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An Evaluation of the Feasibility and Utility of Automated HyperArc Planning for Multiple Brain Metastases: A Comparative Dosimetric Analysis

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ABSTRACT

Purpose: In this study, we explored how automated HyperArc (HA) planning performs compared to manually designed VMAT plans in treating patients with multiple brain metastases.

Materials and Methods: Ten patients with an average of 15 brain metastases (range: 10–23) were retrospectively analyzed. All patients had undergone high-resolution CT imaging (1mm slice thickness) registered to contrast-enhanced MR sequences. Target delineation was performed by a radiation oncologist. For lesions ≥10 mm, the gross tumor volume (GTV) was equal to the planning target volume (PTV), while for smaller lesions, a 1mm isotropic margin was added. VMAT plans were generated using a single isocenter with non-coplanar arcs, while HA plans were retrospectively created with automated optimization. Prescribed doses ranged from 20 to 30 Gy, delivered in 3–5 fractions. The dosimetric parameters compared included conformity index (CI), gradient index (GI), homogeneity index (HI), healthy brain V10Gy and V12Gy volumes, maximum and median doses to the brainstem, and maximum doses to the optic chiasm, optic nerves, eyes, and lenses. Total monitor unit (MU) values were also evaluated.

Results: Target coverage was similar between VMAT and HA plans, with no statistically significant differences in CI ($p = 0.721$) or GI ($p = 0.241$). HA plans showed a trend toward increased dose homogeneity. Notably, HA significantly reduced the dose to healthy brain tissue, with V10Gy and median brain doses lower compared to VMAT. Critical structures, including the brainstem ($p = 0.009$), optic chiasm ($p = 0.013$), and lenses, also received lower doses with HA. In addition, HA plans required approximately 65% fewer monitor units than VMAT ($p = 0.007$), indicating a shorter treatment delivery time.

Conclusion: In patients with ten or more brain metastases, HA provided more favorable dosimetric outcomes for healthy brain tissue and organs at risk, while also improving treatment efficiency. These findings suggest that HA planning can deliver high-quality SRS plans with reduced dependence on manual optimization, making it a promising approach for complex multi-target cases.

Keywords: Hyperarc, VMAT, Multiple brain metastases, stereotactic radiosurgery

ÖZET

Amaç: Bu çalışmada, çoklu beyin metastazı bulunan hastaların tedavisinde otomatik HyperArc (HA) planlamasının, manuel olarak oluşturulan VMAT planlarına kıyasla performansı değerlendirildi.

Gereç ve Yöntem: Ortalama 15 (aralık: 10–23) beyin metastazı bulunan 10 hasta retrospektif olarak incelendi. Tüm hastalara kontrastlı MR görüntüleme ile eşleştirilmiş, 1 mm kesit kalınlığında yüksek çözünürlüklü BT görüntülemesi uygulandı. Hedef hacimler radyasyon onkoloğu tarafından belirlendi. Lezyonlar ≥10 mm olduğunda, tümör hacmi (GTV) planlanan hedef hacim (PTV) marjsız olarak belirlendi, daha küçük lezyonlarda her yönde 1 mm marj eklendi. VMAT planları tek izosentrik ve non-koplanar arklarla oluşturulurken, HA planları otomatik optimizasyonla retrospektif olarak üretildi. Reçete dozları 20–30 Gy arasında olup, 3–5 fraksiyonda uygulandı. Karşılaştırılan dozimetrik parametreler: konformite indeksi (CI), gradyan indeksi (GI), homojenite indeksi (HI), sağlıklı beyin dokusu V10Gy ve V12Gy hacimleri, beyin sapı maksimum ve ortanca dozları, optik kiazma, optik sinirler, gözler ve lensler için maksimum dozlar ile toplam monitör ünit (MU) değerleriydi.

Bulgular: Hedef kapsaması iki teknik arasında benzerdi (CI $p = 0.721$; GI $p = 0.241$). HA, daha iyi homojenlik eğilimi gösterdi ve sağlıklı beyin dokusu ile kritik organlara daha düşük dozlar iletti. Beyin sapı ($p = 0.009$) ve optik kiazma ($p = 0.013$) için dozlar anlamlı olarak daha düşüktü. HA planları ayrıca %65 daha az MU gerektirdi ($p = 0.007$).

Sonuç: On ve üzeri metastazı olan hastalarda HA planlaması, daha iyi kritik organ koruması ve işlem verimliliği sağlayarak kompleks olgular için umut vadeden bir otomasyon yaklaşımı sunmaktadır.

Anahtar Kelimeler: HyperArc,VMAT, Çoklu beyin metestazı, Steriotaktik radyocerrahi

Whole-brain radiotherapy (WBRT) has historically been the standard of care for patients with multiple brain metastases, despite well-established evidence showing its association with neurocognitive decline in long-term survivors. Recent studies have demonstrated that stereotactic radiotherapy (SRT) can provide comparable oncologic control while significantly reducing cognitive side effects and improving quality of life (1,2,3).

SRS and SRT represent highly conformal radiotherapy modalities designed to deliver ablative doses to intracranial lesions within a few fractions. Their ability to create rapid dose fall-off enables protection of nearby critical structures. While Gamma Knife systems are commonly employed, LINAC-based rotational arc delivery is also widely used in the treatment of brain metastases (4,5).

In conventional LINAC-based treatments, multiple volumetric modulated arc therapy (VMAT) fields can be utilized with either single or multiple isocenters to achieve highly conformal dose distributions. Single-isocenter plans are particularly advantageous due to reduced treatment times. VMAT allows for intensity modulation through dynamic movement of multileaf collimators (MLCs), providing excellent dose conformity. However, in cases with numerous brain metastases, treatment planning becomes increasingly complex. Parameters such as field size, lesion distribution, MLC trajectories, and optimal collimator and couch angles must be manually adjusted, requiring time-consuming and skill-intensive optimization by experienced medical physicists. As the number of lesions increases, optimizing the collimator angles becomes more challenging, and plan quality may vary significantly depending on planner expertise and time availability (6,7). To address these limitations, HA™ (HA; Varian Medical Systems) has been developed as a mono-isocentric stereotactic radiotherapy technique specifically designed for the treatment of single or multiple brain metastases (8). The integration of automated planning algorithms into clinical practice presents significant opportunities for improving time management and standardization. HA introduces a predominantly automated planning approach that minimizes user intervention by automatically generating non-coplanar VMAT plans. Although this system substantially expedites the planning process, it remains unclear whether the quality of its automated plans is comparable to that of manually optimized VMAT plans created by experienced physicists. Most existing studies evaluating HA have concentrated on cases with fewer than ten brain lesions (8-11). However, clinical application in patients with ten or more metastases presents distinct challenges regarding dose conformity, normal brain sparing, and treatment efficiency. In this context, the aim of this study is to evaluate whether automatically generated HA plans are dosimetrically and clinically comparable to conventionally planned VMAT treatments manually optimized by experienced medical physicists in patients with ten or more brain metastases. The results of this comparison may offer critical insights into the clinical viability of HA and enhance the understanding of the contribution of human expertise in the radiotherapy planning process.

Materials and Methods

2.1. Patient Selection and Imaging

This study included ten patients whose treatments had been completed at our clinic, with an average number of metastases of 15 (range: 10–27). Analysis of the distribution of primary diseases revealed that two patients had breast cancer, four had lung cancer, and one patient each had renal, parotid, colorectal, and cervical cancers. The number of fractions delivered ranged from 3 to 5, and the prescribed doses varied between 20 and 30 Gy. In all patients included in the study, computed tomography (CT) imaging was performed with 1-mm slice thickness using an IMRT head mask for immobilization. The obtained CT scans were transmitted to the Eclipse treatment planning system (Version 13.6) using DICOM format. Contrast-enhanced T1- and T2-weighted magnetic resonance images were registered to the planning CT for the delineation of target volumes and organs at risk (OARs). Each target volume was contoured by a radiation oncologist using high-resolution settings within the Eclipse system. For large lesions, the gross tumor volume (GTV) was directly considered equivalent to the planning target volume (PTV). For lesions smaller than 10 mm, a 1-mm isotropic margin was added to the GTV to create the corresponding PTV.

2.2. Treatment Planning

All treatment plans were delivered using a TrueBeam STx linear accelerator equipped with a high-definition multileaf collimator (HD-MLC) and operated with 6X flattening filter-free (FFF) photon energy.

VMAT treatment plans were generated using a single isocenter and non-coplanar beam arrangements, with collimator angles manually adjusted according to lesion location. Couch angles were selected based on the number of target volumes, with full or parcial arcs delivered at 0° and up to three or four additional partial arcs at different couch positions, allowing a maximum of five couch angles. At each couch position, two arcs were planned in both the clockwise (CW) and counterclockwise (CCW) directions, with jaw openings manually adjusted based on the spatial distribution of the lesions. In non-coplanar beams, partial gantry rotation angles were maintained between 100°–170° and 350°–190°, depending on the couch orientation. The normal tissue objective (NTO) was manually adjusted, with high priority settings applied to achieve steep dose fall-off. Dose normalization was performed to ensure that 98% of the target volume received at least 98% of the prescribed dose.

For the HA plans, the imaging data, structure sets, treatment plans, and dose distributions of patients who had previously undergone VMAT planning were transferred to the Eclipse treatment planning system (Version 16.1). Since HA optimization requires a dedicated immobilization system, the Encompass patient support system was virtually added to the previously acquired VMAT imaging sets.

HA planning is largely automated; the software determines the center of all metastatic lesions and automatically adjusts the collimator angle for each arc. The "Optimize Collimator Angle" option and the SRS-NTO algorithm were used to enhance dose optimization. For both techniques, dose calculations were performed using the Acuros XB algorithm.

2.3. Plan Evaluation

In the plan evaluation, Paddick Conformity Index (CI), Gradient Index (GI), Homogeneity Index (HI), and healthy brain tissue metrics, including V12, V10, Dmean, and maximum dose (Dmax), were analyzed.

For the brainstem, optic chiasm, optic nerves, eyes, and lenses, dose constraints were applied in accordance with the TG-101 protocol for 3–5 fraction treatments. Following the fulfillment of all critical organ dose constraints, the normal brain tissue was delineated as Brain_PTV, aiming to achieve the lowest possible dose to the surrounding healthy brain parenchyma. Additionally, maximum doses (Dmax) to the brainstem, optic chiasm, optic nerves, eyes, and lenses, as well as the total monitor unit (MU) values, were compared between plans.

2.4. Statistical Analysis

In this study, statistical analyses were performed utilizing SPSS version 23 software. The data were given as the median ± standard deviation. The dosimetric parameters compared between conventional VMAT and HA plans included Dmean to the PTV, Paddick Conformity Index (CI), Gradient Index (GI), Homogeneity Index (HI), as well as metrics for healthy brain tissue (V12, V10, median brain dose, and maximum brain dose) and maximum doses to the brainstem, optic chiasm, optic nerves, eyes, and lenses. To compare the two plans values, the Wilcoxon signed-rank test was applied. A p-value less than 0.05 was considered statistically significant.

Results

The conformity index (CI), gradient index (GI), and homogeneity index (HI) values for the target volumes, as well as the DVH parameters for organs at risk (OARs), including their median ± standard deviation (SD) and the p-values obtained from the statistical comparisons between the two techniques, are summarized in Table 1.

Table 1: In VMAT and HA plans, median±SD for target volume CI, GI and HI, DVH parameters for OARs and *p*-values for comparison between the two techniques are shown

Parameters/Techniques	VMAT (median±SD)	HyperArc (median±SD)	*P*-values
Paddick Conformity Index	0.79±0.085	0.79±0.133	0.721
Gradient Index	7.28±3.989	6.97±3.029	0.241
Heterogenity Index	0.30±0.084	0.26±0.064	**0.036**
Brain Stem Dmax(Gy)	9.89±11.53	5.80±12.18	**0.009**
Brain Stem Dmean(Gy)	4.59±2.26	3.09±2.02	**0.013**
Optic Chiasm Dmax (Gy)	6.72±1.74	5.00±2.29	**0.013**
R_ Optic Nerve Dmax (Gy)	40.2±2.92	4.92±1.87	0.575
L_ Optic Nerve Dmax (Gy)	4.85±4.04	3.57±3.96	0.241
R_ Eye Dmax (Gy)	4.06±2.07	3.71±1.41	0.074
L _Eye Dmax (Gy)	4.29±2.15	2.57±1.83	0.059
R_ Lens Dmax (Gy)	2.26±1.16	1.69±0.9	**0.047**
L _Lens Dmax (Gy)	1.99±1.28	1.79±0.75	0.169
Brain_PTV Dmax (Gy)	33.17±4.56	30.33±4.25	0.037
Brain_PTV Dmean (Gy)	4.61±1.90	4.08±1.66	**0.007**
Brain_PTV V10 (cc)	76.19±129.3	68.37±82.5	**0.017**
Brain_PTV V12 (cc)	46.55±81.2	46.97±55.69	0.114
Monitor Unit (MU)	6074±4278	2514636	**0.007**

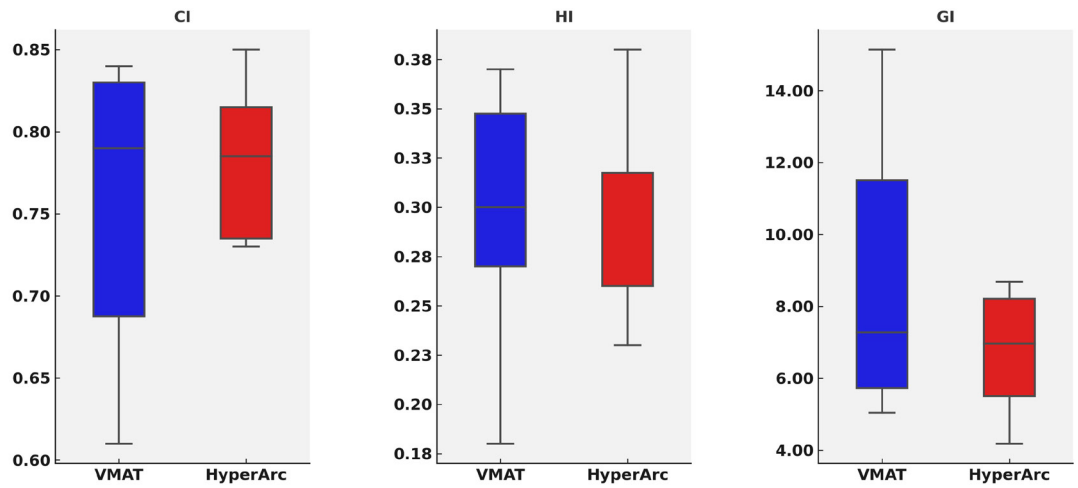

Figure 1: Box plots comparing the CI, HI, GI values with HA and VMAT techniques are shown.

Regarding target coverage, the Paddick CI was 0.79±0.085 for VMAT and 0.79±0.133 for HA plans, with no statistically significant difference observed between the two techniques (p = 0.721). The values of the GI were calculated as 7.28±3.989 for VMAT and 6.97±3.029 for HA(*p*=0.241).

The HI values were 0.30±0.084 for VMAT and 0.26±0.064 for HA, with a statistically significant difference favoring HA (p = 0.036).

Monitor unit (MU) values differed considerably, with VMAT plans requiring 6074±4278 MUs, while HA plans required only 2514±636 MUs. This translated into a significantly shorter treatment delivery time with HA (*p* = 0.007).

Box plots comparing CI, HI, GI and MU of both techniques are shown in Figure 1.

For the brainstem, the values were more conclusive. Compared to VMAT, HA plans led to a meaningful reduction in brainstem average and maximum doses. This was evident in both the peak value 5.80±12.18 Gy for HA vs. 9.89±11.53 Gy for VMAT; p = 0.009 and the average dose 3.09±2.02Gy vs. 4.59±2.26 Gy; p = 0.013.

The optic chiasm showed a similar pattern, with significantly lower dose levels observed under HA planning (p = 0.013).

When looking at the results for optic nerves and eyes, it was found that although HA showed lower maximum doses overall, especially in the eyes, none of these differences reached statistical significance. (right optic nerve p = 0.575, left optic nerve p = 0.241, right eye p = 0.074, left eye p = 0.059).

Notably, the right lens received a significantly lower maximum dose with HA (p = 0.047).

The left lens, however, showed no clear difference between the techniques (p=0.169).

In terms of healthy brain tissue (Brain_PTV), HA again performed better: V10 and Dmean values were both significantly lower (p= 0.017and p= 0.007), while V12 remained comparable (p = 0.114).

Box plots comparing OAR Dmax doses for both techniques are shown in Figure 2 and box plots comparing dosimetric parameters for healthy brain tissue are shown in Figure 3.

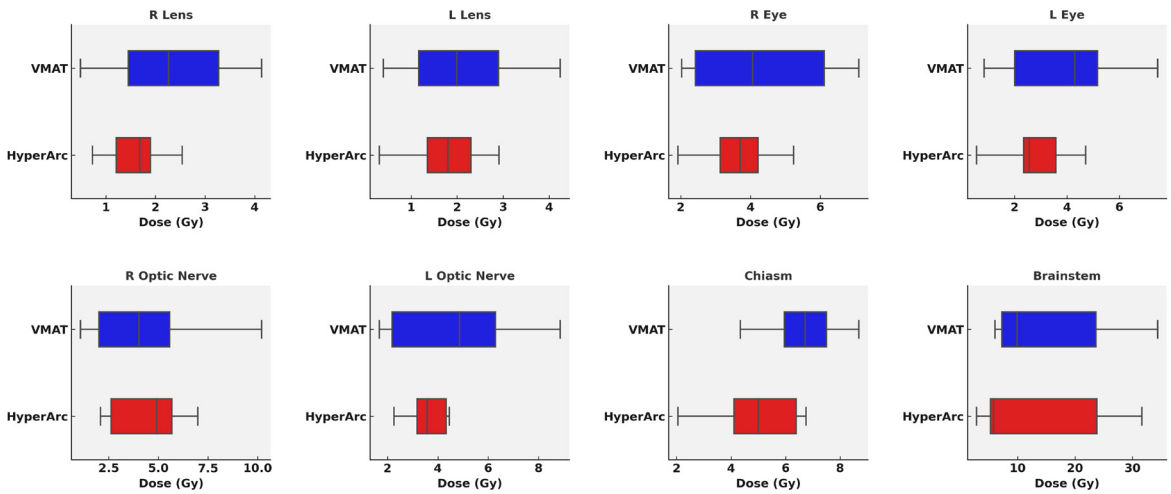

Figure 2: Box plots comparing Dmax doses for L and R Lenses, L and R Eyes, L and R Optic Nerve, Optic Chiasm, and Brainstem in HA and VMAT plans are presented.

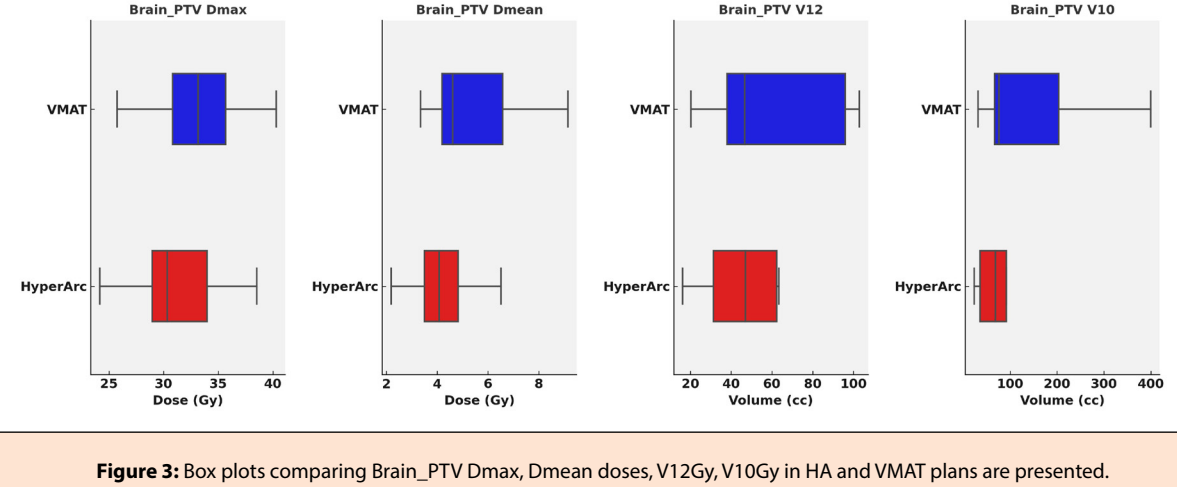

Figure 3: Box plots comparing Brain_PTV Dmax, Dmean doses, V12Gy, V10Gy in HA and VMAT plans are presented.

Discussion

In this study, we investigated the dosimetric performance and clinical feasibility of automated HyperArc (HA) planning for patients with multiple brain metastases, focusing on a challenging sub group with 10 or more lesions. Our results showed that HA plans performed comparably to manually optimized VMAT plans in terms of conformity and dose gradient, while offering distinct advantages in homogeneity, healthy brain tissue sparing, and treatment efficiency.

One of the key observations in this cohort was the relatively high Gradient Index (GI) values across both techniques. This outcome is not unexpected given the complexity introduced by the high number of lesions per patient (mean: 15). While GI values around ≤3 are considered optimal in single-lesion stereotactic radiosurgery (SRS) cases as suggested by Paddick et al. (12), achieving such values becomes inherently more difficult in multi-lesion, single-isocenter settings. In our study, although VMAT showed slightly higher GI values, the difference between both techniques was not statistically significant, and the elevated GI likely reflects the increased inter-lesion spacing and arc modulation challenges rather than suboptimal planning.

HyperArc plans demonstrated significantly better homogeneity within the target volumes. This result aligns with findings by Ruggieri et al., who reported improved dosimetric parameters including CI, GI, and V12 with HA in cases involving up to 10 lesions (8). However, our study goes beyond this lesion range. In our VMAT cohort, we attempted to mitigate inter-lesion overlap and excessive dose spill by applying single-isocenter, non-coplanar arc geometries, thereby mimicking HA strategies. This may explain why our VMAT and HA plans showed similar conformity and V12 values. The comparable performance suggests that experienced planners can approach HA level quality through time-intensive, manual optimization. Nonetheless, HA's fully automated process ensures consistent plan quality while dramatically reducing planning time and variability, which is particularly advantageous in busy clinical environments.

The work by Popple et al. (13) supports this notion, noting that HA can deliver high-quality radiosurgery plans that match the quality of expert manual VMAT plans, even when executed by less experienced planners. Their study also confirmed that single-isocenter, multi-target approaches do not compromise clinical outcomes, with local control rates consistent with historical SRS series.

One of the most clinically significant findings in our analysis was the superior sparing of healthy brain tissue with HA. Although V12 volumes did not significantly differ, both V10 and mean brain dose were notably lower with HA. This is particularly relevant given the association between these dosimetric parameters and the risk of radionecrosis, as highlighted in prior studies by Minniti et al. and Korytko et al. (14,15) Other studies, such as those by Chen et al. and Celen et al (16,17) have also emphasized the sharper dose fall-off achieved with HA, which contributes to reduced radiation exposure to normal parenchyma an outcome we also observed in our cohort.

While HI is not always a primary objective in SRS planning, a lower homogeneity index may suggest higher central dose and, potentially, improved tumor control. This approach is reminiscent of Gamma Knife planning, where 50% isodose prescriptions naturally result in central dose escalation. In our study, HA plans consistently delivered more homogeneous dose distributions compared to VMAT, supporting similar observations made in earlier dosimetric studies (16).

In terms of treatment efficiency, the difference was striking. HA plans required significantly fewer monitor units (MUs), translating into shorter beam-on times. Faster treatments reduce patient discomfort and may help to minimize errors due to intrafractional motion. Previous reports have similarly demonstrated that HA contributes to improved clinical workflow efficiency and patient throughput (8,13,18). When integrated into routine practice, the HA platform may enhance both operational logistics and clinical precision, especially in high-volume centers.

Taken together, our findings reinforce the potential of HA planning as a clinically robust and time-efficient alternative to conventional VMAT. While expert manual planning remains valuable, HA offers a level of standardization and efficiency that can benefit both clinicians and patients. Nevertheless, the system should be used by professionals trained in stereotactic techniques to ensure the appropriateness of clinical decisions and patient safety.

While our results are promising, further studies are needed ideally involving more diverse patient populations and

extended clinical monitoring to better understand how HA planning affects cognitive function, treatment-related toxicity, and long-term tumor control. Whether the observed dosimetric advantages ultimately translate into improved patient outcomes is a question that remains open for future clinical trials.

Conclusion

Although manually optimized VMAT plans remain effective when designed by experienced planners, HA demonstrated the ability to deliver consistently robust plans while requiring much less manual input. This not only helped to standardize plan quality but also shortened treatment delivery times, which is an important factor for patient comfort and workflow efficiency. Equally important, HA planning showed potential benefits in protecting normal brain tissue and reducing unnecessary dose to critical organs. These findings suggest that with the right clinical oversight, automation in radiosurgery planning can be both safe and clinically beneficial.

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