

# Dosimetric comparison between dual-isocentric dynamic conformal arc therapy and mono-isocentric volumetric-modulated arc therapy for two large brain metastases

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## ABSTRACT

Mono-isocentric volumetric-modulated arc therapy (VMAT) can be used to treat multiple brain metastases. It remains unknown whether mono-isocentric VMAT can improve the dose distribution compared with dual-isocentric dynamic conformal arc therapy (DCAT), especially for two brain metastases. We compared the dose distribution between dual-isocentric DCAT and mono-isocentric VMAT for two large brain metastases, and analyzed the relationship between the distance between the two targets and the difference in dose distribution. A total of 19 patients, each with two large brain metastases, were enrolled. The dose prescribed for each planning target volume (PTV) was 28 Gy in five fractions ( $D_{99.8} = 100\%$ ). We created new indices derived from conformity indices suggested by the Radiation Therapy Oncology Group (RTOG; mRTOG-CI) and Paddick *et al.* (mIP-CI), using the dosimetric parameters of the sum of the two PTVs. The median PTV was  $5.05 \text{ cm}^3$  (range, 2.10–28.47). VMAT significantly improved mRTOG-CI and mIP-CI compared with DCAT. In all cases, VMAT was able to improve mRTOG-CI and mIP-CI compared with DCAT. Whereas the normal brain volume receiving 5 Gy was similar between the two modalities, the normal brain receiving 10, 12, 15, 20, 25 and 28 Gy ( $V_{10}$ – $V_{28}$ ) was significantly smaller in VMAT. The mean beam-on times were 213.3 s and 121.9 s in DCAT and VMAT, respectively ( $P < 0.001$ ). Mono-isocentric VMAT improved the target conformity and reduced the beam-on time and  $V_{10}$ – $V_{28}$  of the normal brain for not only two close metastases but also two distant metastases. Mono-isocentric VMAT seems to be a promising treatment technique for two large brain metastases.

**Keywords:** dynamic conformal arc therapy; volumetric-modulated arc therapy; two brain metastases; dosimetric comparison

## INTRODUCTION

Brain metastases are reported to occur in 20–40% of cancer patients during the course of their illness [1]. Various treatment modalities exist for brain metastases, such as surgical resection, whole-brain radiotherapy (WBRT), stereotactic radiosurgery (SRS), hypofractionated stereotactic radiotherapy (HFSRT), chemotherapy, molecular targeted therapy, and best supportive care. SRS for multiple brain

metastases is a well-established treatment option and includes linear-accelerator (LINAC)-based radiosurgery and gamma knife radiosurgery (GKS) [1, 2]. Whereas GKS can treat more than 10 lesions at the same time, conventional LINAC-based radiosurgery using dynamic conformal arc therapy (DCAT) can usually irradiate only 1–4 brain metastases [3]. Because multiple isocenters must be set for each lesion in patients with multiple brain

metastases in conventional LINAC-based radiosurgery systems using DCAT, the treatment time increases as the number of isocenters increases.

Radiotherapy technology has advanced rapidly in recent years, and it is now possible to utilize mono-isocentric volumetric-modulated arc therapy (VMAT) instead of DCAT for multiple brain metastases. Only one isocenter is required for mono-isocentric VMAT to treat multiple targets, and the treatment time for mono-isocentric VMAT is increasingly shorter than that for DCAT as the number of targets increases. Since it takes a long treatment time to treat more than two brain metastases by DCAT, it appears as though it would be desirable to use mono-isocentric VMAT for more than two brain metastases, in institutions with LINAC. On the other hand, two brain metastases can be treated by either mono-isocentric VMAT or dual-isocentric DCAT within a tolerable treatment time in the clinical setting. Although data on the treatment outcomes and dosimetric parameters for mono-isocentric VMAT for multiple brain metastases have already been reported, few patients with two brain metastases were included in these studies, and it remains unknown whether mono-isocentric VMAT can achieve a better dose distribution compared with dual-isocentric DCAT, especially for two brain metastases [4–11]. For cases with two nearby brain metastases, mono-isocentric VMAT seems to achieve higher target conformity using an inverse planning method compared with dual-isocentric DCAT. On the other hand, for cases with two distant metastases, dual-isocentric DCAT may be more suitable compared with mono-isocentric VMAT because mono-isocentric VMAT generates a low-dose spill, and the irradiated volume of the normal brain increases [8]. Therefore, it is necessary to analyze the relationship between the distance between the two targets and the difference in dose distributions between DCAT and VMAT.

VMAT can also be a good modality for large intracranial tumors. In GKS and conventional LINAC-based radiosurgery systems, the prescribed dose for large brain metastases should be reduced compared with that for small targets in view of the severe late side effects, especially radiation necrosis; as a result, the local control rate is worsened [12, 13]. Using inverse planning methods, VMAT can achieve better target conformity and reduce the dose to the surrounding normal tissue compared with the conventional treatment system. Therefore, VMAT appears to be suitable for large or irregular intracranial lesions [11, 14]. Additionally, HFSRT can also achieve good local control for large brain metastases, and HFSRT with VMAT can be achieved safely using a frameless image-guided system (BrainLAB AG, Feldkirchen, Germany) in a LINAC-based radiotherapy system within a short treatment time [15, 16]. Although it appears that mono-isocentric hypofractionated stereotactic VMAT could be the best treatment option for large brain metastases, most reports regarding mono-isocentric VMAT for multiple brain metastases have addressed only small targets with one fraction [4–10].

In this context, we conducted a planning study to compare the dose distribution between dual-isocentric DCAT and mono-isocentric VMAT for two large brain metastases in the setting of HFSRT.

## MATERIALS AND METHODS

This study followed all the dictates of the Declaration of Helsinki, and our Institutional Ethical Review Board approved the research (Approval number E2276). Written consent was obtained from the patients.

### Patient population

Sixty patients with two metastatic brain tumors were treated with SRS or HFSRT at our institution from January 2008 to July 2016. In our department, planning target volumes (PTVs) that exceed 2.0 cm<sup>3</sup> are treated by HFSRT, not only to improve the local control rate but also to reduce late severe toxicity. Thus, among the patients described above, 19 consecutive patients with two PTVs >2.0 cm<sup>3</sup> were included in this study.

### Contouring

Patients were immobilized in thermoplastic masks, and planning computed tomography (CT) images with a thickness of 1.25 mm were acquired by a Light Speed RT scanner (GE Healthcare, Milwaukee, WI, USA). Contouring and treatment planning were performed using Eclipse version 11.0.47 (Varian Medical Systems, Palo Alto, CA, USA). Contrast-enhanced magnetic resonance imaging (MRI) scans were fused with the planning CT images.

The PTV was defined as the gross tumor volume plus a 1 mm margin to allow for set-up errors, as well as inter- and intrafractional errors. The lenses, eyes, optic nerves, chiasm, brainstem, and normal brain were contoured as organs at risk (OARs). Treatment couch structures were included in the dose calculation.

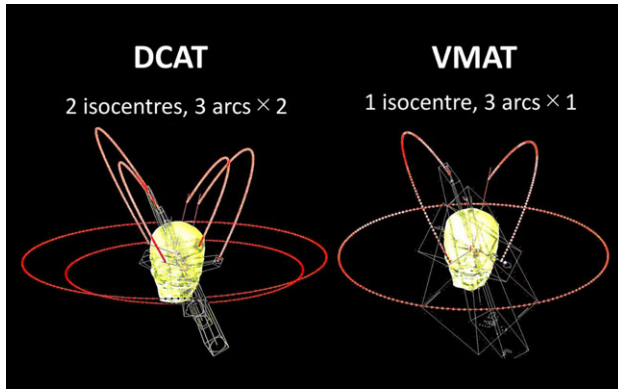
### Treatment planning

Dual-isocentric DCAT and mono-isocentric VMAT plans were created for each of the 19 cases. Flattening filter-free 6 MV photon beams of a Varian TrueBeamSTx LINAC (Varian Medical Systems) were used in all plans. The dose rate was set at 1400 monitor units (MU) per minute. The Acurus XB dose calculation algorithm was employed using a calculation grid size of 1.0 mm. The prescribed dose for each target was set at 28 Gy in 5 fractions. The maximum doses to the brainstem/optic nerve/chiasm and lens were set at less than 20 Gy and 10 Gy in 5 fractions, respectively.

### Dual-isocentric DCAT plans

Two isocenters were set at the centres of each PTV, and two plans were created for each target. The DCAT plan consisted of one coplanar and two non-coplanar arcs to each target (total, six arcs). For each target, one coplanar arc rotated from 181° to 179° with a collimator angle of 0°, and two non-coplanar arcs were placed at couch angles of 60° and 300°. One non-coplanar arc rotated from 20° to 160°, whereas the other non-coplanar arc rotated from 200° to 340° with a collimator angle of 0° (Fig. 1).

We modified the leaf margin, which was the distance from the PTV to the field's edge, to ensure that  $D_{99.8} = 100\%$  (i.e. 99.8% of each PTV was covered by 100% of the prescribed dose) in the sum of the two plans. The maximum dose ( $D_{max}$ ) for each target was set



**Fig. 1.** Arc arrangements of dual-isocentric dynamic conformal arc therapy (DCAT) and mono-isocentric volumetric-modulated arc therapy (VMAT).

within  $40 \pm 1$  Gy, meaning that each PTV was covered by almost 70% of the  $D_{\max}$ . The same leaf margin was applied in all directions to each PTV, while the value was manually modified to ensure that the  $D_{\max}$  was set within  $40 \pm 1$  Gy for each PTV.

#### Mono-isocentric VMAT plans

VMAT plans were created by one coplanar and two non-coplanar arcs with one isocenter (total, three arcs) using the RapidArc system (Varian Medical Systems). The isocenter was set at the centre of the two PTVs. One coplanar arc was rotated from  $181^\circ$  to  $179^\circ$  with a collimator angle of  $45^\circ$ . The gantry's rotation, the angle of the couch, and the angle of the collimator of the two non-coplanar arcs were the same as those used in the DCAT plans. The jaw tracking system (Varian Medical Systems) was employed in all plans.

Optimization was performed to satisfy the following criteria: two PTVs were covered by  $\geq 99.8\%$  of the prescribed dose (thus,  $D_{99.8} \geq 100\%$ ), the  $D_{\max}$  for each target was set within  $40 \pm 1$  Gy, and the doses to the normal brain and OARs were reduced as far as possible.

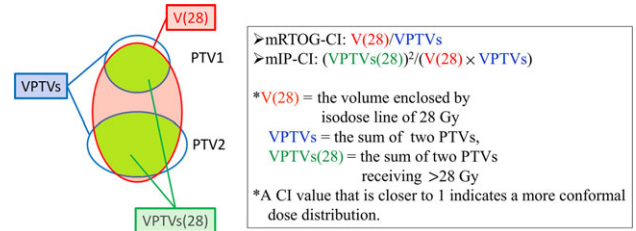
#### Evaluation of treatment plans

We evaluated the target conformity, beam-on time, MU, irradiated volume of the normal brain, and mean dose to the normal brain. We also evaluated the  $D_{2\%}$  to the OARs except for the normal brain, where  $D_{2\%}$  was the dose to 2% of the volume of the OARs.

The beam-on time was calculated by taking into account the dose rate, gantry rotation, and gantry speed.

With regard to the irradiated volume of the normal brain, we evaluated  $V_5$ ,  $V_{10}$ ,  $V_{12}$ ,  $V_{15}$ ,  $V_{20}$ ,  $V_{25}$  and  $V_{28}$ , where  $V_x$  refers to the volume of the normal brain irradiated by more than  $x$  Gy.

The conformity indices defined by the Radiation Therapy Oncology Group (RTOG-CI) and Paddick *et al.* (IP-CI) are usually used to evaluate the conformity for intracranial tumors [17, 18]. However, in cases with particularly large and close lesions, RTOG-CI and IP-CI cannot be calculated because the isodose line of the prescribed dose can be merged and cannot be separated for each target. Thus, we created new indices derived from RTOG-CI and



**Fig. 2.** The concept of the modified RTOG-CI (mRTOG-CI) and modified IP-CI (mIP-CI).

IP-CI using the dosimetric parameters of the sum of the two PTVs to evaluate the target conformity. One index was a modified version of RTOG-CI (mRTOG-CI), defined as  $V(28)/VPTVs$ , where  $V(28)$  was the volume enclosed by an isodose line of 28 Gy, and  $VPTVs$  was the sum of the two PTVs. The other was a modified IP-CI (mIP-CI), defined as  $([VPTVs(28)]^2) / [V(28) \times VPTVs]$ , where  $VPTVs(28)$  was the sum of two PTVs receiving more than 28 Gy (Fig 2).

We calculated the distance between the two targets, the difference in mRTOG-CI/mIP-CI between DCAT and VMAT ( $\Delta$ mRTOG-CI/ $\Delta$ mIP-CI), and the improvement ratio of VMAT to DCAT in mRTOG-CI/mIP-CI (r-mRTOG-CI/r-mIP-CI). The differences in  $V_5/V_{10}/V_{12}/V_{15}/V_{20}/V_{25}/V_{28}$  ( $\Delta V_5-V_{28}$ ) between DCAT and VMAT were also calculated.  $\Delta$ mRTOG-CI/ $\Delta$ mIP-CI/ $\Delta V_5-V_{28}$  refers to the difference between the value of VMAT minus the value of DCAT in mRTOG-CI/mIP-CI/ $V_5-V_{28}$ , respectively. r-mRTOG-CI/r-mIP-CI was defined as follows: r-mRTOG-CI =  $\{ |(mRTOG-CI \text{ in VMAT}) - 1| - |(mRTOG-CI \text{ in DCAT}) - 1| \} / \{ |(mRTOG-CI \text{ in DCAT}) - 1| \}$ , and r-mIP-CI =  $\{ |(mIP-CI \text{ in VMAT}) - 1| - |(mIP-CI \text{ in DCAT}) - 1| \} / \{ |(mIP-CI \text{ in DCAT}) - 1| \}$  (Fig. 3).

The distance between the two targets was defined as the distance between each centroid position of the two PTVs.

#### Statistical analysis

All statistical analyses were performed with the aid of EZR, which is a graphical user interface for R (the R Foundation for Statistical Computing, Vienna, Austria, version 3.2.2) [19]. More precisely, EZR is a modified version of R commander version 1.32, facilitating biostatistical evaluations.

Data from the DCAT and VMAT plans were compared with the Shapiro-Wilk test, the Wilcoxon signed-rank test, and a paired  $t$  test. The following relationships were analysed using Spearman's rank correlation coefficient: the difference between dosimetric parameters and the distance between the two targets, the difference between dosimetric parameters and VPTVs, the distance between the two targets and r-mRTOG-CI/r-mIP-CI, and the difference between the VPTVs and r-mRTOG-CI/r-mIP-CI. A  $P$ -value of  $<0.05$  was considered to indicate statistical significance.

#### RESULTS

The median PTV was  $5.05 \text{ cm}^3$  (range,  $2.10\text{--}28.47 \text{ cm}^3$ ). The mean mRTOG-CI/mIP-CIs were  $1.32/0.75$  and  $1.17/0.85$  in DCAT and

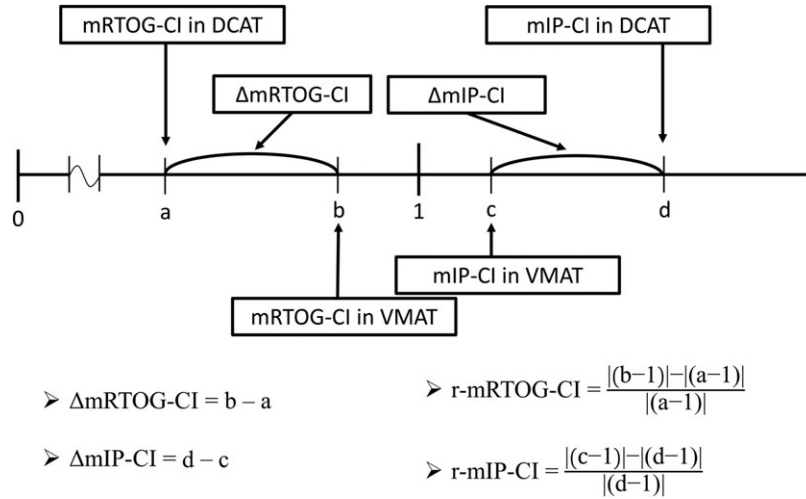


Fig. 3. The calculation of r-mRTOG-CI and r-mIP-CI.

Table 1. Indices of target conformity, monitor units and beam-on time

Index	DCAT	VMAT (Mean $\pm$ SD)	P-value
mRTOG-CI	1.32 $\pm$ 0.07	1.17 $\pm$ 0.06	<0.001
mIP-CI	0.75 $\pm$ 0.04	0.85 $\pm$ 0.04	<0.001
MU	2376 $\pm$ 313	2584 $\pm$ 355	0.071
Beam-on time (s)	213.6 $\pm$ 1.4	116.3 $\pm$ 11.6	<0.001

DCAT = dynamic conformal arc therapy, VMAT = volumetric-modulated arc therapy, SD = standard deviation, mRTOG-CI = modified conformity index (CI) derived from the CI defined by the Radiation Therapy Oncology Group (RTOG) [17], mIP-CI = modified CI derived from the CI defined by Paddick *et al.* [18], MU = monitor units.

VMAT, respectively. Because both mRTOG-CI and mIP-CI of VMAT were closer to 1, indicating more conformal dose distribution, VMAT significantly improved the target conformity compared with DCAT (Table 1). In all cases, including not only the cases with two close metastases but also the cases with two distant metastases, VMAT was able to improve mRTOG-CI and mIP-CI compared with DCAT. The mean MUs were similar between the two groups. The mean beam-on times were 213.3 and 121.9 s in DCAT and VMAT, respectively ( $P < 0.001$ ).

Although there was no significant difference between the two groups for the normal brain V5 and the mean dose to the normal brain, the mean of V10–V28 was significantly reduced in VMAT (Table 2).

The Spearman's rank correlation coefficients of the relationships between  $\Delta mRTOG-CI/\Delta mIP-CI/\Delta V_{5-28}$ ,  $r-mRTOG-CI/r-mIP-CI$ , VPTVs and the distance between the two targets are shown in Table 3. There was a weak correlation, in which absolute Spearman's coefficients were from 0.2 to 0.4, between the distance and  $r-mRTOG-CI/r-mIP-CI/\Delta V_{10-28}$ . Moderate or high correlations, in which absolute Spearman's coefficients were from 0.4 to 1, were

found between the VPTVs and  $\Delta mIP-CI/r-mRTOG-CI/r-mIP-CI/\Delta V_{10-28}$ .

Scatter plots of  $r-mRTOG-CI/r-mIP-CI$ , the distance between the two targets, and VPTVs are shown in Fig. 4. There were weak correlations between the distance and  $r-mRTOG-CI/r-mIP-CI$ , and moderate or high correlations were seen between the VPTVs and  $\Delta mIP-CI/r-mRTOG-CI$  (Fig. 4). The sagittal plane of the dose distribution for a representative case is shown in Fig. 5.

The mean D2% of the brainstem, chiasm, right optic nerve, left optic nerve, and right lens were similar between the two techniques. The mean D2% of the right eye, left eye and left lens were 1.4/1.7, 1.0/1.8 and 0.7/1.2 Gy in DCAT/VMAT, respectively. Although the mean D2% of the right eye, left eye and left lens in VMAT were statistically significantly higher compared with DCAT, the absolute values of those structures were far below the tolerance dose of each structure in both of the groups.

## DISCUSSION

We conducted a planning study to compare the dose distribution between dual-isocentric DCAT and mono-isocentric VMAT for two large brain metastases. VMAT was able to achieve significantly better conformity within a shorter treatment time compared with DCAT, and the normal brain  $V_{10-28}$  was significantly reduced in VMAT. VMAT improved the target conformity and reduced the dose to the normal brain not only for two close metastases but also for two distant metastases. VMAT could, therefore, be a promising treatment modality for two large brain metastases.

Mono-isocentric VMAT has recently been used for patients with multiple brain metastases [5, 6, 9]. Multiple metastases can be treated with mono-isocentric VMAT using advanced radiotherapy techniques, including fine multileaf collimators, jaw tracking systems, and sophisticated optimization methods. Whereas the dosimetric comparison showed the superiority of VMAT compared with DCAT regarding target conformity and the irradiated normal brain volume for multiple brain metastases, there were very few cases, and the volume and number of target lesions varied in these studies [10, 11].

**Table 2. Irradiated volume of the normal brain and mean dose to the normal brain**

Volume (cm <sup>3</sup> )	DCAT	VMAT (Mean ± SD)	P-value
V <sub>5</sub>	180.80 ± 101.32	163.18 ± 99.18	0.096
V <sub>10</sub>	51.91 ± 31.88	44.13 ± 26.74	<0.001
V <sub>12</sub>	37.56 ± 23.25	30.94 ± 18.36	<0.001
V <sub>15</sub>	24.85 ± 15.48	19.96 ± 11.92	<0.001
V <sub>20</sub>	13.52 ± 8.79	10.08 ± 5.85	<0.001
V <sub>25</sub>	7.14 ± 5.19	4.33 ± 2.24	<0.001
V <sub>28</sub>	4.19 ± 3.31	1.79 ± 0.93	<0.001
Mean dose (Gy)	2.60 ± 0.90	2.53 ± 0.76	0.872

DCAT = dynamic conformal arc therapy, VMAT = volumetric-modulated arc therapy, SD = standard deviation, V<sub>x</sub> = the volume of the normal brain receiving x Gy.

**Table 3. Indices of Spearman's rank correlation coefficients**

	Distance between two targets	VPTVs
ΔmRTOG-CI	-0.056	-0.249
ΔmIP-CI	-0.135	0.475
r-mRTOG-CI	-0.333	0.409
r-mIP-CI	-0.374	0.470
ΔV <sub>5</sub>	-0.121	-0.181
ΔV <sub>10</sub>	0.381	-0.672
ΔV <sub>12</sub>	0.344	-0.730
ΔV <sub>15</sub>	0.314	-0.716
ΔV <sub>20</sub>	0.268	-0.760
ΔV <sub>25</sub>	0.249	-0.805
ΔV <sub>28</sub>	0.298	-0.837

DCAT = dynamic conformal arc therapy, VMAT = volumetric-modulated arc therapy, mRTOG-CI = modified conformity index (CI) derived from the CI defined by the Radiation Therapy Oncology Group (RTOG) [17], mIP-CI = modified CI derived from the CI defined by Paddick *et al.* [18], VPTVs = the sum of the two planning target volumes, V<sub>x</sub> = the volume of the normal brain receiving x Gy, Δ = the value of VMAT minus the value of DCAT. r-mRTOG-CI/r-mIP-CI was defined as follows:  

$$r\text{-mRTOG-CI} = \frac{|(m\text{RTOG-CI in VMAT}) - 1| - |(m\text{RTOG-CI in DCAT}) - 1|}{|m\text{RTOG-CI in DCAT}) - 1|}$$

To our knowledge, this is the first study to report a better dose distribution in mono-isocentric VMAT compared with dual-isocentric DCAT, particularly for two large brain metastases.

The beam-on time of VMAT was significantly shorter than that of DCAT even for two PTVs, and it was almost half that of DCAT

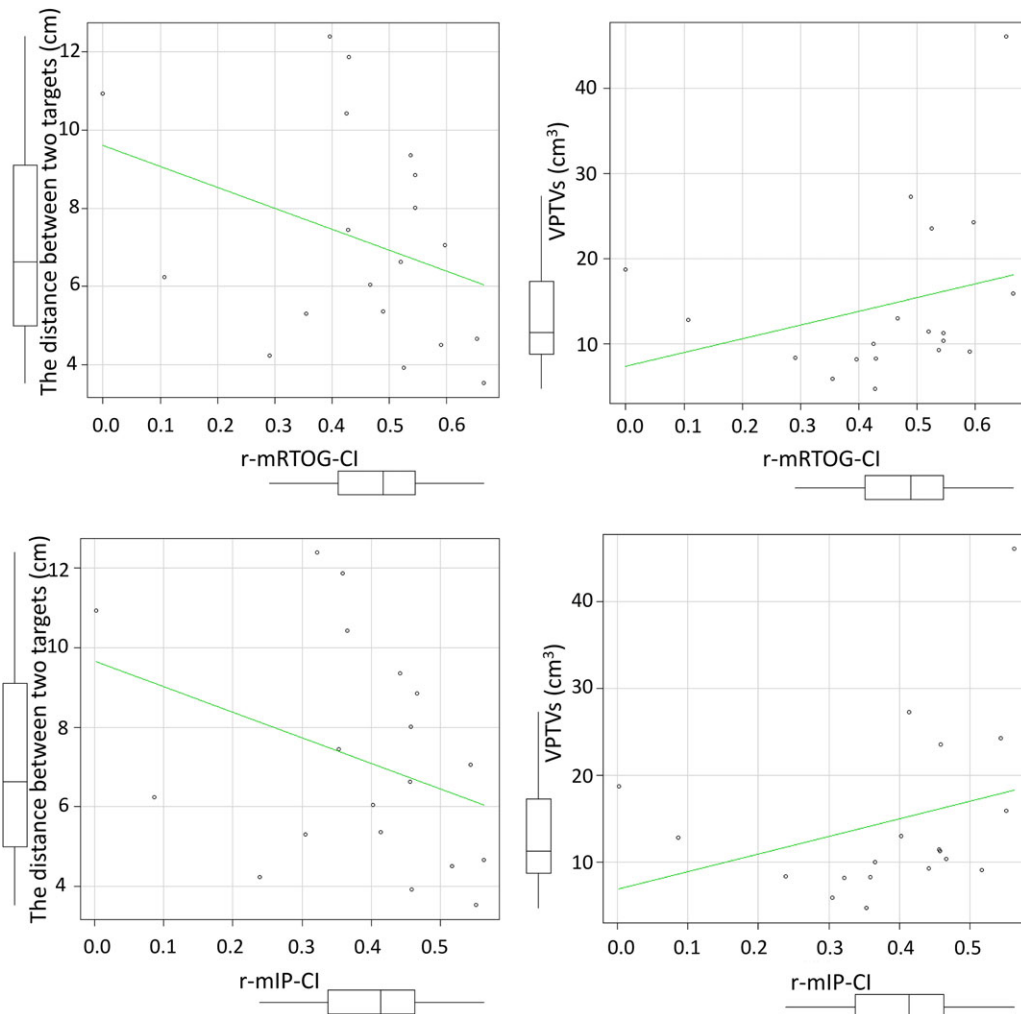
in our study. In the present study, only the beam-on time was evaluated for the treatment time. Mono-isocentric VMAT will additionally shorten the treatment time compared with dual-isocentric DCAT for the following two reasons. First, mono-isocentric VMAT could reduce the total number of arcs compared with dual-isocentric DCAT. A reduced number of arcs enables shortening of the treatment time needed to rotate the couch and the gantry for each arc. Second, there is no need to move the isocenters one after another in mono-isocentric VMAT. The time for moving one isocenter and the need for geometric verification at the other isocenter can be omitted in mono-isocentric VMAT. Reduced treatment time could make the intrafractional error small, improve patients' throughput, and relieve patients' distress. Even if patients have only two intracranial lesions, mono-isocentric VMAT could be the appropriate modality.

The VMAT technique is also useful for large brain metastases. When large brain metastases are treated by SRS with one fraction, the prescribed dose should be reduced for large brain metastases in consideration of the risk of brain necrosis, and the local control rate becomes unsatisfactory as a result [12, 13]. Some of the challenges of large brain tumors involve improving local control as well as reducing toxicity, which includes the use of multisession GKS, LINAC-based HFSRT and LINAC-based HFSRT with VMAT [14, 15, 20, 21]. Our results showed a moderate-to-high correlation among the VPTVs, ΔmIP-CI, r-mRTOG-CI, r-mIP-CI and ΔV<sub>10</sub>-V<sub>28</sub>, which means that VMAT improved the dose distribution as the PTV increased. Although there is no clear evidence regarding the most appropriate modality for large brain metastases, HFSRT with mono-isocentric VMAT could be a good modality for two large brain metastases.

Mono-isocentric VMAT could reduce the dose to the normal brain and may reduce the risk of radiation-induced brain necrosis. V<sub>10</sub>-V<sub>28</sub> was significantly lower in VMAT in the present study. As some patients need to receive intracranial re-irradiation due to intracranial recurrence, it seems sensible to set the dose to the normal brain as low as possible.

To evaluate the conformity index for multiple lesions that are located close to one another, we created new conformity indices derived from RTOG-CI and IP-CI. Our data showed that V<sub>28</sub> was reduced in VMAT, and mRTOG-CI and mIP-CI were also improved in VMAT. The results may support the view that the modified indices are useful for evaluating target conformity for two lesions. However, there are still no adequate indices for multiple intracranial targets, and further discussion regarding suitable conformity indices is needed.

Whereas VMAT seems to improve conformity with the inverse planning method, particularly for patients with two close lesions, our study showed only a weak correlation between the distance and r-mRTOG-CI/r-mIP-CI, and no apparent correlation between the distance and ΔmRTOG-CI/ΔmIP-CI. This means that VMAT can improve target conformity for patients with not only two close metastases but also two distant metastases. Although VMAT generates a low-dose spill, there was no apparent correlation between the distance and ΔV<sub>5</sub> [8]. This may be due to the fact that setting the dose to the normal brain as low as possible and the use of a jaw tracking system may succeed in reducing the low-dose spill despite the distance between the two targets.

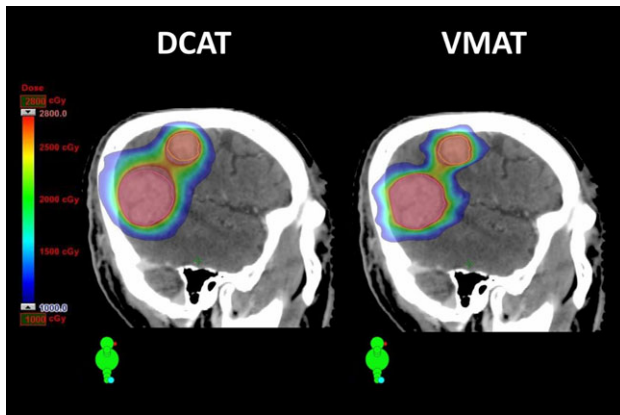


**Fig. 4.** Scatter plots of the improvement ratio of modified RTOG-CI (mRTOG-CI) and modified IP-CI (mIP-CI), the distance between the two targets, and the sum of the two planning target volumes (VPTVs). The improvement ratios of VMAT to DCAT in mRTOG-C/mIP-CI are r-mRTOG-CI/r-mIP-CI, respectively. mRTOG-CI = modified conformity index (CI) derived from the CI defined by the Radiation Therapy Oncology Group (RTOG), mIP-CI = modified CI derived from the CI defined by Paddick *et al.*

The mean D2% of the right eye, left eye and left lens were statistically significantly higher in VMAT compared with DCAT. However, the absolute values of those structures were far below the tolerance dose of each structure in both groups. Therefore, the differences in the mean D2% of the right eye, left eye and left lens between the two groups were considered to be clinically non-significant. Mono-isocentric VMAT could be the better modality compared with DCAT, even taking the doses to the OARs into account, because mono-isocentric VMAT significantly improved target conformity and shortened treatment time.

There are several limitations to our study. First, this planning study compared dose distributions only between dual-isocentric DCAT and mono-isocentric VMAT, and it is unclear whether the higher conformity and lower dose to the normal brain of mono-isocentric VMAT could reduce the toxicity in a clinical setting.

Second, this planning study did not compare the dose distribution between mono-isocentric VMAT and GKS. Some reports showed that GKS was superior to mono-isocentric VMAT with regard to low-dose radiation spillage to the normal brain, whereas another report suggested that the low-dose spillage to the normal brain, conformity, and dose fall-off between the two modalities were similar [4, 7, 8]. Further dosimetric assessments (stratified by the number of tumors, tumor volume, and treatment devices) between mono-isocentric VMAT and other modalities seem to be necessary. Finally, mono-isocentric VMAT must be performed using non-coplanar multiple arcs to achieve high conformity. To deliver non-coplanar beams, radiotherapists must enter the treatment room to rotate the couch. Rotating the couch can increase the total treatment time and further increase the risk of inducing nausea and motion in the patient. As Dynamic WaveArc therapy (DWA)



**Fig. 5.** A sagittal plane showing the dose distribution in a representative case.

realized by the Vero4DRT (Mitsubishi Heavy Industries, Tokyo, Japan; BrainLAB, Feldkirchen, Germany) can irradiate volumetric-modulated sequential non-coplanar arc beams without rotating the couch [22], DWA can omit the time needed to rotate the couch and thus relieve distress in patients receiving mono-isocentric VMAT for multiple brain metastases. DWA might be a good candidate for multiple brain metastases.

In conclusion, we conducted a planning study to compare the dose distribution between dual-isocentric DCAT and mono-isocentric VMAT for two large brain metastases. VMAT improved the target conformity and reduced the beam-on time and  $V_{10}$ - $V_{28}$  of the normal brain for not only two close metastases but also two distant metastases. As the PTV increased, VMAT improved the dose distribution. Mono-isocentric VMAT could be the best modality in patients with two large brain metastases.

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Results from this study were presented at the 76th Annual Meeting of the Japan Radiological Society.

#### CONFLICT OF INTEREST

The authors state that there are no conflicts of interest. The funding source had no role in the study design; collection, analysis and interpretation of data; writing of the report, or decision to submit the article for publication.

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