.7 $\pm$ 110.7	240.6 $\pm$ 94.2	1/8: 0°	0.0058–0.5132	0° (0.5132)
OAR	Lens_R Dmax	247.3 $\pm$ 114.0	238.5 $\pm$ 99.1	1/8: 0°	0.0816–0.4899	0° (0.4899)
OAR	ON_L Dmax	2149.1 $\pm$ 119.7	2128.7 $\pm$ 98.3	6/8: 15°, 45°, 60°, 68°, 75°	0.1808–0.7815	45° (0.7815)
OAR	ON_R Dmax	2143.8 $\pm$ 113.1	2124.2 $\pm$ 96.9	5/8: 15°, 45°, 60°, 68°, 75°	0.3674–0.7057	45° (0.7057)
OAR	OpticChiasm Dmax	1196.8 $\pm$ 145.3	1182.0 $\pm$ 137.7	1/8: 0°	0.0058–0.4957	0° (0.4957)
OAR	Pituitary Dmax	543.2 $\pm$ 108.8	533.0 $\pm$ 99.4	1/8: 0°	0.0933–0.5366	0° (0.5366)
COMPLEXITY						
Complexity	Leaf Travel	4273.0 $\pm$ 706.3	8279.4 $\pm$ 1329.5	8/8: 0°, 15°, 30°, 45°, 60°, 68°, 75°, 90°	0.8748–0.8748	0° (0.8748)
Complexity	MCSv	0.6523 $\pm$ 0.0268	0.6514 $\pm$ 0.0280	1/8: 60°	0.07–0.4957	30° (0.4957)
Complexity	PQS	77.00 $\pm$ 4.92	77.56 $\pm$ 4.79	5/8: 0°, 45°, 60°, 68°, 75°	0.4024–0.7698	45° (0.7698)
Complexity	Total MU	959.9 $\pm$ 320.6	979.2 $\pm$ 312.8	3/8: 45°, 60°, 68°	0.0467–0.7873	60° (0.7873)
Aggregate means are the arithmetic means of the 24 plans at each of the 8 collimator angles (descriptive statistics, N = 192 per arc); inferential tests were performed pairwise at each angle (n = 24) with Benjamini-Hochberg correction (m = 20 per angle family). The “Sig. Angles” column (n/8) gives the number and identity of angles reaching significance after BH correction (adjusted P < 0.05); “Max r Angle” is the angle at which the effect size r peaked (based on the raw effect size and may differ from the BH-significant angle; e.g., MCSv peaked at 30° but reached BH significance only at 60°). The r value for Leaf Travel is constant at 0.8748 because the directions of the 24 paired differences were completely consistent, reaching the theoretical upper limit; this is not a typographical error. Dmax = maximum dose; CI = conformity index; HI = homogeneity index; GI = gradient index; MCSv = modulation complexity score for VMAT; PQS = plan quality score.						

3.3 Combined Evaluation of Target Dosimetry and OAR Sparing

Figure 2 shows the mean ranks of the evaluated metrics across the eight collimator angles. Figure 3 compares dosimetric and plan-complexity metrics between 2Arc and 4Arc plans at the same collimator angles. Four-arc plans generally showed better target dosimetry and lower OAR doses, with little difference in MCSv. Leaf travel and total MUs were higher with 4Arc plans, and GI was also slightly increased. Among the evaluated configurations, 4Arc_C60-300H showed the most favorable balance between target dosimetry and OAR sparing.

3.4 Composite Evaluation of OAR Sparing

Figure 4 presents the composite OAR-sparing Z scores for the different arc-number and collimator-angle combinations; lower scores indicate better overall OAR sparing. The score was calculated by standardizing the Dmax values of 11 OARs across the 16 plan configurations and averaging the resulting z scores with equal weight. It was used as a relative measure of overall OAR sparing. Composite Z scores were higher at 0° and 15° and decreased at larger collimator angles. In the 4Arc group, the lowest score was observed at 75° ($Z = -0.63$), while the scores at 68° and 90° differed from this value by less than 0.03. In the 2Arc group, the lowest score occurred at 68°. At every collimator angle, the composite Z score was lower for 4Arc than for 2Arc plans. In the 4Arc group, composite Z scores were ≤ -0.50 at 60°, 68°, 75°, and 90°, with identical scores of -0.60 at 68° and 90°. The lowest composite Z score did not coincide with the minimum Dmax for every individual OAR. In 4Arc plans, the minimum Dmax values for the optic chiasm, pituitary, and left lens occurred at 90°, whereas the lowest composite score occurred at 75°. This difference reflects the equal weighting of the standardized values for all 11 OARs. Among the evaluated configurations, 4Arc_C75-285H had the lowest composite OAR-sparing Z score. Figure 5 shows axial isodose distributions for a representative 4Arc case at the eight collimator angles. Compared with the smaller-angle plans, C75-285H showed less extension of the high-dose region toward the lenses.

4. Discussion

4.1 Principal Findings

In this study, 384 VMAT plans were generated for 24 patients with TAO using 2Arc and 4Arc configurations at eight collimator angles (0°, 15°, 30°, 45°, 60°, 68°, 75°, and 90°).

Collimator angle significantly affected target and OAR dosimetry in both the 2Arc and 4Arc configurations ($P < 0.001$). Kendall's W ranged from 0.237 to 0.860, indicating that the magnitude of the collimator-angle effect varied across dosimetric parameters.

For both arc configurations, target dosimetry was generally more favorable at 60°–75°, while lower OAR doses were observed over the broader 60°–90° range. In contrast, the 0° and 15° configurations generally showed less favorable dosimetric results. The similar pattern observed with 2Arc and 4Arc plans suggests that the preferred angle range was not markedly altered by the number of arcs.

The dosimetric differences between 2Arc and 4Arc plans also varied with collimator angle. The largest effect sizes were observed mainly at 0°, 15°, 45°, and 75°. Four OAR metrics reached their maximum effect size at 0°, whereas three target metrics reached their maximum at 75°. Among the target metrics, HI and CI differed between 2Arc and 4Arc plans at seven of the eight collimator angles. The largest effect for HI occurred at 75° ($r = 0.834$). For OARs, the largest 2Arc–4Arc effect sizes occurred mainly at 0°, 15°, and 45°. At larger collimator angles, the differences between the two arc configurations were generally smaller, particularly for OAR doses. These findings suggest that the additional dosimetric benefit of 4Arc becomes less pronounced when a favorable collimator angle is used.

The dosimetric improvements with 4Arc were accompanied by greater MLC leaf travel and a small increase in MUs. PQS was also higher, whereas MCSv remained similar between the two arc configurations. GI was slightly higher with 4Arc than with 2Arc plans (4.73 vs 4.68), suggesting slightly greater intermediate-dose spread despite the improvements in target dosimetry and OAR sparing.

4.2 Comparison With Prior Literature

Previous VMAT studies have reported similar findings in other treatment sites. Sherman et al (9) found improved conformity with four arcs in head-and-neck planning, while Kumar et al (20) reported improved plan quality despite higher MUs. Similar findings have also been reported for prostate VMAT (10). Although systemic therapy remains central to the management of active TAO, orbital radiotherapy continues to have a role in selected patients (3–5, 18, 31, 32). Previous studies of orbital radiotherapy have compared VMAT with IMRT (5, 6, 19), but the effect of increasing arc number has received little attention. Our results suggest that four-arc planning can provide additional dosimetric improvement in this setting. Our findings are also consistent with those of Kim et al (12), who reported that collimator angle affected lens dose in 2Arc orbital VMAT. In our study, lower OAR doses were generally observed at collimator angles between 60° and 90° in both the 2Arc and 4Arc configurations. When target and OAR metrics were considered together, 60° showed the

most favorable overall mean-rank profile. In contrast, the lowest composite OAR-sparing Z score was observed at 75°. This difference suggests that the preferred collimator angle may depend on whether target dosimetry or OAR sparing is given greater priority.

4.3 OAR Dose Considerations

The 4Arc lens Dmax in this study (approximately 241 cGy) is below the traditional fractionated-radiotherapy cataract dose threshold but above the International Commission on Radiological Protection (ICRP) Publication 118 threshold of 50 cGy for single-exposure lens opacities (34); per the QUANTEC review (35), the OAR doses in this study fall within the acceptable range for fractionated radiotherapy. Because the prescribed dose was delivered in 10 fractions, the biological effect on the lens cannot be inferred from a single-exposure threshold alone. Long-term clinical follow-up is needed to assess the risk of radiation-induced lens injury after orbital radiotherapy (33, 34).

4.4 Limitations

This study has several limitations. First, this was a retrospective planning study without clinical outcome data. Further studies with long-term follow-up are needed to determine whether the observed dosimetric differences are associated with clinical outcomes such as improvement in proptosis or diplopia and the development of cataracts (22, 27, 28, 33). Second, the relatively small sample size of 24 patients may limit the generalizability of the findings. Third, treatment delivery time and patient-specific QA results were not evaluated, although both are relevant to the clinical use of more complex arc configurations (16, 17). Fourth, only eight predefined collimator angle configurations were evaluated, and other angles may also provide favorable dosimetric results (29, 30). Fifth, the single-center design and the use of a single physicist for treatment planning may limit the generalizability of the findings. Finally, the composite Z score assigned equal weight to all 11 OARs. Because the score was calculated from standardized values, OARs with smaller variation in dose may have had more influence on the overall ranking. This may explain why the lowest composite Z score was found at 75°, although some individual OARs had their lowest Dmax values at other angles. The composite Z score should therefore be viewed as a relative measure of OAR sparing rather than a statistical test and interpreted together with the results for individual OARs.

5. Conclusions

Increasing the number of arcs from two to four improved target homogeneity and conformity and reduced maximum doses to most OARs. These dosimetric improvements were accompanied by greater MLC leaf travel and a small increase in MUs. Collimator angle also had a clear effect on plan dosimetry, with the 0° and 15° configurations generally showing less favorable target and OAR dose metrics. Among the configurations evaluated in this study, 4Arc_C60-300H showed the most favorable overall balance between target dosimetry and OAR sparing, while 4Arc_C75-285H showed the lowest composite OAR-sparing Z score. Further clinical studies are needed to determine whether these dosimetric differences translate into meaningful benefits for patients.

Declarations

Conflict of Interest

[The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.]

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Author Contribution

ZHANG KANG completed all plans of patients. CHEN JINGCONG wrote the main manuscript. CHEN YUHAN edit the manuscript. ZOU LU provided the data support. WANG ZHE polished sentences in article. RAN FENGWEI prepared all tables and figures.

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Data Availability Statement

[The datasets generated and analyzed during the current study are not publicly available due to ethical restrictions and patient privacy concerns, as the data contain potentially identifiable clinical information. The anonymized dose-volume histogram (DVH) data and study protocol are available from the corresponding author upon reasonable request and subject to appropriate data use agreements. Original patient records are restricted and require additional ethics committee approval (approval no. (B)KY202563) for access.]

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Figures

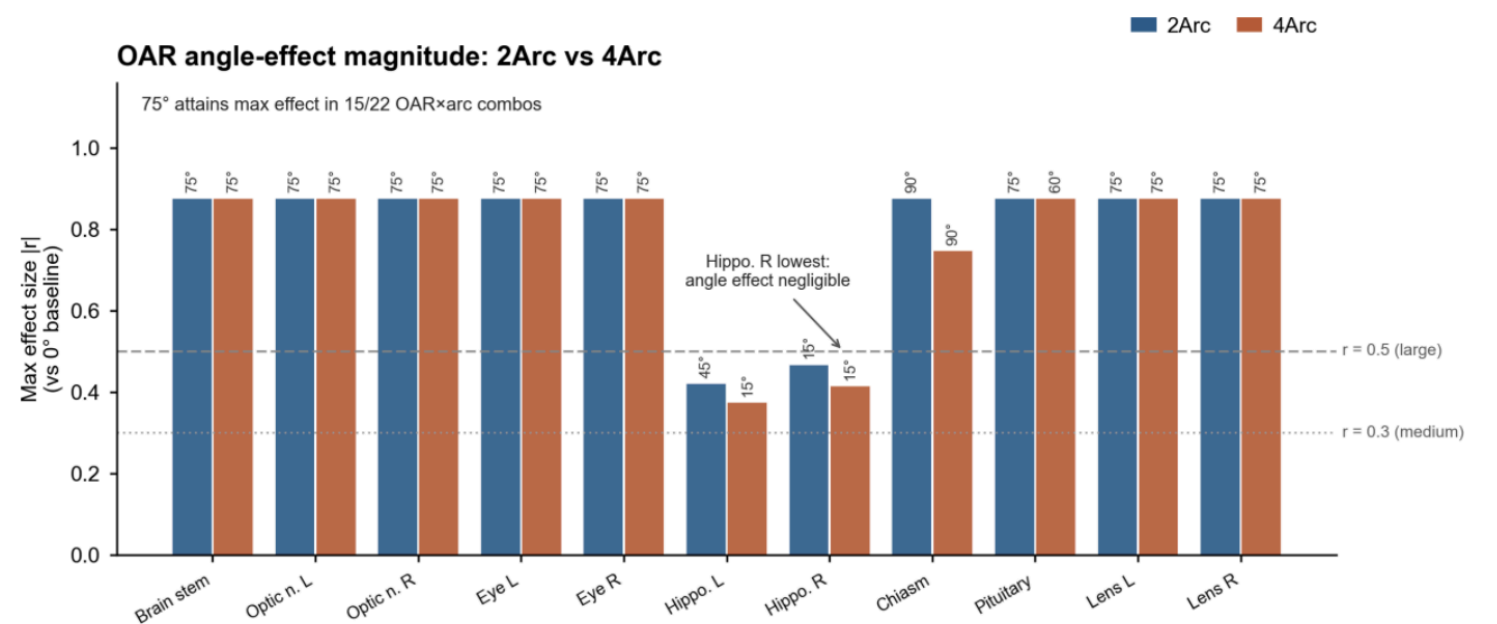


Figure 1

Effect-size (r) analysis of the influence of collimator angle on the dose to each organ at risk for 2Arc and 4Arc plans. Error bars represent 95% confidence intervals; the brainstem, optic nerves, and lenses showed relatively strong modulating effects at most angles, whereas both hippocampi showed the weakest effects.

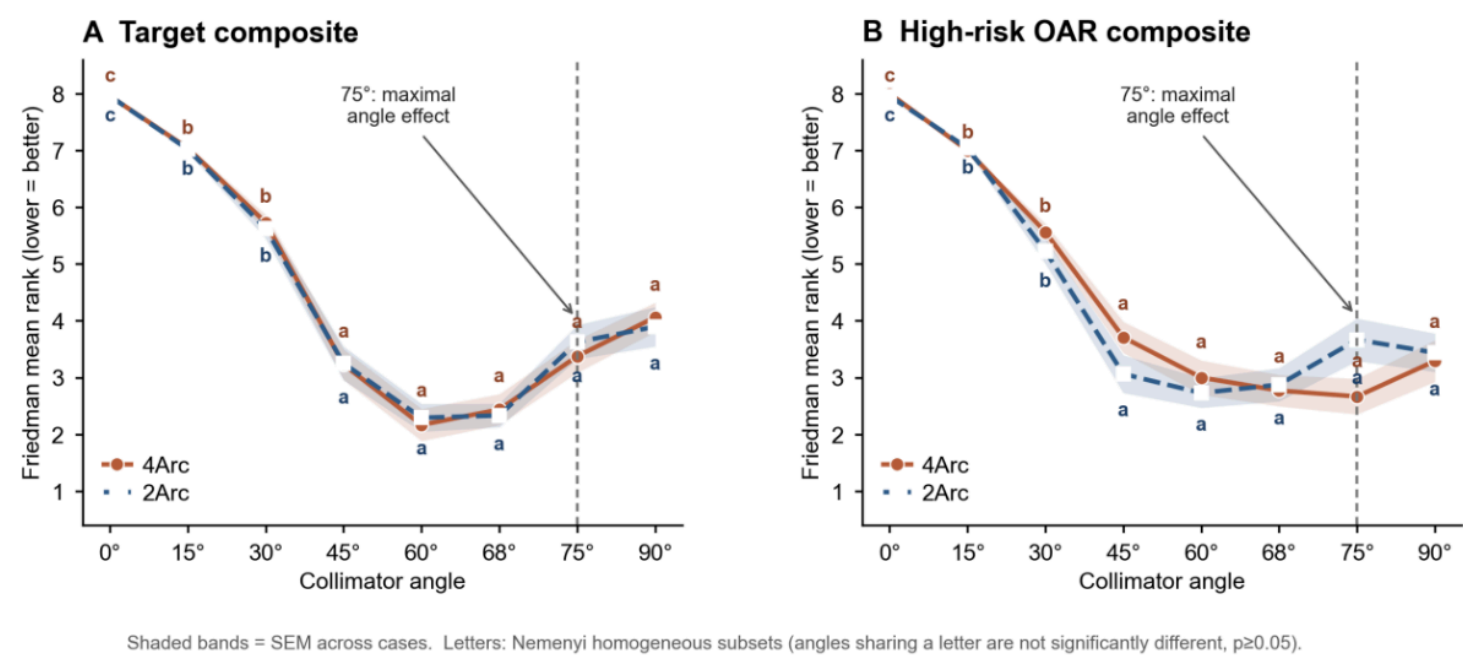


Figure 2

Stratified collimator-angle effect plot (mean ranks). (A) Mean rank of composite target metrics; (B) mean rank of high-risk OAR composite metrics. Lower ranks indicate better dosimetric performance; the 60° collimator angle was optimal overall, and 0°–30° was worst.

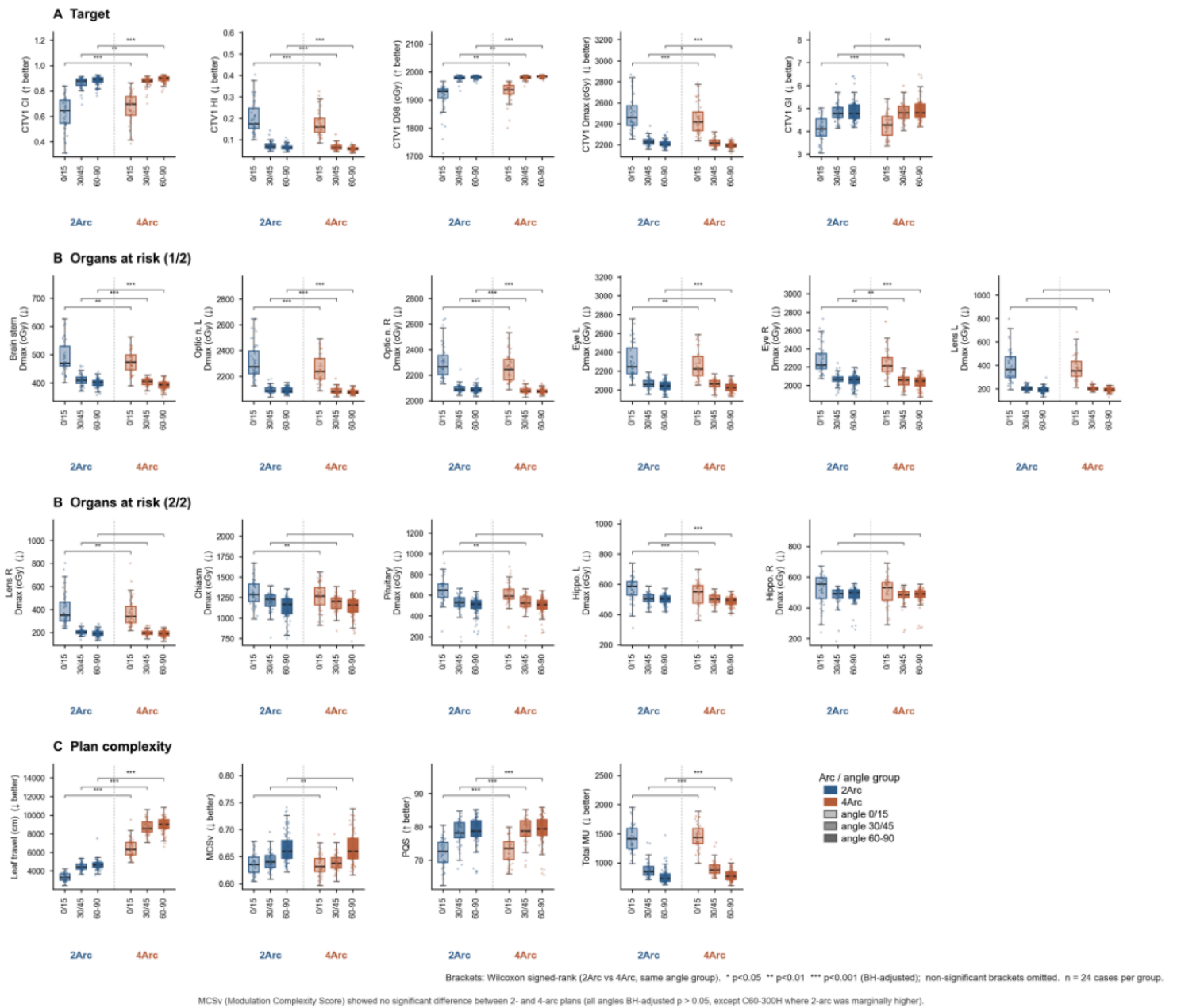


Figure 3

Dosimetric and plan-complexity comparison between 2Arc and 4Arc plans within the same collimator angle ranges. Four-arc plans improved target metrics and reduced doses to most OARs without increasing modulation complexity, at the cost of increased leaf travel and monitor units.

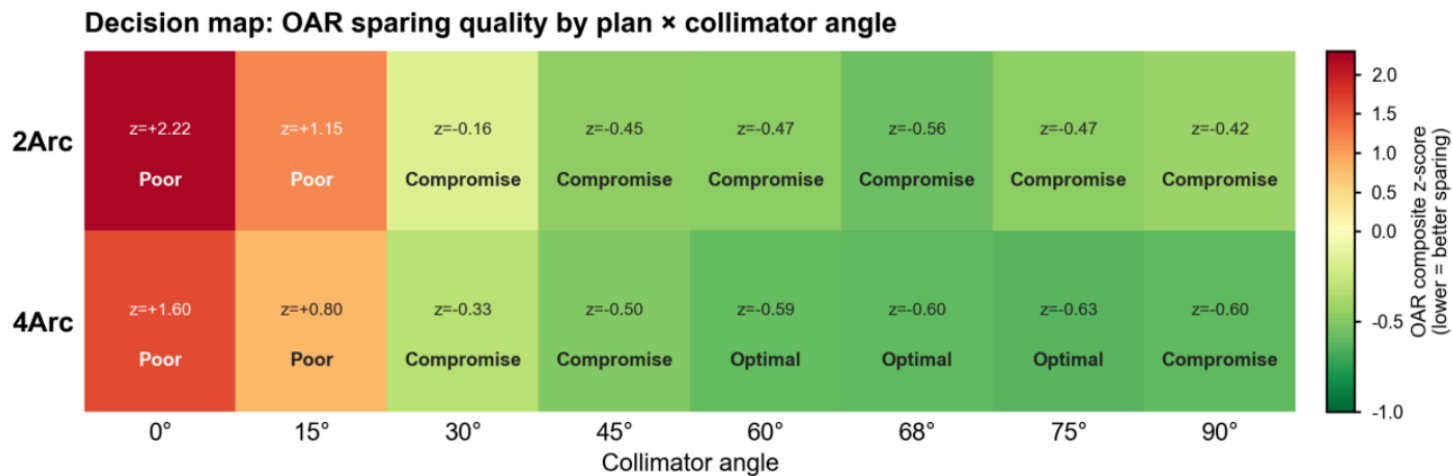


Figure 4

Composite OAR-sparing Z-score decision heatmap. Z is a relative sparing index obtained by equal-weight averaging of the Dmax of 11 OARs in global z-space (it is not a normal test statistic and cannot be interpreted directly as a P value); lower Z indicates better OAR sparing. The Optimal tier is defined as $z \leq -0.50$.

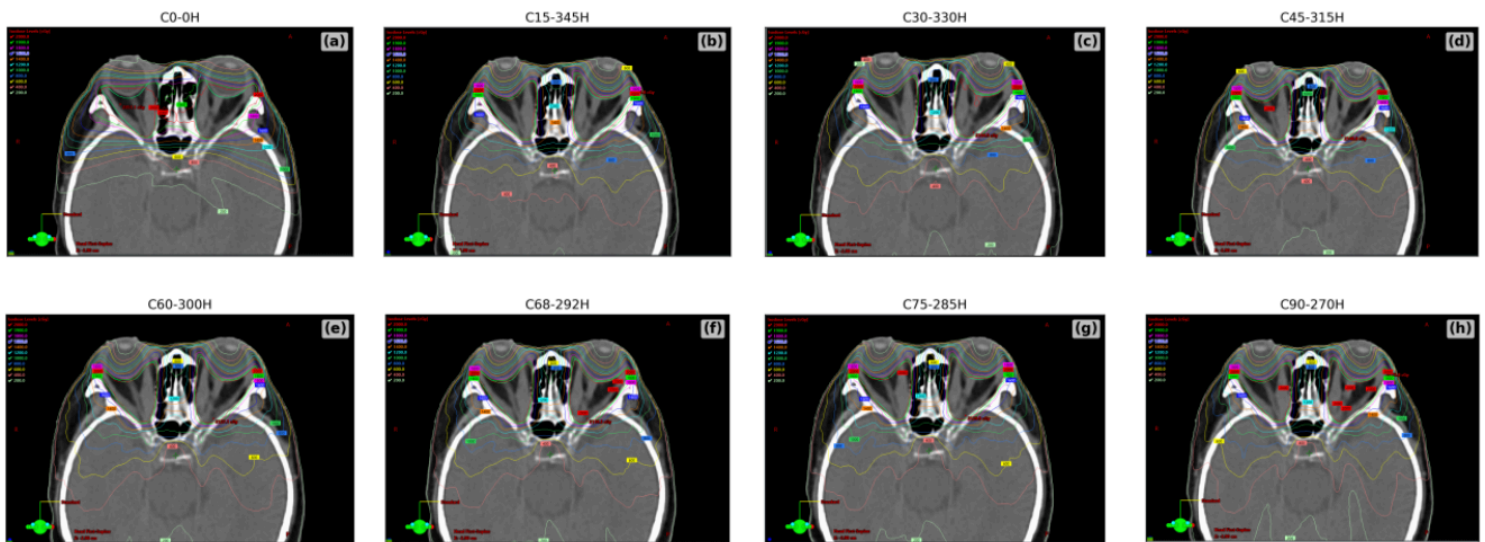


Figure 5

Mid-orbital axial isodose distributions of the 4Arc plan under the 8 collimator angle configurations for a representative case. Compared with other angles, the C75-285H isodose lines are visibly farther from high-risk OARs such as the lenses, with better convergence.

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