Iranian Journal of Medical Physics

ijmp.mums.ac.ir

Dosimetric Comparison of Dynamic Conformal Arc Therapy and Volumetric Modulated Arc Therapy using Stereotactic Radiotherapy for Carcinoma Brain

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ARTICLE INFO

Article type:
Original Paper

Article history:
Received: Mar 15, 2024
Accepted: Sep 13, 2024

Keywords:
Stereotactic Radiation Therapy
Dosimetry
Radiotherapy
Intensity-Modulated
Treatment Planning
Brain Neoplasms

ABSTRACT

Introduction: Stereotactic radiosurgery (SRS) conventionally relies upon dynamic conformal arc therapy (DCAT), yet the untapped potential of volumetric modulated arc therapy (VMAT) has not undergone comprehensive scrutiny. This investigation seeks to bridge this research lacuna by comparing DCAT and VMAT in the context of four-fraction SRS for single brain carcinoma treatment.

Material and Methods: A retrospective cohort of twenty patients with solitary brain tumors was meticulously chosen, and treatment plans using both VMAT and DCAT were devised for each case utilizing congruent CT images. The comparative study analysed factors such as target conformity, monitor units and doses to organs at risk.

Results: VMAT plans notably exhibited enhanced conformity indices with mean and standard deviation values for the Paddick Conformity Index being 0.650 ± 0.18 for DCAT and 0.751 ± 0.08 for VMAT. Also, VMAT reduced radiation doses to pivotal anatomical structures, in contrast to the DCAT plans. However, the VMAT approach necessitated a greater number of Mus than DCAT with the mean and standard deviation being 986.95 ± 146.3 and 571.36 ± 59.6, respectively.

Conclusion: In the realm of SRS for isolated brain carcinoma, VMAT decidedly surpassed DCAT in target conformity as well as in mitigating the risk of brain radiation necrosis. Nonetheless, DCAT find relevance in patients with compromised performance status to prolonged radiotherapy sessions due to its abbreviated duration in the treatment. This research highlights the nuanced considerations inherent in treatment selection and also sheds insightful light on the optimal therapeutic approach.

►*Please cite this article as:*
Pinto SP, Shreekripa R, Dsouza RN, Chandraguthi SG, Velu U. Dosimetric Comparison of Dynamic Conformal Arc Therapy and Volumetric Modulated Arc Therapy using Stereotactic Radiotherapy for Carcinoma Brain. Iran J Med Phys 2025; 22: 98-104. 10.22038/ijmp.2025.78775.2393.

Introduction

Globally, cancer continues to be the primary cause of mortality. “According to the International Agency for Research on Cancer (IARC), there were 7.6 million deaths attributed to cancer, and 12.7 million new cases of cancer were reported annually across the world” [1]. Although, brain tumors accounts for roughly 2% of all cancer cases worldwide, nevertheless, the high morbidity and mortality rates, as well as the fact that many young and middle-aged individuals are affected, results in a considerable impact on the life in comparison to other types of cancers [2].

There are several approaches to manage brain tumors, such as surgery, chemotherapy, immune checkpoint inhibitors, molecular targeted therapy, whole-brain radiotherapy (WBRT) and stereotactic radiosurgery (SRS) [3]. The challenge in administering radiation therapy for patients with brain carcinoma stems from the critical proximity of organs such as the brainstem and optic chiasm to the treatment area. This necessitates enhanced accuracy and precision during radiation therapy, given the narrow margin at the planning target volume (PTV) [4]. Standard treatment for brain tumor is WBRT, however, major adverse effects associated with WBRT predominantly includes irreversible neurological complications like decline in neurocognitive function, dementia, and cerebellar dysfunction [5]. “Therefore, SRS is an alternative treatment that delivers high doses to the affected areas while minimizing damage to healthy brain tissue”[3]. SRS refers to a procedure where ionizing radiation from an external source is utilized to deactivate or eliminate specific targets in the head or spine, identified through detailed imaging with high

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resolution [6]. SRS is a widely recognized treatment choice for brain carcinoma, involving both gamma knife radiosurgery (GKS) and linear-accelerator (LINAC)-based radiosurgery[7-10]. In the past few years, there has been a surge in employing flattening filter-free beams (FFF) in stereotactic radiotherapy owing to the benefits they offer in terms of dosimetry and clinical outcomes [11].

Currently, LINAC-based SRS is widely used globally and plays a crucial role in radiotherapy for brain metastases. The adoption of modern radiotherapy techniques, such as volumetric-modulated arc therapy (VMAT), into clinical practice has significantly enhanced LINAC-based SRS planning. Through the implementation of inverse planning methods, VMAT allows the customization of target conformity and organ-at-risk doses[12]. Recently, there has been growing interest in utilizing the dynamic conformal arc therapy (DCAT) technique in stereotactic radiotherapy (SRT). DCAT is applicable for both single and multiple brain metastases and employs variable dose rate (VDR) and segment shape optimization (SSO). SSO enables beam modulation for improved dose conformity and protection of normal tissues, allowing the Monaco treatment planning system (TPS) to achieve plan quality comparable to VMAT. The combination of SSO and VDR in DCAT reduces cumulative monitor unit (MU) values and results in quicker treatment plans[13]. Conversely, VMAT requires a higher number of MUs to deliver the same dose due to its increased modulation[14]. Exploring the possible benefits of such advancement techniques in treatment planning for the field of radiotherapy proves to be valuable.

Radiation necrosis is a toxicity that sets a limit on the dosage for brain SRS. Previous studies have shown that the risk of radionecrosis after brain SRS is related to the amount of healthy brain tissue exposed to varying radiation doses, and to reduce this risk while maintaining effective local control, fractionated SRS or SRT is suggested as an alternative to single-fraction SRS [15-18]. The four-fraction SRS is universally implemented as a popular radiotherapy regimen for brain SRS[19].

The objective of this study was to examine and differentiate the efficacy of VMAT and DCAT techniques for SRT in treating single brain carcinoma. The comparison was based on factors such as radiation doses to critical organs, cumulative MU values and quality indices. There is currently a lack of extensive research comparing VMAT and DCAT techniques specifically for single brain carcinoma treated with a four-fraction SRS regimen. Most previous studies have focused on single-fraction SRS for single brain metastasis or multi-fraction SRS for multiple brain metastases [3,20-22]. To the best of our understanding, this study represents the initial comparison between VMAT and DCAT techniques in individuals with single brain carcinoma who underwent a four-fraction SRS regimen. The study sheds light on how VMAT and DCAT perform in terms of target conformity and safety, particularly for different sizes and more complex tumors. This information is crucial for optimizing treatment plans to maximize tumour control while minimizing damage to surrounding healthy tissues. This study advances the existing literature by addressing a significant gap, providing a direct comparison of VMAT and DCAT in a new clinical context, and offers practical insights that can improve patient care and treatment planning for single brain carcinoma treated with a four-fraction SRS regimen.

Materials and Methods

The research was carried out in retrospective observational manner, focusing on dosimetric analysis.

Patient selection

This study included 20 patients (10 Male and 10 Female) aged between 20 to 80 with brain carcinoma who underwent brain SRT using the Elekta Versa HD LINAC at our institution. All patients underwent treatment at our institution during the period from 2017 to 2023.

Immobilization and Contouring

Contouring and planning procedures involves the utilization of computed tomography (CT) images. Each patient was positioned supine and immobilized using a thermoplastic mould (ORFIT), after which scans were performed from the vertex to the skull base having slice thickness of 3 mm using Philips Brilliance Big Bore 16 slice CT scanner Various structures, including the brainstem, brain, lenses, optic nerves/chiasm, cochlea and eyes were delineated as organs at risk (OARs) following the standard guidelines put forth by Radiation Therapy Oncology Group (RTOG)[23,24]. The delineation of gross tumor volume (GTV) was conducted based on CT images. To account for patient motion and set-up errors, the PTV was delineated as the GTV with an additional margin of 1 mm [25].

Treatment Planning

DCAT and VMAT plans were created for 20 patients using the Monaco TPS with version 5.11.03. The LINAC features an integrated array of 80 pairs of 5 mm width MLCs at the isocentre and also has an add-on device APEX, which comprises 56 pairs of micro-MLCs with 2.5 mm leaf widths at the isocentre. FFF photon beams with energy 6 MV were employed in every single plans. With a grid size of 3 mm, the dose was computed utilizing the Monte Carlo algorithm. The prescribed dose for the PTV was 16Gy administered in four-fraction, and normalization to $D_{95\%}$ was applied to every plan. For plans utilizing both VMAT and DCAT techniques, the isocentre was positioned at the geometric centre of the PTVs. In case of VMAT plans dual-arc technique was used with gantry angle starting from 180˚ to 360˚ and couch and collimator angle taken

were 0˚. For DCAT plans, couch angle was 0˚ and the gantry was rotated from 180˚ to 360˚ and the collimator angle was set to 270˚. To minimize the dose delivered to OARs, a ring contour was utilized around PTV, ensuring exposure to OARs was kept at a minimum. For DCAT plans 2.5 mm Apex micro-MLCs were used whereas VMAT utilized a 5 mm MLC (Elekta Agility).

Evaluation of the Treatment Plans

The dose distribution between VMAT and DCAT were compared using Paddick's conformity index (IP-CI), given by[3]

1) "$CI= V_{PTV\ (100)}{}^{2} / (V_{100} \times V_{PTV})$"

$V_{PTV\ (100)}$ is considered as volume of PTV which receives the prescribed dose,,

V_{100} is the prescribed dose received by the whole volume, and V_{PTV} is the volume PTV.

2) The estimation of the volume received by the brainstem, optic chiasma and cochlea was conducted by measuring V_{15Gy}, V_{12Gy}, V_{10Gy}, and V_{5Gy}, where

where V_{XGy} represents the volume of any tissue exposed to XGy of radiation.[3]

Statistical Analysis

Software and Version

Statistical analyses were performed using Jamovi software (version 2.3.26). The normality of the data was assessed with the Shapiro-Wilk test. A paired t-test was used to compare DCAT and VMAT treatment plans, as both were applied to the same set of patients and treatment sites, ensuring naturally paired data. A significance level of $P<0.05$ was considered to determine statistical significance.

Results

In this dosimetric study, twenty patients with single brain carcinoma were evaluated. The planning goals for all VMAT and DCAT plans were achieved using an identical optimization protocol. Both techniques demonstrated statistically similar target coverage, with the prescription isodose line covering at least 95% of the planning target volume in each patient.

Table 1 displays the results for the dose-volume parameters and the plan quality indices for both VMAT and DCAT techniques. In comparison to the DCAT technique, the VMAT technique demonstrated significantly superior results for Paddick CI ($p=0.04$) metrics indicating more conformal dose distribution, VMAT significantly improved the target conformity compared with DCAT with mean and SD for Paddiick CI were 0.650 ± 0.18 and 0.751 ± 0.08 for DCAT and VMAT, respectively.

Similarly, the P-values for the other parameters for PTV and GTV (Table 1 and 2), which include $D_{2\%}$, $D_{50\%}$, $D_{98\%}$, and D_{mean} are all greater than 0.05. This suggests that there is no significant statistical difference between the two techniques in relation to these parameters. However, the values in these parameters were comparatively lower in case of VMAT than in DCAT plans except for $D_{98\%}$. In case of $D_{98\%}$ VMAT plans showed superiority compared to DCAT plans.

Table 3a presents information on the radiation doses received by brainstem, optic chiasma and cochlea. All of the P-values are greater than 0.05, which suggests that there is no statistically significant difference between DCAT and VMAT in terms of any of the dose-volume parameters measured. Dose-volume parameters (V_{15Gy}, V_{12Gy}, V_{10Gy}, and V_{5Gy}) that were measured for brainstem, optic chiasma and cochlea were similar in VMAT compared to DCAT plans except for V_{12Gy} and V_{10Gy} in case of cochlea which shows slightly higher values for VMAT than for DCAT. Moreover, the value of D_{max} for brainstem is less in VMAT compared to DCAT plans (Table 3(b))

Table 4 presents a summary of the MUs in DCAT and VMAT plans. The MUs of DCAT plans were significantly smaller than that of VMAT plans ($p< 0.001$). Furthermore, Figure 1 illustrates the dose distributions in the axial plane for two treatment modalities.

Table 1. Overview of the PTV indices

INDEX	DCAT (Mean ± SD)	VMAT (Mean ± SD)	P- VALUE
IP-CI	0.650 ± 0.18	0.751 ± 0.08	0.046
$D_{2\%}$ (Gy)	17.17 ± 0.74	17.08 ± 0.36	0.717
$D_{50\%}$ (Gy)	16.48 ± 0.63	16.45 ± 0.26	0.878
$D_{98\%}$ (Gy)	15.00 ± 0.91	15.29 ± 0.32	0.118
D_{mean} (Gy)	16.42 ± 0.58	16.38 ± 0.24	0.797

PTV planning target volume, DCAT dynamic conformal arc therapy, VMAT volumetric modulated arc therapy, SD standard deviation, IP-CI Ian Paddick's conformity index, $D_{X\%}$ is dose to X% of volume, D_{mean} mean dose of PTV

Table 2. Overview of the GTV indices

INDEX	DCAT (Mean ± SD)	VMAT (Mean ± SD)	P- Value
$D_{2\%}$ (Gy)	17.21 ± 0.75	17.13 ± 0.37	0.733
$D_{50\%}$ (Gy)	16.67 ± 0.70	16.64 ± 0.30	0.869
$D_{98\%}$ (Gy)	15.94 ± 0.61	15.96 ± 0.28	0.905
D_{mean} (Gy)	16.42 ± 0.69	16.64± 0.29	0.875

GTV gross tumor volume, DCAT dynamic conformal arc therapy, VMAT volumetric modulated arc therapy, SD standard deviation, $D_{X\%}$ is dose to X% of volume, D_{mean} mean dose of GTV

Table 3(a). Overview of the volume of Optic Chiasma, Brainstem and Cochlea that received radiation exposure.

INDEX	Optic chiasma			Brainstem			Cochlea		
	DCAT Mean ± SD	VMAT Mean ± SD	p-value	DCAT Mean ± SD	VMAT Mean ± SD	p-value	DCAT Mean ± SD	VMAT Mean ± SD	p-value
V_{15Gy} (cm^3)	0.0012 ±0.005	0.00 ± 0.00	0.33	0.0481 ±0.16	0.0422 ±0.17	0.37	0.0257±0.05	0.0204 ±0.039	0.09
V_{12Gy} (cm^3)	0.006 ± 0.026	0.0012±0.005	0.33	0.34 ± 0.90	0.29 ± 0.87	0.36	0.0363±0.06	0.0380 ± 0.063	0.55
V_{10Gy} (cm^3)	0.010 ± 0.04	0.003 ± 0.01	0.33	0.62 ± 1.50	0.59 ± 1.55	0.7	0.0373±0.06	0.0437 ± 0.069	0.33
V_{5Gy} (cm^3)	0.023 ± 0.10	0.018 ± 0.07	0.33	3.57 ± 4.6	3.46 ± 4.32	0.8	0.0519±0.07	0.0486 ± 0.072	0.32

DCAT dynamic conformal arc therapy, VMAT volumetric modulated arc therapy, SD standard deviation, V_{XGy} is volume of tissue receiving XGy.

Table 3(b). Comparison of D_{max} to the Brainstem across DCAT and VMAT

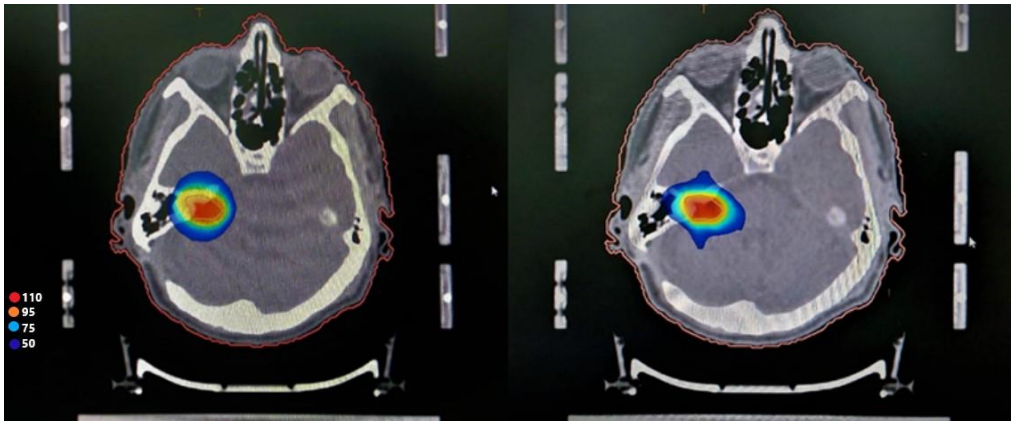
INDEX	DCAT (Mean ± SD)	VMAT (Mean ± SD)	P- VALUE
D_{max}	6.96 ± 6.7	6.85 ± 6.3	0.702

DCAT dynamic conformal arc therapy, VMAT volumetric modulated arc therapy, SD standard deviation, D_{max} maximum dose received

Table 4. The Monitor unit in Dynamic conformal arc therapy and Volumetric modulated arc therapy.

INDEX	DCAT (Mean ± SD)	VMAT (Mean ± SD)	P – VALUE
MU	571.36 ± 59.6	986.95 ± 146.3	<0.001

DCAT dynamic conformal arc therapy, VMAT volumetric modulated arc therapy, SD standard deviation, MU monitor units



a) DCAT PLAN b) VMAT PLAN

Figure. 1. The distribution of dose in a typical case is depicted in an axial plane for Dynamic Conformal Arc Therapy and Volumetric Modulated Arc Therapy DCAT and VMAT plans, respectively.

Discussion

This study analysed dose distribution in DCAT and VMAT plans for single brain carcinoma, finding that VMAT offered better conformity and reduced doses to the brainstem, optic chiasma, and cochlea in multi-fraction SRS. In our study, the median PTV was 4.985 cm^3 (range 0.171–14.07 cm^3), aligning with the range

documented in the study by Nida, Antonio et al., further supporting the validity of our findings [26].

Our research indicates that VMAT plans demonstrate a higher $D_{98\%}$ for the GTV compared to DCAT plans. This elevated $D_{98\%}$ in VMAT plans is anticipated to enhance local tumor control, thereby reducing the likelihood of tumor growth or spread within the targeted region. Supporting this, a recent study by Dupic et al. [27] highlighted the critical importance of achieving a high $D_{98\%}$ of the GTV for effective local control in multi-fraction SRT.[27]

Our study found that VMAT plans achieved superior CI values compared to DCAT plans. VMAT provided a more precise dose distribution closely aligned with the target volume, resulting in a steeper dose gradient outside the target area and reduced radiation exposure to surrounding healthy tissues, thus minimizing potential side effects. For optimal planning in SRT, it is recommended to achieve optimal CI values [28].

In current study, VMAT consistently outperformed DCAT in dose-volume parameters (V_{10Gy} and V_{12Gy}), except for the cochlea. VMAT effectively reduces the risk of brain radiation necrosis and delivers a lower maximum dose (D_{max}) to the brainstem than DCAT. Overall, VMAT offers notable safety and effective advantages for treating brain carcinoma near sensitive structures like the brainstem. Radiation necrosis is one of the most severe side effects following brain radiotherapy[29]. While the risk of radiation necrosis after SRT varies in different studies due to factors like treatment methods, lesion type, target size, and patient selection. Parameters like V_{10Gy} and V_{12Gy} are crucial in estimating the likelihood of radiation necrosis and are considered among the most important factors in assessing the associated risk [30-32]. Hence, both techniques were examined in terms of these two values.

Our study revealed that DCAT provided better conformity for small tumour volumes, while VMAT outperformed DCAT for larger tumours. DCAT excels in targeting small, well-defined volumes with high precision, whereas VMAT's advanced modulation techniques offer superior conformity for larger, more complex tumours while safeguarding adjacent tissues.

Monk et al. demonstrated that the micro-MLC improves target coverage due to its proximity to the patient, reducing penumbra and allowing for better target coverage without significantly increasing maximum doses to OAR; however, such add-on devices necessitate additional commissioning and prolong treatment setup time [33]. While the study conducted by Jin et al. indicates even though narrower leaf-width MLCs achieve better dose conformity compared to wider leaf-width MLCs, this benefit decreases as the target volume increases[34]. Our results showed that, despite using the APEX MLC for DCAT and the Agility MLC for VMAT, parameters like $D_{98\%}$ and doses to OARs were similar. However, VMAT exhibited a superior conformity index compared to DCAT. It is important to note that this study is solely dosimetric and based on treatment planning, with actual patient doses potentially affected by other factors.

Nonetheless, it is evident that achieving an optimal brain SRT plan requires consideration of various factors, including the radiotherapy device's capabilities, patient and tumour characteristics, and plan quality indices. Given that SRT is time-consuming, efficiently completing sessions is crucial, particularly for patients with compromised health or limited endurance. Reducing treatment time minimizes patient movement, enhances comfort, and reduces distress, thereby decreasing treatment-related uncertainties. Consequently, DCAT may offer practical advantages over VMAT for clinicians in daily practice. This is because DCAT can offer comparable target coverage at the same time significantly reducing duration of treatment by 50%. The previous study done by G. Türkkan et al.[20] highlights the time-saving advantage of DCAT in brain SRT when compared to VMAT, this study further supports such findings[20].

Overall, our findings align with previous studies of D. Torizuka et al., G. Türkkan et al. and M. Uto et al. that have compared VMAT and DCAT in brain SRS [3,20,22]. However, it is important to note that this study solely provides dosimetric outcomes.

As patient lifespans increase with advancements in treatment and the need for reirradiation arises in cases of intracranial recurrence, minimizing radiation to healthy brain tissue becomes essential. While VMAT is favoured for its precision and safety, DCAT's shorter treatment durations make it a viable alternative for patients requiring quicker sessions due to their physical condition. Since the differences between these methods are not substantial, either technique can be effectively chosen based on individual patient needs and circumstances.

It is important to acknowledge the constraints associated with this study. First, being retrospective, it cannot confirm whether improvements in target CI and reduction in brain tissue volume receiving V_{10Gy} and V_{12Gy} doses actually resulted in practical advantages. Second, while higher CI values (near to 1.0) and lower doses to normal brain tissue are crucial for effective tumour control and reducing brain necrosis risk, further clinical validation and prospective data are necessary. Third, due to the study's design, we could not determine if VMAT demonstrates superior dosimetric performance compared to DCAT in terms of toxicity in a clinical setting. Finally, only a limited set of parameters were examined, suggesting a need for further research with broader parameters.

Conclusion

When comparing SRS planning techniques for multiple fractions in solitary brain carcinoma, VMAT excels over DCAT in target conformity and reducing the risk of brain radiation necrosis, making it the preferred choice. However, DCAT offers lower MU values and reduces treatment duration by nearly fifty percent compared to VMAT, making it a viable option for

patients with reduced performance status who require shorter radiotherapy sessions.

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