Stereotactic radiotherapy of intracranial tumors : optimizing treatment and improving outcome

Wiggenraad, Rudolf Gerard Jan

CHAPTER 2

Optimizing Treatment

2a: STEREOTACTIC RADIOTHERAPYOF INTRACRANIALTUMORS: ACOMPARISON OF INTENSITY-MODULATED RADIOTHERAPY AND DYNAMIC CONFORMAL ARC

RUUD WIGGENRAAD, ANNA PETOUKHOVA, LIA VERSLUIS AND JAN VAN SANTVOORT

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ABSTRACT

Purpose: Intensity-modulated radiotherapy (IMRT) and dynamic conformal arc (DCA) are two state-of-the-art techniques for linac-based stereotactic radiotherapy (SRT) using the micromultileaf collimator. The purpose of this planning study is to examine the relative merits of these techniques in the treatment of intracranial tumors.

Materials and Methods: SRT treatment plans were made for 25 patients with a glioma or meningioma. For all patients, we made an IMRT and a DCA plan. Plans were evaluated using: target coverage, conformity index (CI), homogeneity index (HI), doses in critical structures, number of monitor units needed, and equivalent uniform dose (EUD) in planning target volume (PTV) and critical structures.

Results: In the overall comparison of both techniques, we found adequate target coverage in all cases; a better mean CI with IMRT in concave tumors ($p = 0.027$); a better mean HI with DCA in meningiomas, complex tumors, and small (< 92 mL) tumors ($p = 0.000$, $p = 0.005$, and $p = 0.005$, respectively); and a higher EUD in the PTV with DCA in convex tumors (gliomas) and large tumors ($p = 0.000$ and $p = 0.003$, respectively). In all patients, significantly more monitor units were needed with IMRT. The results of the overall comparison did not enable us to pre¬dict the preference for one of the techniques in individual patients. The DCA plan was acceptable in 23 patients and the IMRT plan in 19 patients. DCA was preferred in 18 of 25 patients.

Conclusions: DCA is our preferred SRT technique for most intracranial tumors. Tumor type, size, or shape do not predict a preference for DCA or IMRT.

INTRODUCTION

For more than a decade, stereotactic radiotherapy (SRT) has been standard treatment for several intracranial targets. The very high conformality makes it an attractive treatment option, specifically for solitary metastases, benign tumors, targets close to critical structures, and for reirradiation. Fractionated treatments have become a possibility with the development of linac-based SRT and relocatable head frames. At present, several treatment techniques are available in linacbased SRT, but in an individual case the best choice for one or other of these techniques is not always obvious, in spite of several planning studies that have been published [1–6].

Dynamic conformal arc (DCA) and intensity-modulated radiotherapy (IMRT) techniques have become available in SRT with the introduction of the micromultileaf collimator. Two comparative planning studies conclude that DCA is to be preferred for small lesions up to 2 cm^3 [2, 3]. Few studies, however, have addressed the relative merits of both techniques in the treatment of more complex intracranial tumors. For larger and irregularly shaped lesions, adequate treatment plans can be made using IMRT, but the place of DCA in these situations needs further clarification. Moreover, these techniques differ in required workload for quality assurance and the generation of treatment plans (forward planning for DCA and inverse planning for IMRT).

This planning study compares DCA and IMRT in intracranial targets. The purpose of this study is to determine if one of these techniques qualifies as best choice, given the anatomical characteristics of a tumor.

MATERIALS AND METHODS

PATIENTS AND PRESCRIBED TREATMENT

Twenty-five patients with intracranial tumors were selected for this study. We selected patients with targets with different sites, sizes, and shapes to be able to study the relative merits of IMRT and DCA in these different situations. As we wanted to focus on larger targets, we selected patients with a glioma or meningioma and a planning target volume (PTV) larger than 6 cm^3.

Table 1 shows the characteristics of the patients, the tumors, and the prescribed treatments. To be able to study the effect of the PTV shape on the criteria for plan intercomparison, we classified the target shapes into three categories: convex, concave, and complex. All gliomas had a regular convex shape and all but one convexity meningiomas were concave. The base of skull meningiomas were all irregularly shaped, mostly because of extensions in the cavernous sinus and through foramina. This was also the case for a very complex frontal convexity meningioma that extended into the skull base. The shapes of these targets were classified as complex.

To be able to study the effect of the PTV volume, we also classified the targets into two categories based on size: smaller and larger than the median volume of 92 mL.

TREATMENT PLANNING

Each patient was scanned by computed tomography while fixed in the stereotactic head frame (BrainLAB AG, Feldkirchen, Germany). Scans were made with 2-mm slice thickness. A standard upper jaw support provided by Brainlab was used for patients without dentition and for most dentate patients, and a customized vacuum mouth piece was used for some dentate patients [7]. All patients also had an MRI scan (voxel size 1.1 x 1.1 x 1.3 mm^3; T1-weighted with intravenous gadolinium and T2-weighted) of the brain. Coregistration of computed tomography and MRI was done on i-Plan RT Image version 3.0 (BrainLAB).

All contouring was done on i-Plan RT Image version 3.0. The gross tumor volume (GTV)

and the relevant critical structures were contoured on contrast-enhanced MRI scans (T1-weighted MRI with intravenous gadolinium and T2-weighted MRI). In glioma patients, the clinical target volume (CTV) was formed by expanding the GTV with 15 mm, except in regions where natural boundaries precluded microscopic tumor spread. In meningioma patients, we did not use any GTV to CTV margin, assuming no microscopic spread beyond the visible tumor. The positioning accuracy of the mask system together with the use of the Exactrac system allows the use of a 2-mm margin between CTV and PTV [7]. For patients in whom the CTV was in close contact with critical structures, the CTV-PTV margin was adapted manually to avoid overlapping of the PTV and these critical structures. Additionally, we contoured the total brain minus the PTV.

Patient nr	Gender	Age	Diagnosis	Site	PTV (cc)	Shape of target	Prescribed dose	Prescription isodose	Critical structures
1	M	46	Glioma (recurrence)	Convexity	29	convex	4 x 8Gy	100%	No
2	M	45	Glioma (recurrence)	Convexity	55	convex	30 x 1.8Gy	100%	No
3	M	57	Glioma (recurrence)	Convexity	102	convex	30 x 1.8Gy	100%	No
4	M	52	Glioma	Convexity	121	convex	30 x 2Gy	100%	No
5	M	61	Glioma	Convexity	146	convex	30 x 2Gy	100%	No
6	F	68	Glioma	Convexity	147	convex	30 x 2Gy	100%	No
7	M	67	Glioma	Convexity	148	convex	30 x 2Gy	100%	No
8	F	55	Glioma	Convexity	152	convex	30 x 2Gy	100%	No
9	M	62	Glioma	Convexity	235	convex	30 x 2Gy	100%	No
10	F	37	Glioma	Convexity	276	convex	30 x 1.8Gy	100%	No
11	M	62	Glioma	Convexity	304	convex	30 x 2Gy	100%	No
12	M	41	Glioma	Brainstem	85	convex	28 x 2Gy	100%	No
13	F	23	Glioma	Brainstem	97	convex	30 x 2Gy	100%	No
14	F	40	Glioma	Brainstem	146	convex	30 x 1.8Gy	100%	No
15	F	60	Meningioma	Skull base	6	complex	28 x 1.8Gy	80%	Optic nerve, Chiasm
16	M	76	Meningioma	Skull base	8	complex	5 x 5Gy	80%	Optic nerve, Chiasm
17	F	42	Meningioma	Skull base	15	complex	28 x 1.8Gy	80%	Optic nerve, Chiasm Brainstem
18	F	72	Meningioma	Skull base	15	complex	28 x 1.8Gy	80%	Optic nerve Chiasm
19	F	57	Meningioma	Skull base	21	complex	28 x 1.8Gy	80%	Optic nerve, Chiasm
20	F	38	Meningioma	Convexity	48	concave	28 x 1.8Gy	80%	No
21	F	36	Meningioma (atypical)	Convexity	66	concave	30 x 1.8Gy	80%	No
22	M	74	Meningioma (atypical)	Convexity	81	concave	30 x 1.8Gy	80%	No
23	F	68	Meningioma	Skull base	87	complex	28 x 1.8Gy	80%	Optic nerve, Chiasm
24	F	62	Meningioma (atypical)	Convexity	92	complex	30 x 1.8Gy	80%	Optic nerve, Chiasm
25	F	37	Meningioma	Skull base	142	complex	28 x 1.8Gy	80%	Optic nerve, Chiasm Brainstem

Table 1. Characteristics of the patients, the tumours and the prescribed treatments.

All treatment plans were made on Brainscan 5.31 (BrainLAB). For every patient, two plans were made for comparison: an inversely planned IMRT plan and a forwardly planned DCA

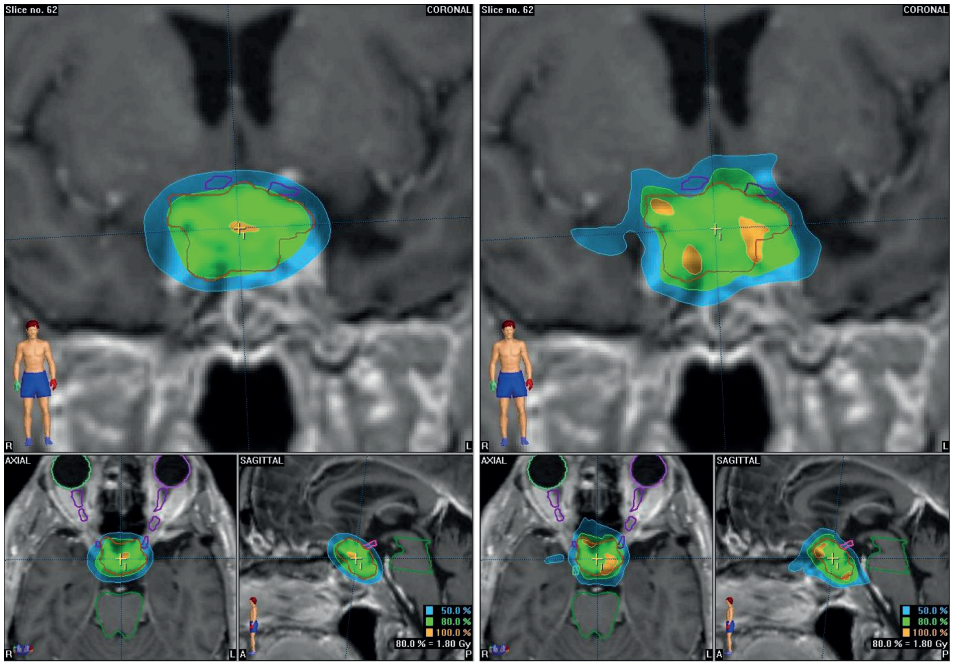

Figure 1. Example of the dose distribution of a patient with a small skull base tumor (Patient 15) with dynamic conformalarc (left) and intensity-modulated radiotherapy (right).

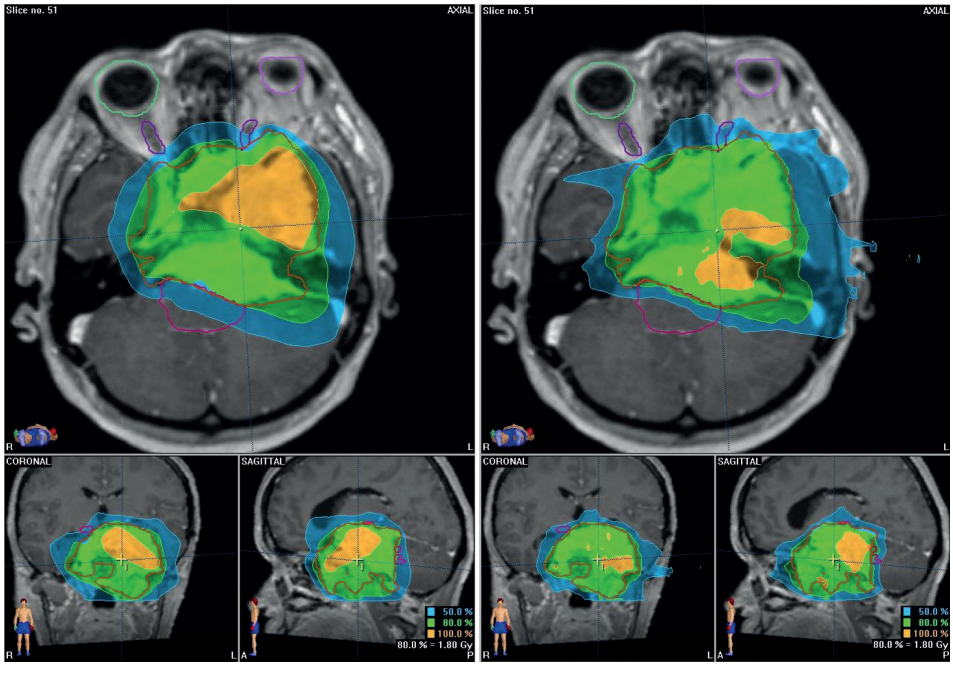

Figure 2. Example of the dose distribution of a patient with a large skull base tumor (Patient 25) with dynamic conformalarc (left) and intensity-modulated radiotherapy (right).

plan (Fig. 1, 2). Calculations of dose–volume histograms were done with a grid size of 2 mm. For small objects, an adaptive grid size was used.
In DCA planning, the critical organs were avoided as much as possible by selecting the optimal table positions, arc angles, and leave positions using the beam's-eye view. In IMRT planning, we did not use a standard set of dose–volume constraints for every patient. In our experience, adaptation of the dose–volume constraints on an individual basis enabled better avoidance of critical organs. Moreover, Brainscan always produces four differentIMRT plans, each with a different balance between the importance given to PTVcoverage and organ-atrisk sparing. For IMRT, manually optimized beam directions were used. The optimal number and orientation of the beams were determined by comparing IMRT plans with varying beam configurations. In all patients, four to six noncoplanar beams yielded a result that was optimal, combined with a realistic treatment time.
Some of the patients were treated with DCA when IMRT was not yet used in clinical practice. For them, IMRT plans were made for this study after they had been treated. For most patients, both DCA and IMRT were available and they were treated according to the plan that was considered preferable.

PLAN COMPARISON

Criteria. Treatment plan intercomparisons were performed using the following criteria: target coverage, conformity index, homogeneity index, and dose in critical organs. To gain more insight into the effect of inhomogeneous dose distributions, the equivalent uniform dose (EUD) in the PTV and critical organs were derived from the dose–volume histogram [8]. Furthermore, the number of monitor units necessary for each plan was recorded.

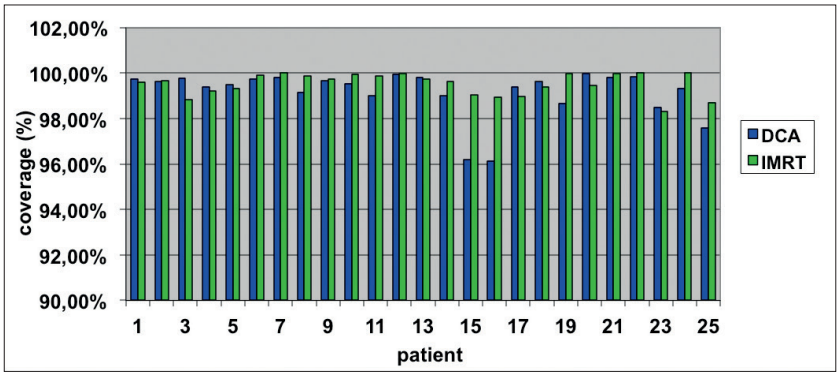

Figure 3. The target coverage of both the dynamic conformal arc and the intensity-modulated radiotherapy plans.

In all plans, 100% of the dose was in the isocenter. Target coverage was defined as the percentage of the PTV covered by the 80% isodose in meningiomas and the 95% isodose in gliomas. The planning goal always was 100% target coverage; a coverage of less than 95% was not accepted.
The conformity index (CI) was defined as in Brainscan as:

$$CI = 1 + V_n/V_t$$

where V_n is the volume of normal tissue receiving the prescribed dose and V_t is the volume of the target receiving the prescribed dose (or 95% of the prescribed dose in gliomas). The ideal CI is 1, a CI higher than 1.5 was considered insufficient, and a CI higher than 2 was

not accepted. As Vn, we used in this formula the volume of total brain minus PTV.
The homogeneity index (HI) was defined for stereotactic radiotherapy as:

$$HI = D_{max}/D_{prescribed}$$

where D_{max} and $D_{prescribed}$ are the maximum and the prescribed dose, respectively. The ideal HI depends on the prescription isodose. When the dose is prescribed to the 80% isodose, the ideal HI is 1.25. Following the principles of stereotactic radiotherapy, the HI should preferably be below 2; between 2 and 2.5 would be acceptable [9].
Analogous with this, for the glioma plans that are prescribed to 100% and for which the 95% isodose should encompass the PTV, we define the HI as:

$$HI = D_{max}/D_{95\%}$$

Dose prescription in gliomas was done using the International Commission on Radiation Units and Measurements (ICRU) criteria, because the CTV usually contains normal brain tissue where hotspots should be avoided. However, we accepted small hotspots (within 7% of the PTV) between 107% and 110%, with a corresponding HI value up to 1.16 [10].
Only patients with meningiomas (who had the dose specified to the 80% isodose) had critical structures close to the target. Only the optic nerve closest to the PTV was considered. The other optic nerve either received a lower dose, or was not classified as a critical structure (in one patient who almost lost the vision of the left eye because of tumor encasement of the left optic nerve).
As clinical dose constraints, we defined
• for the brainstem: 60 Gy maximum point dose and 56 Gy in not more than 2% of the volume.
• for the optic nerves and the optic chiasm: 56 Gy maximum point dose and 50 Gy in not more than 2% of the volume (or 25 Gy maximum point dose in the patient who received 5 x 5 Gy).

However, the planning goal was always the lowest achievable dose in the critical organs.
The EUD was calculated using the equation:

$$EUD = (1/N \sum_i D_i^a)^{1/a}$$

where N is the number of voxels in the anatomic structure of interest, D_i is the ith voxel, and a is the tumor or normal tissue-specific parameter describing the dose–volume effect [11].
We used in the equation as parameter a: –8 for PTV, 4.6 for brainstem, and 7.4 for optic nerve and chiasm [8].
The EUD in the PTV and organs at risk were calculated. In a comparison of different plans, the preferable plan is the one with the highest EUD for the PTV or the lowest EUD for normal tissue and critical structures.

OVERALL COMPARISON OF THE TECHNIQUES

The merits of both techniques were compared for the entire patient cohort. For this comparison, all mentioned criteria were used. The dose in the critical organs was only considered if it was unacceptably high. Furthermore, we compared the techniques according to the diagnosis (glioma or meningioma) and the size and shape of the target.

INDIVIDUAL COMPARISON OF THE TECHNIQUES

We also compared DCA with IMRT for each patient and classified the plans as acceptable or unacceptable, based on the previously mentioned criteria. All plans had been visually inspected and were judged as optimal for the applied technique. If both plans were acceptable, one

of the techniques could be preferable in case of a clear difference with respect to one or more of the criteria. Our preference for one of the two plans was mostly based on the assessment of the CI, HI, and dose in the critical structures. A difference of the CI or the HI of more than 5% (of the mean value for DCA and IMRT) resulted in a preference for the technique with the best index, unless there was a difference in the dose in the critical structures that was considered clinically relevant. Our preference was based much less on visual inspection, which we did not find very useful for comparison of optimal plans, or target coverage. In cases without a clear difference between the plans, we preferred DCA.

STATISTICS

For the statistical analysis we used SPSS, version 16 (SPSS Inc., Chicago, IL). To analyze the differences between the DCA and IMRT plans for each of the previously described criteria, a paired samples t test was used. The same method was applied to various groups of patients classified according to diagnosis, size, or shape of the PTV. The level of statistical significance was considered $p < 0.05$ for all calculations; therefore, a 95% confidence interval was applied.

RESULTS

OVERALL COMPARISON OF THE TECHNIQUES

Target coverage. Figure 3 shows the target coverage of both the DCA and the IMRT plans of all patients. With both techniques, acceptable target coverage was possible in all patients. It was higher than 99% in every plan of the 14 glioma patients and higher than 96% in every plan of the 11 meningioma patients. The mean coverage with the DCA and IMRT plans was 99.1% and 99.5%, respectively. This difference was statistically significant ($p = 0.048$).

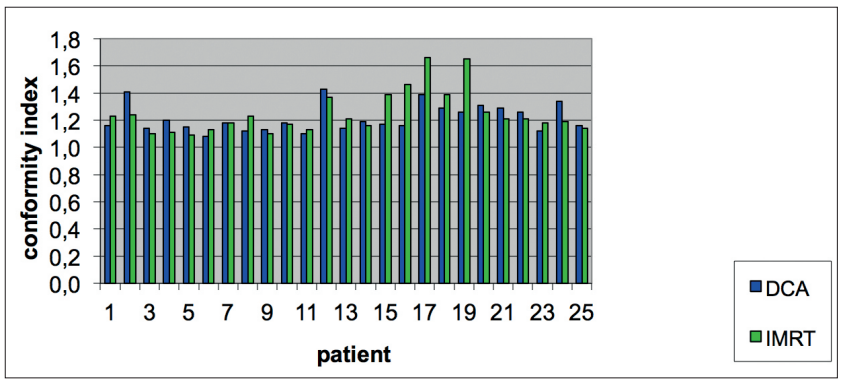

Figure 4. The conformity indices of both the dynamic conformal arc and the intensity-modulated radiotherapy plans.

Conformity. Figure 4 shows the conformity index for total brain minus PTV of all patients using both treatment techniques. The CI of all patients was well below the value two with both techniques. Table 2 shows the relation of the CI to tumor type, shape, and size. For the entire patient group, there was no statistically significant difference between both techniques with respect to mean CI ($p = 0.241$). The mean CI in concave tumors was significantly better with IMRT ($p = 0.027$). However, only 3 patients had concave tumors; therefore, statistics should be interpreted with caution.

Homogeneity. Figure 5 shows all homogeneity indices and Table 2 shows the relation of the HI to tumor type, shape, and size. There was no statistically significant difference between the mean homogeneity indices of DCA and IMRT for all patients ($p = 0.234$). In meningiomas

and complex-shaped tumors, the mean HI was significantly lower with DCA (p = 0.000 and p = 0.005, respectively). In smaller tumors, DCA plans had a lower mean HI than IMRT, but in larger tumors there was no significant difference.

EUD. Figure 6 shows the EUDs of the PTV and total brain minus PTV for all patients. Table 2 shows the relation of the EUD in the PTV to tumor type, shape, and size. For the entire patient group, no significant difference existed between the mean EUDs in the PTV of DCA and IMRT (p = 0.112). Convex tumors (the same cohort as the gliomas) and large tumors had a higher mean EUD with DCA than with IMRT (p = 0.000, and p = 0.003, respectively). These were the categories without significant differences with respect to HI and CI.

	Homogeneity index			Conformity index			Extrapolated uniform dose (Gy)		
	DCA mean (SD)	IMRT mean (SD)	p	DCA mean (SD)	IMRT mean (SD)	p	DCA mean (SD)	IMRT mean (SD)	p
Entire patient group (n=25)	1.221 (0.083)	1.237 (0.126)	0.234	1.214 (0.100)	1.248 (0.157)	0.241	57.7 (9.5)	56.8 (9.7)	0.112
Gliomas (n=14)	1.154 (0.036)	1.130 (0.020)	0.095	1.186 (0.105)	1.175 (0.077)	0.573	57.7 (7.7)	56.0 (7.45)	**0.000**
Meningiomas (n=11)	1.306 (0.023)	1.374 (0.030)	**0.000**	1.250 (0.086)	1.340 (0.186)	0.127	57.7 (11.9)	57.8 (12.3)	0.958
Convex tumours (n=14)	1.154 (0.036)	1.130 (0.020)	0.095	1.186 (0.105)	1.175 (0.077)	0.573	57.7 (7.7)	56.0 (7.5)	**0.000**
Complex shaped tumours (n=8)	1.304 (0.026)	1.364 (0.024)	**0.005**	1.236 (0.098)	1.383 (0.204)	0.056	55.3 (13.3)	54.9 (13.3)	0.782
Concave tumours (n=3)	1.313 (0.015)	1.400 (0.035)	0.093	1.287 (0.025)	1.227 (0.029)	**0.027**	64.0 (2.2)	65.5 (3.5)	0.412
Small tumours (<92cc) (n=12)	1.263 (0.073)	1.318 (0.113)	**0.005**	1.271 (0.104)	1.354 (0.166)	0.130	54.7 (13.1)	54.4 (13.4)	0.797
Large tumours (92cc or more) (n=13)	1.183 (0.074)	1.163 (0.086)	0.215	1.162 (0.064)	1.149 (0.045)	0.504	60.4 (2.8)	58.9 (3.5)	**0.003**
Optic nerve (n=8)							28.8 (12.0)	29.5 (10.8)	0.785
Chiasm (n=8)							30.9 (11.3)	29.4 (15.3)	0.561

Table 2. Overall comparison of the techniques.
Homogeneity index, conformity index and EUD in the PTV with both techniques in relation to tumour type, shape and size. EUD in the critical structures with both techniques. Values that are statistically signifcant are in bold.

ORGANS AT RISK

Table 3 shows the D_{max} (maximum point dose), the D_2, D_{30}, D_{80} (dose exceeded in 2%, 30%, and 80% of the volume), and the EUD of the critical structures. In 3 patients [15, 18, and 25) neither technique completely matched the constraints. The mean EUD in the critical structures did not differ significantly between both techniques (Table 2).

Figure 7 shows the mean dose–volume histogram of brain minus PTV in both the DCA and the IMRT plans. There was no statistically significant difference between both techniques with respect to the dose in brain minus PTV (p = 0.611).

MONITOR UNITS

For comparison of the plans, the IMRT/DCA ratio of the number of monitor units needed was recorded for each patient. The mean IMRT/DCA ratio of the number of monitor units was 2.2 (SD 0.4). In all patients, significantly more monitor units were needed for IMRT plans than for DCA plans.

INDIVIDUAL COMPARISON OF THE TECHNIQUES

Table 4 shows the comparison of the plans of all individual patients with both techniques. Based on this comparison, DCA was preferred in 18 patients and IMRT in 7 patients.
We found that the preference for one of the techniques in the individual patients could not be predicted from the overall comparison based on diagnosis, shape, or size of the tumors.

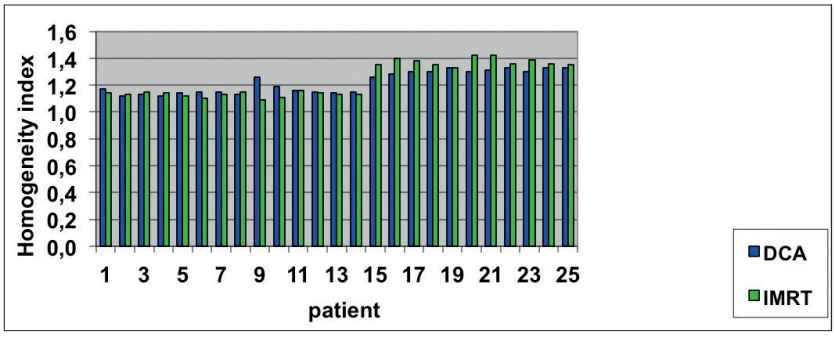

Figure 5. The homogeneity indices of both the dynamic conformal arc and the intensity-modulated radiotherapy plans.

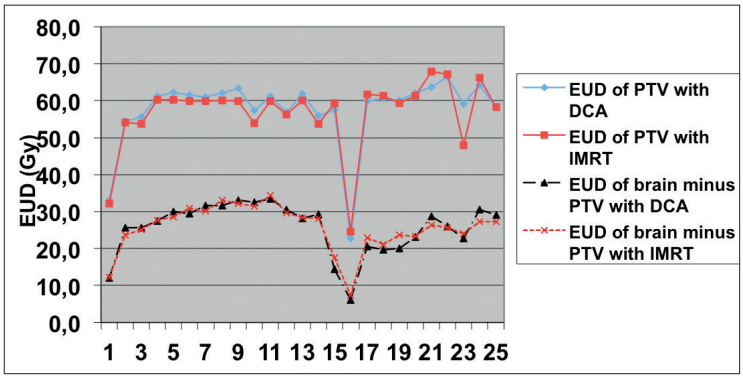

Figure 6. Equivalent uniform dose of the planning target volume (PTV) and total brain minus PTV with both the dynamic conformal arc and the intensity-modulated radiotherapy plans.

DISCUSSION

This study compared IMRT and DCA in intracranial tumors of various sites, sizes, and shapes. In the overall comparison of both techniques, we found adequate target coverage in all cases and differences in mean CI, HI, and EUD in subgroups. In all patients, significantly more monitor units were needed for IMRT plans than for DCA plans. The DCA plan was acceptable in 23 patients and the IMRT plan in 19 patients. DCA was preferred in 18 of the 25 patients.
Only a few studies comparing DCA and IMRT for brain tumors have been published. Ding *et al.* performed a planning study in 15 patients comparing three-dimensional conformal radiotherapy, DCA, and IMRT for stereotactic brain tumor treatment [3]. The authors' conclusion is similar to ours, namely that DCA is suitable for most cases in stereotactic brain tumor treatment. However, we do not agree with their conclusion that IMRT plans are the best in larger tumors. Their results in tumors larger than 100 mL are based on only 2 patients,

whereas we studied 11 patients with tumors larger than 100 mL.
The group of the University of Erlangen compared DCA and IMRT in pituitary tumors and small skull base tumors [1, 2]. They concluded that DCA was to be preferred in these small skull base tumors (until 10.4 cm3) [2]. However, for pituitary tumors, IMRT was superior in their hands [1]. The discrepancy between the conclusions in both papers is not fully explained. Because DCA is a forwardly planned technique, the experience of the planner to some extent determines the quality of the plan and thus also influences the result of a comparative planning study.

Case	PTV dose (Gy)	Optic nerve					Chiasm					Brainstem				
		D_{80}	D_{30}	D_2	D_{max}	EUD (Gy)	D_{80}	D_{30}	D_2	D_{max}	EUD (Gy)	80	30	2	D_{max}	EUD (Gy)
15	DCA	3.9	13.4	50.0	**56.1**	34.3	18.6	39.6	51.0	54.2	40.3					
	IMRT	3.2	12.4	**54.8**	**58.6**	38.8	18.3	46.8	55.7	**58.6**	45.4					
16	DCA	0.5	10.8	17.2	20.9	10.1	6.4	9.8	15.9	18.1	9.3					
	IMRT	0.9	10.3	16.6	20.3	9.7	4.0	8.8	15.2	17.8	8.8					
17	DCA	1.3	4.2	16.4	25.8	12.3	12.9	31.2	41.7	45.4	32.0	17.2	31.1	47.0	52.9	32.0
	IMRT	3.2	10.7	32.4	38.4	23.0	10.0	29.1	48.4	52.9	35.5	5.2	12.9	40.3	50.4	23.0
18	DCA	4.5	37.2	**52.0**	**56.7**	39.3	25.8	35.5	45.6	50.4	36.1					
	IMRT	8.4	39.7	**54.3**	**58.0**	42.1	14.7	28.9	47.3	52.9	34.3					
19	DCA	2.6	5.9	41.0	46.0	27.9	17.6	28.9	42.2	47.3	31.7					
	IMRT	10.4	17.0	**50.8**	54.8	34.4	10.1	26.9	43.7	48.5	32.5					
23	DCA	38.4	44.0	47.7	49.8	43.0	20.3	24.9	31.7	34.0	25.4					
	IMRT	9.5	29.6	42.6	47.3	32.0	5.0	6.8	10.7	14.5	8.2					
24	DCA	18.9	32.0	47.3	51.3	35.2	22.1	25.7	31.1	33.1	25.8					
	IMRT	19.9	30.2	47.9	**57.4**	35.1	16.3	19.9	28.3	31.7	21.5					
25	DCA	15.3	25.5	38.9	44.7	28.5	43.1	47.3	51.7	54.2	46.7	26.6	41.2	51.7	**60.5**	39.3
	IMRT	8.9	12.4	29.3	40.3	21.2	44.1	50.0	55.1	57.3	49.0	20.2	41.7	55.9	**61.1**	40.6

Table 3. Doses in the critical structures
Abbreviations: DCA = dynamic conformal arc; IMRT = intensity-modulated radiotherapy; PTV = planning target volume; D_{max} = maximum point dose ; D_2 = dose exceeded in 2% of the volume of the structure; D_{30} = dose exceeded in 30% of the volume of the structure; D_{80} = dose exceeded in 80% of the volume of the structure. Values that do not match the constraints are in bold.

IMRT and DCA have both been compared with other stereotactic techniques in brain tumors. Perks *et al.* compared DCA with gamma knife radiosurgery in acoustic neuromas [12]. They found a slightly better conformity index for gamma knife, but a more homogeneous dose distribution for DCA. They concluded that both techniques had advantages and disadvantages. Nakamura *et al.* compared gamma knife radiosurgery with IMRT in small and medium sized skull base tumors [13]. They found that IMRT was better in almost all aspects. Baumert *et al.* compared IMRT with conformal beam in skull base meningiomas [6]. IMRT was superior in almost all aspects, especially in large and irregular targets. IMRT was also compared with tomotherapy; neither technique seemed clearly superior to the other [4, 14].
In our opinion, dose homogeneity is an important aspect of plan quality, although it does not always receive attention in planning studies [4, 6]. In our patients with tumors smaller than 92 mL, the mean HI was better with DCA than IMRT. In a study comparing DCA and IMRT in very small skull base tumors, Ernst-Stecken *et al.* also report lower HI with DCA compared with IMRT [2]. Dose gradients can be important when normal structures such as cranial nerves or the carotid artery are in the PTV. For this reason, we consider the lower mean HI in meningiomas/complex tumors with DCA to be an advantage. In some individual patients, a high HI even caused the rejection of a plan as unacceptable. The char-

acterization of dose homogeneity is not complete with HI only. We found that some patient categories without any difference in mean HI and CI (gliomas/convex tumors/ larger tumors) had a significantly higher mean EUD with DCA. The type of dose distribution between the maximum dose and the prescription dose may explain this higher EUD with DCA. However, we did not base any clinical decision on the EUD values, because the EUD concept has not gained general acceptance and because of the uncertainty of the values of the parameter for the different organs.

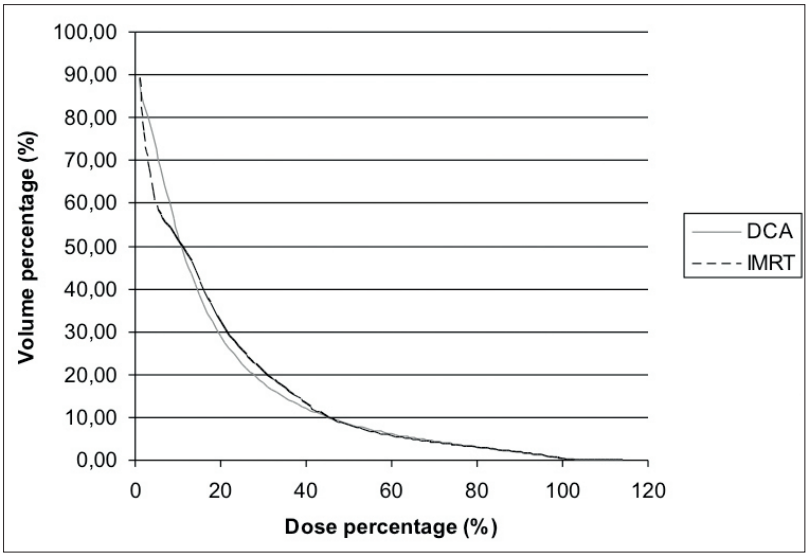

Figure 7. Mean dose–volume histogram of brain minus planning target volume in both the dynamic conformal arc and the intensity-modulated radiotherapy plans.

Gliomas have been treated following the ICRU guidelines to avoid large inhomogeneities, because the target not only contains tumor, but also normal brain with microscopic tumor extensions [15]. Still, the criteria for dose homogeneity of the ICRU were not met in the glioma patients, for whom we had to accept small hotspots up to 110%. In this study, the HI definition, originally devised for radiosurgery, had to be adopted for this patient group by taking the 95% isodose in the formula for the prescribed dose [9]. In doing so, the HI would be acceptable up to 1.16. The question can be asked if the ICRU guidelines are appropriate for techniques such as IMRT and DCA. Das *et al.* report a retrospective analysis of 803 patients with tumors in brain, head and neck, or prostate treated with IMRT [10]. The maximum dose was more than 10% higher than the prescribed dose in 46% of these patients. They also report substantial variation in prescribed and administered dose among institutions.

Several different conformity indices are proposed in the literature [16]. We decided to use the definition from Brainscan, because it gives information about the volume of healthy tissue receiving the prescribed dose. This CI is only informative if the target coverage is adequate, which was the case in all patients with both techniques. The mean CI was only different in concave tumors, where IMRT was better. However, this difference was considered clinically relevant in only 1 patient. In most cases, CI was adequate for both techniques and in only 2 patients, with small complex tumors, CI was unacceptable with IMRT.

Sparing the optic system is a challenge when the tumor is in close contact with it, as was the case in eight of the patients. It is uncertain what dose can be accepted as safe for the optic nerves or chiasm. Most information comes from series with homogeneous dose distributions in the optic system [17, 18]. A dose below 56 Gy in 2-Gy fractions seems safe. However, in

stereotactic radiotherapy, very sharp dose gradients exist in or close to the optic system. In these situations, the question arises if a higher point dose or a higher dose in part of the organ at risk may be accepted. But one could also argue that the radiation tolerance of an optic nerve compressed by a tumor for longer periods may be less than that of an uncompressed nerve. Therefore it is our opinion that it is safest to keep the dose in the optic nerve or chiasm below 50 Gy and to accept 56 Gy in not more than 2% of its volume. When the tumor is in contact with the optic system, the choice between optimal target coverage and higher dose in the optic system may have to be taken.

Patient	Coverage DCA	Coverage IMRT	CI DCA	CI IMRT	HI DCA	HI IMRT	Critical Structures DCA	Critical Structures IMRT	Acceptable plan	Preferred plan
1	+	+	+	+	+	+	+	+	Both	DCA
2	+	+	+	+	+	+	+	+	Both	IMRT
3	+	+	+	+	+	+	+	+	Both	DCA
4	+	+	+	+	+	+	+	+	Both	IMRT
5	+	+	+	+	+	+	+	+	Both	IMRT
6	+	+	+	+	+	+	+	+	Both	DCA
7	+	+	+	+	+	+	+	+	Both	DCA
8	+	+	+	+	+	+	+	+	Both	DCA
9	+	+	+	+	-	+	+	+	IMRT	IMRT
10	+	+	+	+	-	+	+	+	IMRT	IMRT
11	+	+	+	+	+	+	+	+	Both	DCA
12	+	+	+	+	+	+	+	+	Both	DCA
13	+	+	+	+	+	+	+	+	Both	DCA
14	+	+	+	+	+	+	+	+	Both	DCA
15	+	+	+	+	+	+	-	-	None	DCA
16	+	+	+	+	+	+	+	+	Both	DCA
17	+	+	+	-	+	+	+	+	DCA	DCA
18	+	+	+	+	+	+	-	-	None	DCA
19	+	+	+	-	+	+	+	-	DCA	DCA
20	+	+	+	+	+	+	+	+	Both	DCA
21	+	+	+	+	+	+	+	+	Both	IMRT
22	+	+	+	+	+	+	+	+	Both	DCA
23	+	+	+	+	+	+	+	+	Both	IMRT
24	+	+	+	+	+	+	+	-	DCA	DCA
25	+	+	+	+	+	+	-	-	None	DCA

Table 4. Plan comparison for all individual patients.
Abbreviations: DCA = dynamic conformal arc; IMRT = intensity-modulated radiotherapy; CI = conformity index. + Defined criteria or constraints are met. – Defined criteria or constraints are not met. * In Patients 15, 18, and 25, none of the techniques fully matched the dose constraints in the critical organs, but in all 3 patients DCA plan was accepted in clinical practice, because the doses in the critical organs were close to the maximum allowed doses.

In all patients, more monitor units were needed for the IMRT plans than for the DCA plans. IMRT is expected to cause more secondary malignancies compared with three-dimensional conformal radiotherapy through two mechanisms: the first is more monitor units with IMRT and the second is the exposure of a larger volume of normal tissue to low radiation doses in IMRT [19]. In this comparison of IMRT with DCA, we did find that more monitor units were needed with IMRT, but we did not find a statistically significant difference between both techniques with respect to the volume of irradiated brain tissue (Fig. 7). Although there is no proof of the relation between the number of monitor units and the risk of radiation-

induced malignancies, in our opinion the difference in monitor units needed is an important argument in favor of DCA, when plans are comparable in other aspects.
In conclusion, we prefer DCA as SRT technique for most intracranial tumors. Tumor type, size, or shape does not predict a preference for a DCA or IMRT plan. If the patient's IMRT and DCA plans are comparable, we prefer DCA, because less time-consuming quality assurance is needed and fewer monitor units are used with DCA than with IMRT. Our policy is to start making a DCA plan for all patients with intracranial tumors, only proceeding to an IMRT plan if the DCA plan is unacceptable or if we expect a significant improvement.

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