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Dosimetric Evaluation of Two Linac-Based Stereotactic Radiosurgery Approaches in the Management of Single Brain Metastasis

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Abstract

Background: Stereotactic radiosurgery (SRS) relies on precise, highly conformal radiation with sharp dose falloff to protect adjacent normal brain tissue. Differences in multileaf collimator (MLC) configuration and planning system algorithms can affect dosimetric performance and delivery efficiency, supporting the need for comparative assessment of current techniques. The present study aimed to compare the dosimetric parameters and treatment efficiency of SRS plans using RapidArc with an HD120 MLC against volumetric modulated arc therapy (VMAT) using the Agility-MLC in patients diagnosed with a single brain metastasis.

Method: In this retrospective dosimetric study of 12 patients who received single-fraction 22 Gy SRS for single brain metastasis, paired treatment plans were generated for each case: (i) a RapidArc plan in Eclipse with an HD120-MLC and (ii) a VMAT plan in Monaco with an Agility-MLC. Target coverage, conformity index, homogeneity index, gradient index (GI), and organ-at-risk (OAR) doses were compared alongside efficiency indicators monitor units (MUs) and beam-on time (BOT). Paired t-tests performed in SPSS v28.0 by international business machines (IBM) determined statistical significance, with $P < 0.05$ considered significant.

Results: Both techniques achieved acceptable target coverage and met OAR constraints. RapidArc showed significantly improved gross tumor volume (GTV) homogeneity ($P = 0.00047$), lower GI ($P = 0.04238$), and lower normal brain volume receiving at least 12Gy (V12Gy, $P = 0.005$). VMAT plans required fewer MUs ($P = 0.011$) and had shorter BOT ($P = 0.04$), indicating improved efficiency. No significant differences were observed in maximum doses to the brainstem, optic apparatus, and cochlea.

Conclusion: Both RapidArc and VMAT delivered clinically acceptable SRS plans. In our patient population RapidArc offered superior homogeneity and better sparing of normal brain tissue.

***Keywords*:** Stereotactic radiosurgery, Brain neoplasms, Radiotherapy planning, Intensity-modulated, Organs at risk

1. Introduction

Stereotactic radiosurgery (SRS) is a type of radiation treatment that uses focused beams to deliver a high dose of radiation to a specific area, like a brain tumor, while causing little damage to the nearby healthy tissue. It is a highly accurate form of therapeutic radiation used to treat abnormalities in the brain. The use of SRS alone provides very high rates of tumor response and local control.[1, 2] SRS, surgery, and whole-brain radiation therapy are all commonly used in the treatment of brain metastases.[3] Brain metastases are the most frequent type of brain tumor and represent a significant cause of morbidity and mortality, ranking as the tenth leading cause of death in both men and women. They occur in approximately 20%-40% of adult cancer patients.[4, 5] While surgery and chemotherapy play important roles in the management of brain metastases, radiation therapy has become an essential treatment modality. Gamma Knife (GK) is a widely used technology for administering SRS, particularly for patients with either a single small brain metastasis or multiple brain metastases.[6, 7] However, due to the limited availability of GK systems, many hospitals depend on conventional linear accelerators (LINACs). To address this, advanced LINACs equipped with specially designed multileaf collimators (MLCs) or cones have been developed to deliver SRS with precision comparable to that of GK.

The increasing availability of conventional LINACs, along with continuous advancements in hardware and software, has driven the development of new technologies supporting LINAC-based SRS for treating both single and multiple brain metastases.[8] Numerous studies have compared different SRS and stereotactic radiotherapy (SRT) strategies, evaluating their respective advantages and disadvantages.[3, 9, 10] These findings have informed clinical decision-making and the selection of appropriate radiotherapy techniques. Volumetric-modulated arc therapy–based SRS (VMAT-SRS) showed favorable early clinical outcomes, including robust tumor response, high local control rates, and minimal acute toxicity.[11] Zyad A. Tawfik et al. compared three-dimensional conformal radiotherapy (3DCRT), intensity-modulated radiotherapy (IMRT), and RapidArc and concluded that RapidArc effectively limited both the maximum dose and the volume of normal brain tissue exposed to radiation.[12] However, a direct comparison of plan quality among various SRS techniques, particularly between MLC-based LINACs using VMAT, is still needed.

The present study aimed to evaluate the differences in SRS treatment for a single brain metastasis by comparing a RapidArc plan using an HD120 MLC with a VMAT plan employing an Agility MLC. Given the basic differences in MLC design factors, such as leaf width and leaf speed, as well as dose calculation algorithms that have a direct impact on plan quality, dose distribution, and normal tissue sparing, a technical comparison between HD120 and Agility MLCs is crucial. This comparison demonstrates how MLC design influences accuracy, effectiveness, and safety of SRS planning while directing technique selection according to clinical priorities. The comparison focuses on both plan quality and treatment efficiency, assessed using dosimetric parameters (target coverage and dose to critical structures) and treatment parameters (number of monitor units [MUs] and beam-on time [BOT]).

2. Materials and Methods

2.1. Patient selection and contouring

A retrospective study was performed on 12 patients presenting with a single brain metastasis measuring less than 4 cm. Patients with multiple metastases, lesions larger than 4 cm, poor performance status and a history of prior cranial irradiation were excluded. The final cohort comprised 12 patients, including 7 females and 5 males, with a mean age of 58 ± 5 years. Breast carcinoma was the predominant primary malignancy among female patients, whereas lung and colorectal cancers were the principal primary tumor sites in male patients. Together, these characteristics define a middle-aged adult cohort with distinct sex-related patterns in primary tumor origin. All 12 patients underwent radical radiotherapy using the SRS technique, receiving a total dose of 22 Gy in a single fraction. Patients were immobilized in the supine position, with arms by their sides, using three-clamp brain thermoplastic masks. Intravenous contrast-enhanced computed tomography (CT) scans with 1.25 mm slice thickness were acquired using a 16-slice GE Discovery radiotherapy CT scanner (GE Healthcare, Chicago, USA).

To compare the treatment plans, imaging data were transferred via the Digital Imaging and Communications in Medicine (DICOM) network to both the Eclipse and Monaco treatment planning systems (TPS) for contouring. Target volumes and critical structures were delineated on the same CT datasets according to the Radiation Therapy Oncology Group (RTOG) contouring guidelines by a single experienced radiation oncologist to maintain consistency. The normal brain tissue (Brain-GTV) was defined by excluding the gross tumor volume (GTV) from the whole brain volume without applying any additional margin.

2.2. Linear Accelerators and TPS

The Varian Novalis Tx Linac, equipped with an HD120 MLC and 6X-SRS photon beam, was used for RapidArc planning. The HD120 MLC consists of 120 leaves: 32 central leaves with a width of 0.25 cm and 28 outer leaves with a width of 0.50 cm, capable of defining a maximum field size of 22 cm (Y-axis) × 32 cm (X-axis) and a leaf thickness of 6.9 cm. Treatment planning was performed using Eclipse TPS version 15.6.04, and final dose calculations employed the Acuros XB algorithm with a 1 mm grid resolution.

The VMAT plan was generated using an Elekta Versa HD Linac (Elekta AB, Stockholm, Sweden) with the Agility MLC and a 6 MV flattening filter free (6FFF) beam configuration. Agility MLC consists of 80 pairs of opposing leaves, each projecting a 0.5 cm width at the isocenter. The tungsten leaves in the Agility MLC are 9 cm thick and have a leaf speed of 3.5 cm/s. The carriage can travel up to 3 cm/s, giving a maximum MLC speed of 6.5 cm/s.[13] The high dose rate of FFF beams is especially beneficial in SRS and SBRT, as well as in treatments that require organ motion management. FFF beams had lower average MLC transmissions than the flattened beams.[14] The VMAT plans were generated using Monaco TPS version 6.01, with dose calculations based on the Monte Carlo algorithm with a 1 mm grid resolution.

2.3. Treatment planning and evaluation

Each patient had two SRS plans generated: one using Eclipse TPS for the Novalis Tx with the HD120 MLC (RapidArc) and the other using Monaco TPS for the Elekta Versa HD with Agility MLC (VMAT). The RapidArc plans used 6 MV SRS photon beams with a maximum dose rate of 1000 MU/min, while VMAT plans used 6FFF photon beams with dose rates ranging from 1000 to 1400 MU/min. To ensure uniformity in planning quality, each treatment plan was created by a single expert physicist.

For both techniques, six to seven partial arcs were used per plan. Gantry, collimator, and couch angles were selected based on the anatomical location of the target volume. Couch parameters were

incorporated into the planning process to account for megavoltage beam attenuation. All plans received a cumulative dose of 22 Gy to the planning target volume (PTV) in a single fraction. Giving GTV 100% of the prescribed dosage and PTV at least 90% of the prescribed dosage was the intended objective. Using the same planning criteria and a comparable priority, both plans were optimized. The following were the dose constraints for OARs: Brain-GTV volume receiving ≥12 Gy (V12Gy): < 10 cc; brainstem: maximum dose received by 0.035 cc volume (D0.035 cc) < 15 Gy; optic chiasm and optic nerves: D0.035 cc < 12 Gy; cochlea: D0.035 cc < 9 Gy. The treatment planning objectives used for this study were based on RTOG 90-05 guidelines and are summarized in Table 1.[15]

2.4. Plan evaluation metrics

Plan quality was assessed using the homogeneity index (HI), conformity index (CI), gradient index (GI), and mean dose for both GTV and PTV. HI was calculated as HI=(D2%−D98%)/D50%, where D2%, D98%, and D50% represent the minimum dose received by 2%, 98%, and 50% of the target volume, respectively. An HI value of 0 indicates perfect dose homogeneity.[16] CI was computed as CI = VPD/VT, where VPD is the volume receiving 100% of the prescribed dose and VT is the volume of the target. A CI value of 1 indicates ideal conformity.[17] GI was employed to compare treatment plans with equivalent conformity. A simple expression of GI was introduced by Paddick et al. GI is expressed as GI = V50%RI / VRI, where VRI is the volume of reference isodose and V50%RI is the volume of 50% of reference isodose.[18]

The mean dose, HI, and CI were analyzed for both GTV and PTV. For critical structures, dose analyses were performed using dose-volume histograms and $D_{0.035\ cc}$ was used to evaluate the brainstem, optic nerves, optic chiasm, and cochlea. The volume receiving at least 12 Gy (V12Gy) was used to evaluate the dose exposure of the Brain-GTV to 12 Gy or more. Treatment efficiency was evaluated by comparing the number of MUs per plan and BOT between RapidArc and VMAT plans.

2.5. Statistical Analysis

Statistical analysis was performed using SPSS software version 28.0 (IBM, Armonk, NY, USA) via paired t-test, with a P-value < 0.05 considered statistically significant.

2.6. Ethical Committee Approval

The Basavatarakam Indo-American Cancer Hospital and Research Institute ethics committee approved this study (IEC/2025/AC/39). Informed consent was obtained from all the participants included in the study.

3. Results

3.1. Target volume dosimetry and treatment efficiency

Table 2 outlines the dose-volume statistics for GTV and PTV, as well as treatment efficiency parameters. RapidArc and VMAT both produced clinically acceptable single-isocenter SRS plans, delivering comparable mean doses to GTV (23.24 ± 0.30 Gy vs. 23.49 ± 0.55 Gy, $P = 0.19$) and PTV (22.22 ± 0.16 Gy vs. 22.30 ± 0.37 Gy, $P = 0.46$). Plan CI did not differ significantly between techniques. However, RapidArc yielded better dose homogeneity within GTV (HI = 0.04 ± 0.01 vs. 0.07 ± 0.03, $P < 0.001$) and PTV (HI = 0.15 ± 0.02 vs. 0.18 ± 0.04, $P = 0.02$) and a steeper dose fall-off, reflected by a lower gradient index (7.16 ± 1.74 vs. 9.20 ± 2.73, $P = 0.04$). RapidArc achieved these gains at the cost of higher number of MUs (4405 ± 540 vs. 3762 ± 599, $P = 0.01$) and a longer beam-on time (4.67 ± 1.14 min vs. 3.83 ± 0.58 min, $P = 0.04$).

These dosimetric advantages suggest that RapidArc may offer improved normal-tissue sparing without compromising target coverage, while VMAT maintains greater delivery efficiency.

Figure 1 provides a visual comparison of dose distributions between RapidArc and VMAT treatment plans for a case of single brain metastasis, displayed in axial, sagittal,

and coronal views. The colored dose wash represents different isodose levels, while the overlaid contours delineate the target and OARs.

3.2. OAR sparing

The dose statistics for critical structures were summarized in Table 3. RapidArc achieved a markedly lower volume of normal brain receiving ≥ 12 Gy (V12 Gy = 13.7 ± 4.2 cc) than VMAT (19.4 ± 4.9 cc), a 29 % relative reduction that reached statistical significance ($P = 0.005$). RapidArc and VMAT delivered comparable maximum doses ($D_{0.035\,cc}$) to all evaluated OARs, with no statistically significant differences observed for the brainstem (2.95 ± 1.98 Gy vs 2.22 ± 1.60 Gy; $P = 0.333$), optic chiasma (0.94 ± 0.51 Gy vs 0.97 ± 0.63 Gy; $P = 0.890$), left optic nerve (0.61 ± 0.34 Gy vs 0.52 ± 0.30 Gy; $P = 0.491$), right optic nerve (0.60 ± 0.43 Gy vs 0.29 ± 0.20 Gy; $P = 0.503$), left cochlea (0.65 ± 0.49 Gy vs 0.69 ± 0.59 Gy; $P = 0.881$), and right cochlea (0.45 ± 0.23 Gy vs 0.47 ± 0.30 Gy; $P = 0.854$). Both modalities achieved doses well below established clinical tolerance limits.

These findings indicate that, while overall OAR sparing is comparable, RapidArc offers a distinct advantage in limiting intermediate-dose spillage to normal brain tissue. Prospective clinical studies are warranted to confirm whether the dosimetric benefits observed, particularly the reduction in brain V12 Gy with RapidArc, translate into measurable improvements in neurocognitive function, toxicity profiles, and long-term patient outcomes.

Figure 2 displays comparative bar charts for four key dosimetric and delivery efficiency parameters between RapidArc (blue bars) and VMAT (orange bars) across 12 patients treated for single brain metastasis. Each subplot presents patient-wise values, along with statistical significance (*P*-values) for group comparisons.

RapidArc provided better normal brain sparing (lower V12Gy, $P < 0.01$) and sharper dose fall-off (lower GI, $P = 0.04$), while VMAT offered improved delivery efficiency with fewer number of MUs ($P = 0.01$) and shorter BOT ($P = 0.04$). The trade-off highlights the clinical balance between dosimetric precision and delivery speed, emphasizing the need for personalized treatment selection based on clinical priorities.

4. Discussion

For single-fraction 22Gy SRS targeting single brain metastasis, this retrospective analysis shows that both RapidArc with the Varian HD120 MLC and VMAT with the Elekta Agility MLC achieved good conformal target coverage. While VMAT decreased MUs by around 15% and shortened BOT by about 18%, RapidArc achieved a noticeably higher HI, a steeper GI, and a 29% reduction in normal brain V12 Gy. It is most likely that dosimetric superiority of RapidArc is due to leaf aperture.

In complex, off-axis SRS arcs, 2.5 mm central leaves of the HD120 MLC (projected at isocenter) allow for finer modulation and a smaller penumbra than 5 mm leaves of Agility.[3, 19] On the other hand, the Agility MLC's 6.5 cm/s leaf speed and the 6 FFF beam's greater dosage rate (1400 MU/min) are both known to result in quicker delivery times in stereotactic processes, which accounts for VMAT plan efficiency advantage. [20, 21] Therefore, our findings quantify an intuitive trade-off: whereas FFF/Agility packages favor throughput, lower leaf width and flattened beams improve spatial accuracy at the cost of a higher number of MUs and BOT. Liu et al.[4] compared non-coplanar RapidArc SRS plans with GK for multiple brain metastases and concluded that RapidArc can provide equivalent target coverage and clinically acceptable dosimetric outcomes, particularly in terms of minimizing low-dose exposure to normal brain tissue. VMAT has proven to be a safe and feasible technique for treating patients with brain metastases. Arc-based techniques offer

shorter treatment times, steeper dose fall-off, and sparing of normal tissue compared with other major modalities. Arc-based techniques are associated with minimal toxicity, and demonstrate favorable outcomes in terms of local control and overall survival.[22] Despite these advancements, further research is needed to evaluate and differentiate LINAC-based SRS techniques. To the best of our knowledge, no published study has separated collimator design as a variable and directly compared the HD120 and Agility MLCs for a single brain lesion. We present quantitative proof that the finer leaf system reduces the clinical proxy for radionecrosis risk (brain V12Gy), a measure that is becoming more and more associated with late toxicity. Through timely reporting of both MUs and real beams for partial arc schemes, the work contextualizes the dosimetric benefits.

The novelty of our study lies within the fact that this is the first-ever cross-platform comparison of HD120 and Agility MLCs in single-fraction SRS, using contemporary dosage engines (Acuros XB vs. Monte Carlo), similar patient datasets, couch angles, and 1 mm grid spacing. A balanced perspective for decision-making is provided by the simultaneous consideration of dosimetric, gradient, and efficiency measures.

The main limitation of the present study is small sample size (n = 12) and its retrospective design. We included the first 12 patients who met the inclusion criteria for the study. Future studies with larger, prospective cohorts and incorporation of clinical endpoints such as toxicity and local control are warranted to further validate these findings.

Conclusion

For single brain metastasis, RapidArc HD120 and VMAT Agility both produced excellent, guideline-compliant SRS plans. While the Agility FFF platform reduces treatment time with fewer monitor units, finer leaves of HD120 resulted in a superior dose gradient and lower dose to normal brain tissue.

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Authors' Contribution

Mr. Guduru Srikanth: Study design, data acquisition, data analysis and interpretation, drafting, manuscript critical review, and final approval; Dr. Rohith Singareddy: Study design, data acquisition, drafting, manuscript critical review, and final approval; Dr. NVN Madhusudhana Sresty: Data analysis, drafting, manuscript review, and final approval; Dr. Deleep Kumar Gudipudi: Data analysis, drafting, manuscript review, and final approval; Dr. Aparna Dode: Study design, data analysis, drafting, manuscript critical review, and final approval. All authors have read and approved the final manuscript and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Conflict of Interest

None declared.

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Table 1. Treatment planning objectives for target volumes and organs at risk based on RTOG guidelines

Structure	**Parameter**	**Constraint**
GTV	$D_{100}\%$	> 100% of prescribed dose
PTV	$D_{100}\%$	> 90% of prescribed dose
Brain − GTV	D_{10}cc	< 12 Gy
Brainstem	Dmax ($_{0.035\ cc}$)	< 15 Gy
Optic chiasm	Dmax ($_{0.035\ cc}$)	< 12 Gy
Optic nerves	Dmax ($_{0.035\ cc}$)	< 12 Gy
Cochlea	Dmax ($_{0.035\ cc}$)	< 9 Gy

GTV: Gross tumor volume; PTV: Planning target volume; RTOG: the Radiation Therapy Oncology Group

Table 2. Comparison of target dose-volume statistics and treatment efficiency parameters between RapidArc and VMAT techniques

Parameter	Metric	RapidArc			VMAT			*P*-value
		Mean	SD	95% CI	Mean	SD	95% CI	
GTV dose	Mean (Gy)	23.24	0.30	0.19	23.49	0.55	0.31	0.19
	CI	1.01	0.03	0.02	1.02	0.05	0.00	0.45
	HI	0.04	0.01	0.01	0.07	0.03	0.02	<0.01*
PTV dose	Mean (Gy)	22.22	0.16	0.10	22.30	0.37	0.24	0.46
	HI	0.15	0.02	0.01	0.18	0.04	0.02	0.02*
Gradient index	GI	7.16	1.74	1.11	9.20	2.73	1.73	0.04*
Efficiency	MU	4405	540	343	3762	599	274	0.01*
	BOT (min)	4.67	1.14	0.72	3.83	0.58	0.28	0.04*

GTV: Gross tumor volume; PTV: Planning target volume; CI: Conformity index; HI: Homogeneity index; GI: Gradient index; MU: Monitor units; BOT: Beam-on time (in minutes); SD: Standard deviation; 95% CI: 95% confidence interval; VMAT: Volumetric modulated arc therapy. *$P < 0.05$ considered statistically significant

Table 3. Comparison of dose-volume statistics for organs at risk between RapidArc and VMAT techniques

Organ at risk	Metric	RapidArc			VMAT			*P*-value
		Mean	SD	95%CI	Mean	SD	95%CI	
Brain	**V12Gy(cc)**	13.70	4.17	2.65	19.39	4.86	4.27	<0.01*
Brainstem	**$D_{0.035cc}$ (Gy)**	2.95	1.98	1.26	2.22	1.60	1.02	0.33
Optic chiasm	**$D_{0.035cc}$ (Gy)**	0.94	0.51	0.33	0.97	0.63	0.43	0.89
LT optic nerve	**$D_{0.035cc}$ (Gy)**	0.61	0.34	0.22	0.52	0.30	0.19	0.49
RT optic nerve	**$D_{0.035cc}$ (Gy)**	0.60	0.43	0.27	0.50	0.29	0.20	0.50
LT cochlea	**$D_{0.035cc}$ (Gy)**	0.65	0.49	0.31	0.69	0.59	0.74	0.88
RT cochlea	**$D_{0.035cc}$ (Gy)**	0.45	0.23	0.15	0.47	0.30	0.19	0.85

SD: Standard deviation; 95%CI: 95% confidence interval; V_{12Gy}: Volume of brain tissue receiving ≥12 Gy excluding GTV; $D_{0.035cc}$: Maximum dose received by 0.035 cc of the organ; LT: Left; RT: Right; OAR: Organ at risk. VMAT: Volumetric modulated arc therapy; *$P < 0.05$ considered statistically significant.

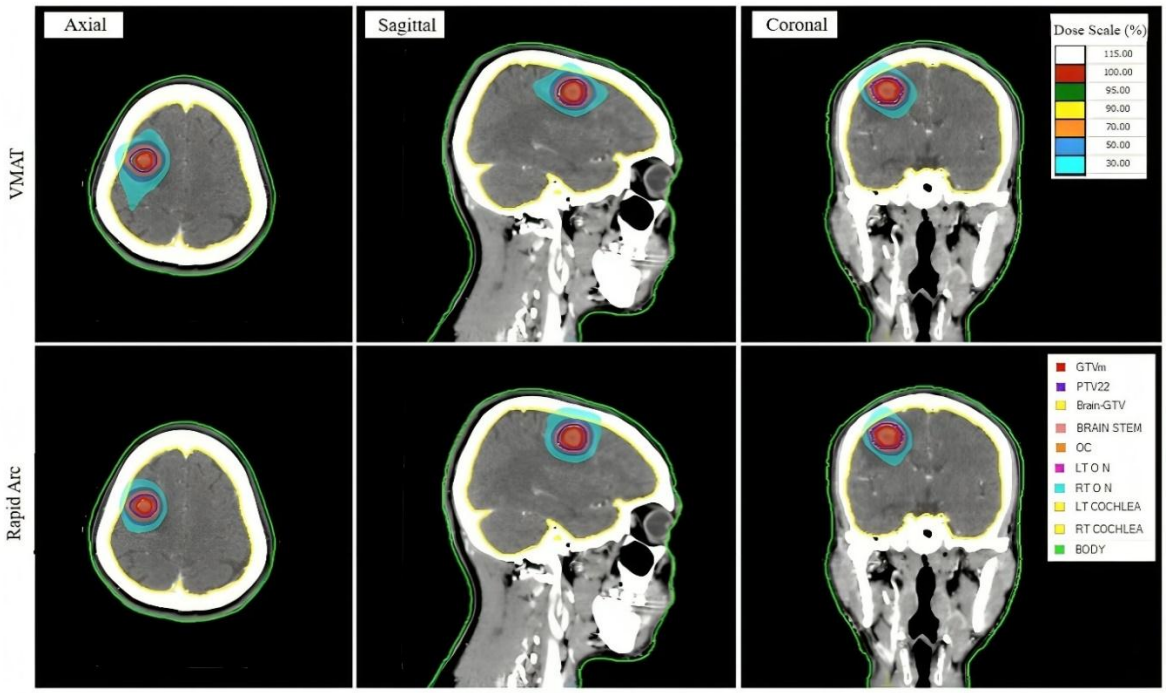

Figure 1. Axial, sagittal, and coronal CT images comparing dose distributions for VMAT (top row) and RapidArc (bottom row) SRS plans for a single brain metastasis case. Dose color wash represents isodose levels as a percentage of the prescription dose. RapidArc demonstrates superior dose conformity and steeper dose fall-off, resulting in reduced intermediate dose spillage to surrounding brain tissue.

CT: Computed tomography; VMAT: Volumetric modulated arc therapy; SRS: Stereotactic radiosurgery

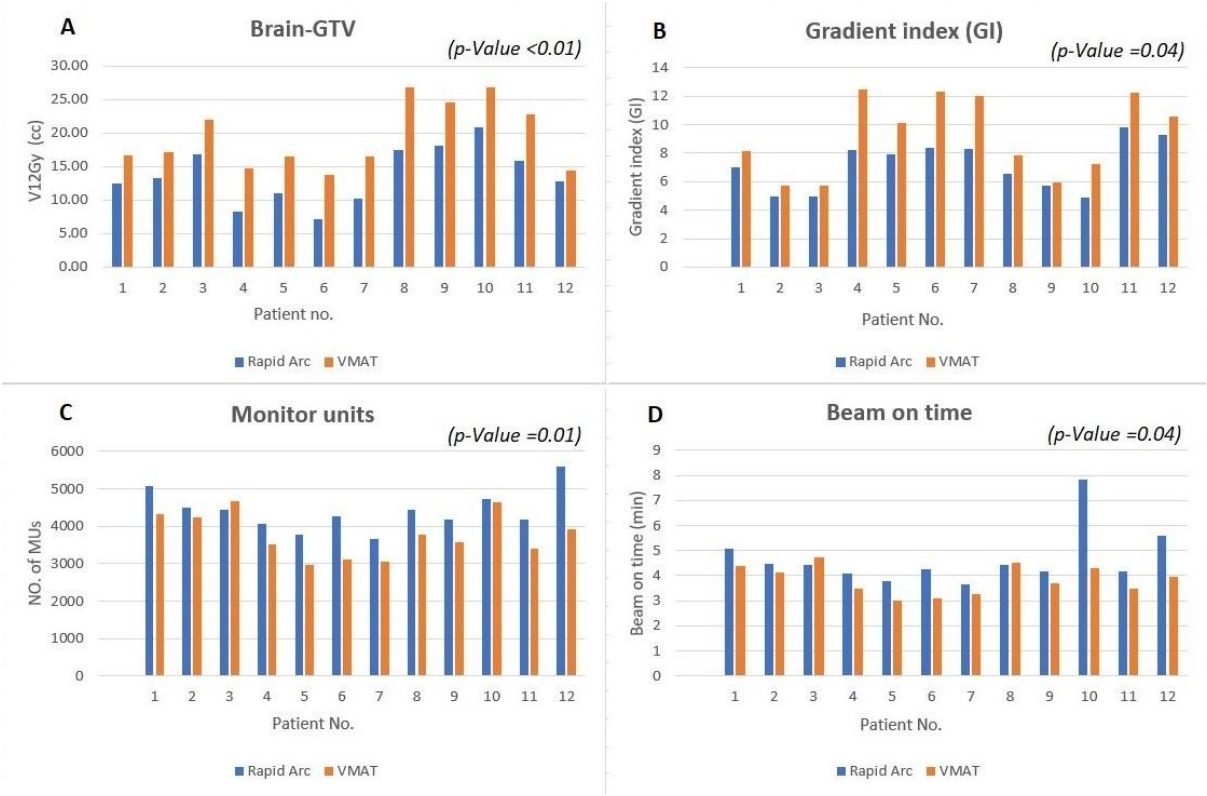

Figure 2. This figure shows a patient-wise comparison of dosimetric and delivery parameters (A. Volume of Brain-GTV receiving ≥12 Gy, in cc; B. Gradient index; C. Number of MUs; and D. Beam-on time in minutes) for 12 single brain metastasis cases treated with RapidArc (blue) and VMAT (orange).

GTV: Gross tumor volume; MUs: Monito units; VMAT: Volumetric modulated arc therapy