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Original Research Article

Comparative study of dynamic conformal arc therapy and volumetric modulated arc therapy for treating single brain metastases: A retrospective analysis of dosimetric and clinical outcomes

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ABSTRACT

Background and purpose: Stereotactic radiation therapy (SRT) is commonly used to treat brain metastases (BMs). This retrospective study compared two SRT techniques, dynamic conformal arc therapy (DCAT) and volumetric modulated arc therapy (VMAT), for single BM treatments.
Material and methods: Data of patients treated between January 2010 and June 2020 were considered. Patients with multiple BMs, resected BMs, reirradiation, whole-brain radiation therapy and brainstem metastases were excluded. We focused our analysis on 97 patients who received 23.1 Gy in three fractions. Acute toxicities and follow-up outcomes were recorded. Dosimetric data were analyzed in two subgroups (PTV $\leq$ 10 cc and PTV $>$ 10 cc).
Results: DCAT and VMAT were used in 70 (72.2 %) and 27 (27.8 %) patients, respectively. Acute toxicities were not significantly different between groups ($p = 0.259$), and no difference was detected in the incidence rate of radionecrosis, local recurrence and cerebral recurrence ($p > 0.999$, $p > 0.999$ and $p = 0.682$, respectively). PTV coverage was better with DCAT for small volumes (PTV $\leq$ 10 cc). Mean conformity index (CI) was significantly higher with VMAT and mean gradient index (GI) was significantly lower with DCAT whatever volume subgroups ($p < 0.001$). DCAT had more heterogeneous plans and VMAT required more monitor units. DCAT resulted in reduced low and intermediate doses, whereas VMAT led to decreased high doses.
Conclusion: DCAT and VMAT are two effective and safe SRT techniques for BMs treatment. In the era of re-irradiation, it is important to reduce the doses delivered to healthy tissues. Further prospective studies are needed to validate these findings.

1. Introduction

Brain metastases (BMs) are the most common intracranial malignant tumors and are found in approximately 20–40 % of cancer patients [1,2]. Regardless of the primary tumor's histology, about 70 % of patients have single BM at the diagnosis of metastases [3,4].

Stereotactic radiation therapy (SRT) is an accurate technique that uses converging small beams to administer high doses of radiation to

Abbreviations: BMs, brain metastases; CI, conformity index; CR, cerebral recurrence; DCAT, dynamic conformal arc therapy; DS-GPA, Diagnosis-Specific Graded Prognostic Assessment; DVH, dose-volume histogram; GI, gradient index; GTV, gross tumor volume; HI, homogeneity index; KPS, Karnofsky performance status; LINAC, linear accelerator; LR, local recurrence; MLC, multileaf collimators; MRI, magnetic resonance imaging; PTV, planning target volume; RN, radionecrosis; RPA, Recursive Partitioning Analysis; SRT, stereotactic radiation therapy; TPS, Treatment planning system; VMAT, volumetric modulated arc therapy; WBRT, whole-brain radiation therapy.

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small tumor volume while sparing the neighboring healthy tissues. SRT has largely replaced whole-brain radiation therapy (WBRT) for treating BMs [5,6] and it can yield comparable therapeutic outcomes to surgical intervention [7]. Dynamic conformal arc therapy (DCAT) and volumetric modulated arc therapy (VMAT) are two commonly used techniques to plan SRT delivered by conventional linear accelerators (LINACs) equipped with multileaf collimators (MLCs).

Advances in medical oncology treatments has extended the survival of patients with BMs. Among patients treated with SRT for BMs, approximately 40–60 % may experience cerebral recurrence (CR) of BMs in other areas of the brain, while 10–25 % may encounter local recurrence (LR) within one year following SRT [2,8]. Consequently, an increasing number of patients will undergo multiple sessions of SRT over their course of life [9]. Therefore, it becomes crucial to optimize dosimetric targets from the initial brain irradiation to minimize the risk of long-term side effects, such as radionecrosis (RN) [10,11].

The aim of this retrospective study was to analyze dosimetric parameters between DCAT and VMAT techniques on target volumes and healthy brain tissue for single BM treatments. Additionally, the clinical outcome was compared between the two groups.

2. Materials and methods

2.1. Patient and treatment modalities

We used our institutional database to identify patients who received SRT for BMs between January 2010 and June 2020. We excluded patients with multiple BMs, resected BMs, cerebral reirradiation, WBRT and brainstem metastases. Out of 1,240 patients treated with SRT for BMs, 152 were treated for a single BM. Among these, we analyzed dosimetric data of patients who received a total dose of 23.1 Gy in three fractions of 7.7 Gy every other day at the planning target volume (PTV) envelope (70 % isodose line), for a total of 97 patients.

For the above patients, a planning CT of 1.25-mm thickness (GE Optima RT 580, GE HealthCare, Chicago, Illinois, United States) with a frameless mask from Brainlab® was acquired and matched with the dosimetric magnetic resonance imaging (MRI) sequences (1.3-mm thickness). The dosimetric MRI took place within the 15 days before SRT, and the gross tumor volume (GTV) was defined as the post gadolinium contrast-enhanced region on the T1 MRI sequences. A 2-mm three-dimensional margin was added to the GTV to assign the PTV. Treatments were planned with either the iPlan® RT Dose V4.5.5 (Brainlab® AG, Feldkirchen, Germany) or the Eclipse® System V15.6 (Varian Medical Systems®, Palo Alto, CA, USA) with a 1.25 mm grid calculation. Treatments were delivered using SRS-6MV beam from a Novalis Tx™ (Varian Medical Systems®, Palo Alto, CA, USA) or a 6MV-FFF beam from a TrueBeam STx™ (Varian Medical Systems®, Palo Alto, CA, USA). The specific national guidelines were used for the organs at risk radiation dose constraints [12]. DCAT and VMAT were used for 70 (72.2 %) and 27 (27.8 %) patients, respectively. Before 2014, only DCAT was used, after which the VMAT has been introduced to our RT department and became the primary technique for treating big and complex BMs. All DCAT plans were created with three, four or five non-coplanar arcs for 35 (50 %), 31 (44.3 %) and 4 (5.7 %) patients, respectively. VMAT plans were created with two or three arcs for 13 (48.2 %) and 14 (51.8 %) patients, respectively. Among patients treated with VMAT, the plans were created with coplanar arcs for 15 (55.6 %) patients and a combination of coplanar and non-coplanar arcs for 12 (44.4 %) patients. Most patients (n = 91; 93.8 %) received prophylactic corticosteroids during irradiation. Six patients did not receive corticosteroids due to immunotherapy. Systemic therapy, whether present, had been stopped 48–72 h before the first day of radiotherapy and resumed afterwards.

For each patient, we calculated the Recursive Partitioning Analysis (RPA) and the Diagnosis-Specific Graded Prognostic Assessment (DS-GPA) scores [13–15].

This study follows the French law as it has been declared to the CNIL (*Commission Nationale de l'informatique et des libertés*) using the MR004 form on https://www.health-data-hub.fr/ under the number F20201119113809. This study was approved by the Institutional Review Board of our institution (n° IRB-2023-1).

2.2. Evaluation of treatment plans

The treatment plan analyzes were based on dose-volume histogram (DVH) data on Artiview® (Aquilab by Coexya) to overcome the problem of different definitions of the structure volume according to treatment planning system (TPS). For target volume coverage, $V_{70\%}$, $V_{90\%}$, $V_{100\%}$, $D_{2\%}$, $D_{50\%}$ and $D_{98\%}$ to the GTV and PTV were noted. For healthy brain dose delivery, $V_{23.1Gy}$, V_{21Gy}, V_{18Gy}, V_{14Gy}, V_{12Gy}, V_{10Gy}, V_{5Gy} were used for Brain-PTV and Brain-GTV. We recorded the number of monitor units. We also calculated three indexes for the PTV: the Paddick conformity index (CI), the gradient index (GI) and the homogeneity index (HI).

The Paddick CI was defined as follows [16]:

$$CI = \frac{(PTVreceiving \geq 23.1Gy)^2}{PTV \times Totalvolumereceiving \geq 23.1Gy}$$

CI ranges from 0 to 1 and the best conformity is when CI = 1.

The GI was calculated as follows [17]:

$$GI = \frac{Totalvolumereceiving \geq 11.55Gy(50\%Dcoverage)}{Totalvolumereceiving \geq 23.1Gy(100\%Dcoverage)}$$

A lower GI represents a faster dose falloff in normal brain tissue from the PTV.

The HI was defined as [18]:

$$HI = \frac{PTVD2\%}{23.1Gy}$$

The plan is homogeneous when HI equals 1 and becomes heterogeneous as it deviates from 1.

2.3. Acute toxicities reporting

Each patient met with the referring radiation oncologist in a pre-treatment consultation to plan the SRT. Information on the medical history, oncological treatments, corticosteroid therapy, and the different neurological symptoms were collected. During the treatment, the patients had a weekly consultation with the radiation oncologist to evaluate the tolerance of the treatment. The use of corticosteroid therapy and neurological symptoms were recorded and scored according to the Common Terminology Criteria for Adverse Events version 5.0 (CTCAE v.5.0) [19].

2.4. Follow-up

MRI was performed every three months during the first two years after SRT, then every six months, to diagnose RN, LR, CR, or therapeutic efficacy. A new contrast enhancement outside the previously treated BM was categorized as a CR. A contrast enhancement inside the previously treated BM suggested a LR or a RN. To differentiate both, 18-fluorodeoxyglucose (FDG) PET-CT, surgery, corticosteroids test or a new MRI in a short interval were realized [20–23].

2.5. Statistical analysis

Numeric variables were expressed as mean (±SD) and discrete outcomes as absolute and relative (%) frequencies. We created two groups according to the SRT techniques (DCAT or VMAT). Group comparability was assessed by comparing baseline patients and lesions' characteristics between groups. Normality and hetereoskedasticity of continuous data

were assessed with Shapiro-Wilk and Levene's test respectively. Continuous outcomes were compared with ANOVA, welch ANOVA or Kruskal-Wallis tests according to data distribution. Discrete outcomes were compared with chi-squared or Fisher's exact test accordingly. The alpha risk was set to 5 % and two-tailed tests were used.

Statistical analysis was performed with EasyMedStat (version 3.27; https://www.easymedstat.com).

3. Results

3.1. Patient and lesion characteristics

The characteristics of the patients and BMs are summarized in Table 1. The proportion of men was significantly higher in VMAT group than in DCAT group (77.8 % *vs* 52.9 %, respectively, p = 0.044). The mean age at the SRT, the mean time between primitive diagnosis and SRT, the mean KPS, the incidences of patients with extracranial metastases or with a controlled primitive site did not differ between groups. The distribution of patients according to primitive sites, DS-GPA classes and RPA groups did not vary between both techniques.

Mean GTV and PTV were significantly higher in VMAT group, 10.29 (±12.38) cc and 16.48 (±16.68) cc, respectively than in DCAT group, 5.55 (±6.11) cc and 9.58 (±8.83) cc, respectively (p = 0.019 and p = 0.014 for mean GTV and PTV, respectively). There was no difference between groups for the localization (sub- or supra-tentorial), the shape (concave or convex) or the presence of oedema.

Table 1
Patient and lesion characteristics (n = 97).

Characteristics	DCAT n = 70	VMAT n = 27	p-Value
Gender			
Male	37 (52.9 %)	21 (77.8 %)	**0.044**
Female	33 (47.1 %)	6 (22.2 %)	
Age at treatment – mean (years)	67.4 (±11.4) Range: (37.0; 89.0)	68.1 (±10.4) Range: (32.0; 82.0)	0.527
Time between primitive diagnosis and BM treatment – mean (months)	37.2 (±55.1) Range: (0.0; 288.0)	34.1 (±43.9) Range: (0.0; 156.0)	0.974
KPS – mean (%)	79.1 (±15.8) Range: (20.0; 100.0)	79.6 (±13.4) Range: (50.0; 100.0)	0.902
DS-GPA class	16 (23.9 %)	6 (25.0 %)	0.437
1	26 (38.8 %)	13 (54.2 %)	
2	20 (29.8 %)	5 (20.8 %)	
3	5 (7.5 %)	0 (0.0 %)	
4	N = 67	N = 24	
RPA group			0.089
I	6 (8.6 %)	1 (3.7 %)	
IIa	20 (28.6 %)	4 (14.8 %)	
IIb	16 (22.8 %)	14 (51.9 %)	
IIc	19 (27.1 %)	5 (18.5 %)	
III	9 (12.9 %)	3 (11.1 %)	
Primitive histology			
Lungs	35 (50.0 %)	18 (66.7 %)	0.198
Breast	9 (12.9 %)	1 (3.7 %)	
Digestive	9 (12.9 %)	4 (14.8 %)	
Melanoma	8 (11.4 %)	1 (3.7 %)	
Kidney	6 (8.5 %)	0 (0.0 %)	
Others	3 (4.3 %)	3 (11.1 %)	
Extracranial metastases			
Yes	40 (57.1 %)	20 (74.1 %)	0.192
No	30 (42.9 %)	7 (25.9 %)	
Control of the primary tumor site			
Yes	22 (31.4 %)	8 (29.6 %)	>0.999
No	48 (68.6 %)	19 (70.4 %)	
GTV volume – mean (cc)	5.55 (±6.11) Range: (0.11; 31.24)	10.29 (±12.38) Range: (0.15; 61.77)	**0.019**
PTV volume – mean (cc)	9.58 (±8.83) Range: (0.58; 43.2)	16.48 (±16.68) Range: (0.71; 83.45)	**0.014**
Localization			
sub tentorial	16 (22.9 %)	5 (18.5 %)	0.786
supra tentorial	54 (77.1 %)	22 (81.5 %)	
Œdema			
Yes	19 (27.1 %)	12 (44.4 %)	0.144
No	51 (72.9 %)	15 (55.6 %)	
Shape			
concave	27 (38.6 %)	9 (33.3 %)	0.807
convex	43 (61.4 %)	18 (66.7 %)	

3.2. Acute toxicities and follow-up

The proportions of patients with symptoms before and during the SRT treatment were not significantly different between DCAT and VMAT groups (p = 0.058 and p = 0.259, respectively). The mean follow-up after SRT was 17.5 months (range: 0.0; 141.0) in DCAT group and 10.6 months (range: 1.0; 47.0) in VMAT group (p = 0.463). There was no significant difference between groups for incidence of RN, LR and CR (p > 0.999, p > 0.999 and p = 0.682, respectively). Table 2 summarizes acute toxicities and follow-up outcomes.

3.3. Dosimetric data

As mean PTV was significantly different between both techniques, and statistically correlated with the various dosimetric variables, we analyzed the dosimetric data in the two volume subgroups (PTV ≤ 10 cc and PTV > 10 cc). Thus, in subgroup PTV ≤ 10 cc, mean PTV was 2.16 (±1.43) cc in DCAT group and 2.35 (±1.52) cc in VMAT group (p = 0.46). In subgroup PTV > 10 cc, mean PTV was 19.22 (±8.62) cc in DCAT group and 24.3 (±17.79) cc in VMAT group (p = 0.377).

3.3.1. Target volume coverage

In Table 3, PTV and GTV coverage are listed. PTV coverage (PTV_V70%) were slightly better in DCAT group when PTV ≤ 10 cc (p < 0.001) and the difference is statistically significant. However, if PTV > 10 cc, no difference in terms of coverage was observed between the

Table 2
Acute toxicities and follow-up (n = 97).

	DCAT n = 70	VMAT n = 27	p-Value
Symptom before treatment			
grade 0	45 (64.3 %)	13 (48.15 %)	0.058
grade 1	17 (24.3 %)	13 (48.15 %)	
grade 2	8 (11.4 %)	1 (3.7 %)	
Symptom during treatment			0.259
grade 0	41 (58.6 %)	11 (40.7 %)	
grade 1	20 (28.6 %)	12 (44.5 %)	
grade 2	9 (12.8 %)	4 (14.8 %)	
Radionecrosis			
Yes	5 (7.2 %)	1 (3.7 %)	>0.999
No	65 (92.8 %)	26 (96.3 %)	
Local recurrence			
Yes	3 (4.3 %)	1 (3.7 %)	>0.999
No	67 (95.7 %)	26 (96.3 %)	
Cerebral recurrence			
Yes	5 (7.1 %)	3 (11.1 %)	0.682
No	65 (92.9 %)	24 (88.9 %)	
Death			
Yes	60 (85.7 %)	24 (88.9 %)	>0.999
No	10 (14.3 %)	3 (11.1 %)	
Delay between radiotherapy and death – mean (months)	8.6 (±9.6) Range: (0.0; 43.0) n = 60	7.6 (±7.6) Range: (1.0; 27.0) n = 24	0.647
Follow-up post-SRT – mean (months)	17.5 (±27.8) Range: (0.0; 141.0)	10.6 (±11.8) Range: (1.0; 47.0)	0.463

Table 3
Target volume coverage according to the SRT technique (DCAT or VMAT) for PTV ≤ 10 cc and PTV > 10 cc (n = 97).

Variables (mean)	PTV ≤ 10 cc			PTV > 10 cc		
	DCAT n = 46	VMAT n = 11	p-Value	DCAT n = 24	VMAT n = 16	p-Value
PTV_V70% (%)	99.97 (±0.0535) Range: (99.76; 100.0)	99.81 (±0.197) Range: (99.31; 100.0)	**<0.001**	99.86 (±0.231) Range: (99.03; 100.0)	99.83 (±0.148) Range: (99.49; 99.99)	0.097
PTV_V90% (%)	64.76 (±6.41) Range: (50.98; 79.61)	29.95 (±5.46) Range: (20.08; 36.48)	**<0.001**	61.65 (±5.26) Range: (49.54; 71.5)	32.76 (±10.28) Range: (15.96; 49.9)	**<0.001**
PTV_V100% (%)	0.0317 (±0.101) Range: (0.01; 0.7)	1.53 (±2.05) Range: (0.0; 6.87)	**<0.001**	0.0121 (±0.00415) Range: (0.01; 0.02)	4.26 (±4.65) Range: (0.0; 16.06)	**<0.001**
PTV_D2% (Gy)	33.17 (±0.234) Range: (32.58; 33.75)	32.8 (±0.518) Range: (32.22; 34.03)	**0.042**	34.04 (±0.552) Range: (32.82; 34.88)	33.19 (±0.833) Range: (32.0; 34.62)	**<0.001**
PTV_D50% (Gy)	30.92 (±0.417) Range: (29.82; 31.58)	27.92 (±0.548) Range: (27.04; 28.68)	**<0.001**	31.58 (±0.428) Range: (30.27; 32.36)	28.25 (±0.849) Range: (26.71; 29.69)	**<0.001**
PTV_D98% (Gy)	25.96 (±0.743) Range: (24.63; 27.79)	23.96 (±0.542) Range: (23.57; 25.49)	**<0.001**	26.13 (±0.737) Range: (24.83; 27.63)	23.93 (±0.321) Range: (23.55; 24.78)	**<0.001**
GTV_V90% (%)	99.14 (±1.17) Range: (94.57; 100.0)	66.82 (±16.2) Range: (51.35; 100.0)	**<0.001**	86.69 (±8.12) Range: (70.11; 99.19)	50.9 (±17.21) Range: (23.29; 82.35)	**<0.001**
GTV_V100% (%)	0.0965 (±0.376) Range: (0.01; 2.59)	4.91 (±9.58) Range: (0.0; 33.07)	**0.001**	0.0167 (±0.00816) Range: (0.01; 0.04)	6.81 (±7.91) Range: (0.0; 27.5)	**<0.001**
GTV_D2% (Gy)	33.27 (±0.223) Range: (32.69; 33.85)	33.07 (±0.578) Range: (32.52; 34.58)	**0.007**	34.12 (±0.558) Range: (32.9; 34.99)	33.34 (±0.83) Range: (32.26; 34.83)	**<0.001**
GTV_D50% (Gy)	32.25 (±0.15) Range: (31.79; 32.56)	30.53 (±0.77) Range: (29.76; 32.46)	**<0.001**	32.4 (±0.349) Range: (31.08; 32.9)	29.69 (±1.08) Range: (27.78; 31.71)	**<0.001**
GTV_D98% (Gy)	30.52 (±0.349) Range: (29.92; 31.58)	27.37 (±1.32) Range: (26.22; 30.4)	**<0.001**	29.82 (±0.426) Range: (28.48; 30.68)	26.29 (±1.1) Range: (23.75; 28.04)	**<0.001**

DCAT and VMAT group (p = 0.097). In the two subgroups, a significantly greater percentage of the PTV and GTV received at least 90 % of the dose, in DCAT group (p < 0.001 for both) and $D_{2\%}$, $D_{50\%}$ and $D_{98\%}$ for PTV and GTV were significantly higher in DCAT group (p = 0.042 and p = 0.007 for $D_{2\%}$ for PTV and GTV in PTV ≤ 10 cc subgroups, p < 0.001 for others).

3.3.2. Dosimetric indexes and monitor units

For PTV ≤ 10 cc, mean CI was significantly higher with VMAT than with DCAT, 0.86 (±0.1) *vs* 0.74 (±0.07), (p < 0.001), respectively, and mean CI was also significantly higher with VMAT than with DCAT for PTV > 10 cc, 0.88 (±0.05) *vs* 0.77 (±0.05), (p < 0.001), respectively.

Mean GI was significantly lower with DCAT than with VMAT, for PTV ≤ 10 cc, 2.71 (±0.27) *vs* 3.92 (±1.09), (p < 0.001), respectively, and, for PTV > 10 cc, 2.48 (±0.2) *vs* 3.31 (±0.57), (p < 0.001), respectively. Consequently, there had a faster dose fall-off in normal brain tissue from the PTV with DCAT, for both subgroups.

The plans for DCAT treatment were significantly more heterogeneous than plans for VMAT treatment, whatever the subgroups (p = 0.042 and p < 0.001 for PTV ≤ 10 cc and > 10 cc, respectively).

The mean number of monitor unit was significantly higher in VMAT group, for both subgroups (p < 0.001 and p < 0.001 for PTV ≤ 10 cc and > 10 cc, respectively). Table 4 summarizes dosimetric indexes and number of monitor units.

3.3.3. Doses to healthy brain

Table 5 shows DVH results for healthy brain. We reported the "Brain minus PTV" volume and the "Brain minus GTV" volume, the latter integrating the healthy tissue between the GTV and the PTV. In both subgroups (PTV ≤ or > 10 cc), for "Brain minus PTV" and "Brain minus GTV" volumes, the mean V_{5Gy}, V_{10Gy}, V_{12Gy}, V_{14Gy} and V_{18Gy} tended to be lower in DCAT group while the mean V_{21Gy} and $V_{23.1Gy}$ tended to be lower in VMAT group, yet the differences were not statistically significant, except for the $V_{23.1Gy}$.

4. Discussion

In this retrospective study, VMAT and DCAT have been compared for the treatment of a single BM. Notably, no patients received WBRT before or after the studied treatment or a subsequent SRT, thus all toxicities can be associated only to the studied SRT, with no cumulative doses.

Regardless of the SRT technique used, our study found no significant differences in acute and late toxicities, LR or CR, and overall survival. To the best of our knowledge, the studies comparing VMAT and DCAT to date, have been *in silico* studies, therefore, no clinical data is available to correlate dosimetric differences with potential clinical outcome differences [24–27].

In this cohort, we showed that BMs were bigger in VMAT group than in DCAT group. This could be explained by the different algorithms used in both techniques. DCAT uses direct planning, whereas VMAT uses inverse planning. The latter is better in terms of CI and time-consuming

Table 4
Dosimetric indexes and monitor units according to the SRT technique (DCAT or VMAT) for PTV ≤ 10 cc and PTV > 10 cc (n = 97).

Variables (mean)	PTV ≤ 10 cc			PTV > 10 cc		
	DCAT n = 46	VMAT n = 11	p-Value	DCAT n = 24	VMAT n = 16	p-Value
Conformity index (CI)	0.74 (±0.07) Range: (0.53; 0.88)	0.86 (±0.1) Range: (0.57; 0.92)	**<0.001**	0.77 (±0.05) Range: (0.68; 0.87)	0.88 (±0.05) Range: (0.72; 0.95)	**<0.001**
Gradient index (GI)	2.71 (±0.27) Range: (2.35; 3.72)	3.92 (±1.09) Range: (2.78; 6.4)	**<0.001**	2.48 (±0.2) Range: (2.2; 2.98)	3.31 (±0.57) Range: (2.53; 4.22)	**<0.001**
Homogeneity index (HI)	1.44 (±0.01) Range: (1.41; 1.46)	1.42 (±0.02) Range: (1.39; 1.47)	**0.042**	1.47 (±0.02) Range: (1.42; 1.51)	1.44 (±0.04) Range: (1.39; 1.5)	**<0.001**
Number of monitor units	4578 (±444.9) Range: (3591; 5718)	7076 (±1780.1) Range: (5479; 11892)	**<0.001**	4199 (±414.52) Range: (3414; 5214)	7375 (±1307.6) Range: (5565; 10989)	**<0.001**

Table 5
Dose to healthy brain according to the SRT technique (DCAT or VMAT) for PTV ≤ 10 cc and PTV > 10 cc (n = 97).

Variables (mean)	PTV ≤ 10 cc			PTV > 10 cc		
	DCAT n = 46	VMAT n = 11	p-Value	DCAT n = 24	VMAT n = 16	p-Value
Brain minus PTV_V5Gy (cc)	42.95 (±22.96) Range: (8.08; 91.87)	59.65 (±43.56) Range: (17.17; 154.38)	0.368	151.66 (±73.53) Range: (58.98; 329.92)	181.68 (±103.63) Range: (50.35; 473.56)	0.37
Brain minus PTV_V10Gy (cc)	13.27 (±6.59) Range: (2.82; 26.37)	18.2 (±11.75) Range: (5.09; 42.67)	0.064	48.09 (±21.47) Range: (20.22; 87.74)	64.32 (±43.72) Range: (16.45; 199.7)	0.264
Brain minus PTV_V12Gy (cc)	9.52 (±4.67) Range: (2.16; 18.72)	12.43 (±7.42) Range: (3.59; 26.93)	0.107	34.57 (±15.51) Range: (14.61; 64.01)	44.61 (±28.56) Range: (11.97; 131.17)	0.264
Brain minus PTV_V14Gy (cc)	7.04 (±3.4) Range: (1.67; 13.69)	8.71 (±4.96) Range: (2.58; 17.89)	0.189	25.61 (±11.59) Range: (10.9; 49.03)	31.48 (±18.93) Range: (8.96; 87.46)	0.341
Brain minus PTV_V18Gy (cc)	4.05 (±1.84) Range: (1.29; 7.69)	4.23 (±2.27) Range: (1.32; 8.3)	0.779	14.3 (±6.57) Range: (6.52; 28.36)	15.41 (±8.82) Range: (4.58; 40.43)	0.649
Brain minus PTV_V21Gy (cc)	2.43 (±1.14) Range: (0.84; 4.73)	1.98 (±1.03) Range: (0.68; 3.87)	0.233	8.8 (±4.32) Range: (3.92; 18.67)	7.3 (±4.19) Range: (2.13; 18.85)	0.263
Brain minus PTV_V23.1 (cc)	1.6 (±0.754) Range: (0.49; 3.2)	0.621 (±0.333) Range: (0.28; 1.35)	**<0.001**	5.74 (±3.12) Range: (2.33; 12.91)	2.34 (±1.61) Range: (0.6; 6.15)	**<0.001**
Brain minus GTV_V5Gy (cc)	45.26 (±23.91) Range: (8.44; 96.0)	62.32 (±44.83) Range: (18.22; 160.1)	0.401	158.38 (±75.36) Range: (62.54; 339.94)	189.05 (±106.72) Range: (53.26; 492.78)	0.355
Brain minus GTV_V10Gy (cc)	15.54 (±7.56) Range: (3.18; 30.03)	20.87 (±13.07) Range: (6.18; 48.1)	0.077	54.68 (±23.49) Range: (24.07; 97.48)	71.92 (±47.12) Range: (19.88; 218.96)	0.252
Brain minus GTV_V12Gy (cc)	11.77 (±5.63) Range: (2.52; 22.41)	15.09 (±8.77) Range: (4.68; 32.39)	0.123	41.16 (±17.44) Range: (18.49; 73.1)	52.21 (±31.98) Range: (15.38; 150.56)	0.275
Brain minus GTV_V14Gy (cc)	9.29 (±4.34) Range: (2.03; 17.35)	11.37 (±6.32) Range: (3.66; 23.38)	0.197	32.22 (±13.55) Range: (14.72; 58.07)	39.07 (±22.29) Range: (12.31; 106.53)	0.37
Brain minus GTV_V18Gy (cc)	6.26 (±2.84) Range: (1.5; 11.22)	6.89 (±3.65) Range: (2.13; 13.7)	0.532	20.9 (±8.54) Range: (10.14; 37.68)	23.0 (±12.17) Range: (7.96; 59.55)	0.553
Brain minus GTV_V21Gy (cc)	4.72 (±2.12) Range: (1.04; 8.44)	4.64 (±2.46) Range: (1.36; 9.32)	0.917	15.34 (±6.22) Range: (7.73; 27.65)	14.86 (±7.54) Range: (5.5; 37.89)	0.772
Brain minus GTV_V23.1 Gy (cc)	3.86 (±1.73) Range: (0.88; 6.91)	3.25 (±1.75) Range: (0.95; 6.66)	0.296	12.32 (±4.99) Range: (6.33; 22.28)	13.53 (±15.81) Range: (3.86; 70.02)	0.224

as volume increases and becomes complex [25,26]. Since 2014, when the VMAT was deployed in our RT department, the teams have prioritized its use for high-volume treatment. This difference of volume was a limitation to compare SRT techniques because PTV and dosimetric variables were correlated, which increased the bias risk of the whole analysis. To compensate for this limitation, analyzes were done on two subgroups based on the PTV (≤10 cc and > 10 cc), since no significant difference in PTV had been detected between both techniques.

We found that PTV coverage was slightly higher with DCAT than with VMAT for PTV ≤ 10 cc and the difference was statistically significant, but the results were equivalent between techniques for larger PTVs. This is in line with the article of Brun *et al.* which did not show any difference of target coverage between VMAT and DCAT for large volumes (mean PTV was 14.5 cc (10.5–21.4 cc)) [24]. However, percentage of the PTV and GTV receiving at least 90 % of the dose and $D_{2\%}$, $D_{50\%}$ and $D_{98\%}$ for PTV and GTV were significantly higher in the DCAT group, regardless of the volume subgroup. One study showed that GTV_$D_{98\%}$ was a significant predictive factor of local control in multifractionated SRT (23.1 Gy in three fractions) for unresected BMs, particularly if GTV_$D_{98\%}$ was ≥ 29–29.4 Gy [28]. In contrast, in our results we observed four LR, among which three had a GTV_$D_{98\%}$ > to 29.4 Gy. This apparent difference should be carefully considered due to the low number of events in our series. However, our results differ also from those of Torizuka *et al.* who did not find any significant difference in $D_{2\%}$, $D_{50\%}$ and $D_{98\%}$ for PTV and GTV except for $D_{98\%}$ of GTV which was significantly better with VMAT with no-coplanar arcs. These reverse results could be explained by the fact that authors used the same TPS and calculation algorithm for both techniques [27], while in our study, calculations were performed with two distinct TPS.

We showed a better CI with VMAT and a better GI with DCAT in both volume subgroups. These results are consistent with the literature [24–27] and can explain the results of doses delivered in the healthy brain. Indeed, we observed that the mean V_{5Gy}, V_{10Gy}, V_{12Gy}, V_{14Gy} and V_{18Gy} tended to be lower in DCAT group compared to VMAT, while the mean V_{21Gy} and $V_{23.1Gy}$ were lower in VMAT group. As the dose was prescribed on the 70 % isodose, 23.1 Gy was the dose that must surround the PTV. As the CI is better in VMAT, the 70 % isodose overflows less onto the healthy brain and the $V_{23.1Gy}$ and V_{21Gy} are consequently lower. However, the total volume receiving ≥ 11.55 Gy is lower in DCAT group (Table 6) and therefore low and intermediate doses in the healthy brain tissues are also inferior with DCAT. This allows us to say that the lower GI in DCAT group means a greater dose falloff outside the PTV. This observation is particularly important, especially given the increasing demand for brain re-irradiation. The dose received by healthy tissue must be considered from the initial irradiation. Notably, certain researchers have demonstrated that volumes overlapping with the 12 Gy isodose during the initial SRT and the 18 Gy isodose during subsequent SRT sessions were indicative of RN [11,29]. Moreover, our results are in line with a recent study which showed that GI alone was not synonym of less low and intermediate doses [30].

The dosimetric differences highlighted between the two techniques can also be partially explained using coplanar arcs in majority of VMAT plans. Furthermore, VMAT is characterized by consistently smaller field sizes and increased leaf motion compared to DCAT, resulting in reduced overall delivery accuracy. To address this issue, each VMAT beam is subject to a quality assessment with EPID (Electronic Portal Imaging Device) plan to check that the predicted dose distribution is consistent with the delivered dose distribution.

Finally, VMAT resulted in more monitor units, causing longer treatment times due to blade transmission and intensity modulation. Even if the difference is small and has little impact in terms of the risk of intrafraction movement given the current restraint tools, this criterion can be considered in patient comfort, and must be considered if multiples locations are to be irradiated in the same session without using a unique isocenter.

This study also has some limitations. This is a retrospective study with few patients, even though the studied cohort size was bigger than previous *in silico* dosimetric studies in the literature [24–27]. This was due to the multiple exclusion criteria applied for patient selection, and to the fact that they should have received no other cerebral radiotherapy

Table 6
Total volume receiving ≥ V11.55 Gy and ≥ V23.1 Gy according to the SRT technique (DCAT or VMAT) for PTV ≤ 10 cc and PTV > 10 cc (n = 97).

Variables (mean)	PTV ≤ 10 cc			PTV > 10 cc		
	DCAT n = 46	VMAT n = 11	p-Value	DCAT n = 24	VMAT n = 16	p-Value
Total volume receiving ≥ V11.55 Gy (cc)	15.93 (±8.24) Range: (2.65; 33.85)	20.99 (±11.17) Range: (5.41; 39.36)	0.094	62.74 (±29.9) Range: (32.37; 140.94)	87.84 (±59) Range: (32.5; 277.62)	0.084
Total volume receiving ≥ V23.1 Gy (cc)	6 (±3.18) Range: (0.87; 12.44)	5.73 (±3.17) Range: (1.24; 9.77)	0.796	25.36 (±12.21) Range: (12.5; 59.31)	27.28 (±19.58) Range: (11.57; 91.49)	0.945

before or after SRT. Furthermore, we did not compare both techniques for each patient, therefore, some bias exists due to the difference in PTV and sample size between both techniques.

Moreover, some patients were treated 10 years ago and over the time, practices have evolved in our department. One change concerned the constraint imposed on the treatment TPS regarding the coverage of PTV with 70 % isodose of the prescribed dose (PTV_$V_{70\%}$) is no longer strictly at 100 % since 2017. Indeed, Supplementary Figure S1 shows that after 2017, the PTV_$V_{70\%}$ is more often between 99.6 % and 99.99 %. However, we performed the same dosimetric data analysis only with patients treated after 2017 and results were equivalent (Supplementary Table S2-S4).

Even if we compared dosimetric plans used the prescribed dose and normalized isodose in the periphery of PTV, the calculation algorithms for DCAT (PBC with iPlan® RT Dose) and VMAT (AAA with Eclipse® System) were different.

In conclusion, this retrospective study provides valuable insights by comparing VMAT and DCAT for the treatment of single BMs. Planning calculation differences were observed, with DCAT presenting superior PTV coverage for small volumes and better GI reducing low and intermediate doses, while VMAT presented better CI and therefore fewer high doses. However, our results indicate similar rates of toxicity, local control, and overall survival between both techniques. Further prospective studies with randomized cohorts, notably on the BMs volume and clinical data, are warranted to validate these dosimetric findings and try to correlate with clinical outcomes.

Declaration of competing 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.phro.2024.100591.

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