Dose-volume Analysis of Different Stereotactic Radiotherapy Mono-isocentric Techniques

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Several stereotactic irradiation techniques, using Linacs with the patient in lying and sitting position and a Gamma Knife Unit, were compared with regard to mono-isocentric three-dimensional dose distributions. Three types of target volumes, a sphere and two ellipsoids, were used for the comparisons. All three targets were centered on a real head, reconstructed from transversal CT scans. The ARTEMIS 3D Treatment Planning System, developed by the Tenon Hospital, Paris, was used for the dosimetry and the dose-volume histogram (DVH) calculation. For the comparative study, several quantitative parameters were used, derived from the dose-volume histogram calculation. Differential DVHs were plotted for each target volume and beam arrangement. Irradiation techniques were compared by deriving quantitative parameters from the DVHs such as mean and integral dose delivered to the target and normal tissue irradiated, as well as by the relative volume of the examined areas. All techniques used in this study produced very similar dose distributions. The small differences confirm the capability of the studied techniques to produce the same irradiation effects. By changing from the spherical target shape to a more elliptical shape, more of the normal tissue was irradiated with higher doses. For elliptical cases we therefore identified a need for more conformal stereotactic planning.

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Stereotactic external beam radiotherapy (SRT) using a linear accelerator (1, 2) is based on the principle of the multi-source cobalt unit, where multiple sources are arranged in a hemisphere around the target (3). Multiple non-coplanar arcs have provided the nearest approximation and this technique has been accepted as the conventional stereotactic treatment from Linacs, although such an arrangement only produces spherical target volumes. Stereotactic radiotherapy has been used mainly to treat arteriovenous malformations (AVMs). The collimator diameters available from the linear accelerator-based stereotactic techniques also afford the opportunity to treat a wide variety of brain tumors. The rationale for using stereotactic techniques to treat malignant diseases in the brain is that for a given tumor dose, the radiation burden on the surrounding normal tissues can be minimized. This allows the dose to the target to be increased, because here we are also discussing non-tumor targets such as the AVMs.

Several techniques have been reported in the literature, such as single arc, multiple arcs or dynamic rotation (1, 4–7). The irradiation technique also depends on the head fixation, whether the patient is lying down on the Linac table or seated in a chair (8). In this study we report different techniques used by several European Radiotherapy Centers, members of the DYNARAD project. This project, within the framework of the European Community BIOMED I program, concerns the development and standardization of new dynamic radiotherapy techniques. One part of this project has been devoted to the development and standardization of the stereotactic radiotherapy techniques.

A comparison of different techniques, limited to transverse, coronal and sagittal planes, could provide information on the dose distributions to sensitive structures situated in these planes (9), but the planar data do not give the full picture (10). A dose-volume distribution is a more appropriate method of comparison as it also gives quantitative results. The cumulative (or integral) DVH can specify the fraction of the target volume raised to specific dose values. This can be computed from a differential DVH showing the number of dose voxels raised to each

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dose level. Several authors argue that the DVH is an effective tool in evaluating 3-D plans (11–14). The use of DVH as a basis for comparison between three-dimensional dose distributions provided by different stereotactic radiotherapy techniques has been reported in the literature (10, 15–20). In this study a DVH analysis of radiosurgical techniques, based on Linac and Gamma Knife, will be reported.

Before studying the methods for treating irregular volumes, it is important to define a satisfactory method for treating simple target shapes in terms of arc arrangement. In order to address this problem we have calculated the dose-volume distributions for one spherical and two ellipsoid target volumes, treated by different techniques of the DYNARAD participating centers. This serves as a ‘map’ in the process of standardizing SRT.

MATERIAL AND METHODS

The Treatment Planning System (TPS) used was the ARTEMIS 3D TPS for stereotactic radiotherapy, developed at Tenon Hospital, Paris, in collaboration with the Dosigray Company. The ARTEMIS 3D stereotactic radiotherapy dose calculation software was first developed on a VaxStation DEC 3200 in the VMS environment and then adapted to a more powerful computer, the DecStation 5000/240 (DEC) in the Unix environment. The programming languages are FORTRAN and C (21–23). The ARTEMIS 3D permits both qualitative evaluation such as isodose displays or dose-distribution profiles, and quantitative evaluation, such as dose-volume histograms. Head CT scan images were transferred to the ARTEMIS 3D TPS. The slice thickness was 2.5 mm for the whole head. For the dosimetry, a 15 MV linear accelerator was used. The dose matrix used for the calculation of each case was 100 mm × 100 mm × 100 mm (voxel size 1 mm^3).

For this study, we have chosen three target shapes: a sphere and two ellipsoids, in order to examine the capability of each technique to treat spherical as well as non-spherical lesions. The three target volume shapes are: a sphere of $A = 19$ mm diameter; an ellipsoid of A mm, 0.75A mm and 0.75A mm dimensions; and an ellipsoid of A mm, 0.5A mm, 0.5A mm dimensions (Fig. 1). All the above targets were positioned centrally and the isocenter coordinates into the stereotactic coordinate system were -1 mm, -1.5 mm and 0 mm for the left–right, anterior–posterior and inferior–superior directions, respectively. The volume of the sphere (SPH) was 3.826 cm^3, for the first ellipsoid (EL_1) was 2.367 cm^3 and for the second ellipsoid (EL_2) was 1.161 cm^3.

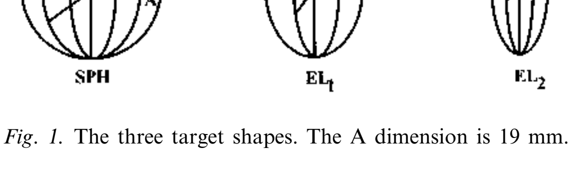

Fig. 1. The three target shapes. The A dimension is 19 mm.

It has been shown that the location of the lesion in the patient’s head does not in fact influence the dose distribution for mono-isocentric cases (24). Thus we can consider that the results are representative for different locations, except of course for the extremely superficial locations. However, these last cases are rarely encountered in clinical practice. The choice of target shape is based on three conditions: (i) in the majority of actual clinical cases, the mono-isocentrically planned target volumes have almost spherical or ellipsoidal shapes, (ii) the effect of the irradiation technique used is easier and clearer when symmetrical targets are treated and (iii) the complex target volumes, multi-isocentrically planned, are usually split up into simple spheres or ellipsoids for the selected isocenters and beam configuration (25).

The diameter of the circular collimator used, 20 mm, was chosen to give complete coverage of the target, leaving no margin. There was only one isocenter for all the techniques used for the comparison. The radiation treatment, for all the techniques, was designed to deliver 25 Gy to the 70% reference isodose curve.

The principal goal of this study was to compare different multi-arc techniques (as shown in Fig. 2). For linking the above with simpler, classical techniques, we also studied a limited 3-arc technique (T2) and the complete rotation (T1). The multi-arc techniques used are: T3 Centre Alexis Vautrin, Nancy (26), T4 Institute Curie, Paris (27), T5 Radiologische Klinik der Universitaït, Tubingen (26), T6 ‘Vicenza’ Presidio Ospedaliero (26), T7 Centro de Oncologia, Coimbra/Hospital Puerta de Hierro, Madrid (26), T8 Tenon Hospital, Paris (21), T9 Karolinska Institute, Stockholm (3). It should be mentioned here that the beam configuration chosen demonstrated the maximum irradiation space that the participating centers could use. There has not been any attempt to optimize the treatment plans by changing the weighting factors or by any other means. Nevertheless, two additional beam configurations have been realized, one adjusted to the target EL_1 (T10) with a collimator of 16 mm in diameter and one adjusted to the target EL_2 (T11) with a collimator of 12 mm in diameter. For these configurations, adapted right–left (RL) and anterior–posterior (AP) angular apertures are used; $RL = 40–320°$, $AP = 45–135°$ for the EL_1 and $RL = 50–310°$, $AP = 55–125°$ for the EL_2. Both the optimized techniques could be performed by all the participating centers, as the proposed beam configuration is within their limits of arc and table positions.

For the Gamma Knife Unit (T9), all 201 sources were used without conformation to the target shape as for the Linac techniques. The collimators had the maximum diameter available, 18 mm. For the compatibility of the

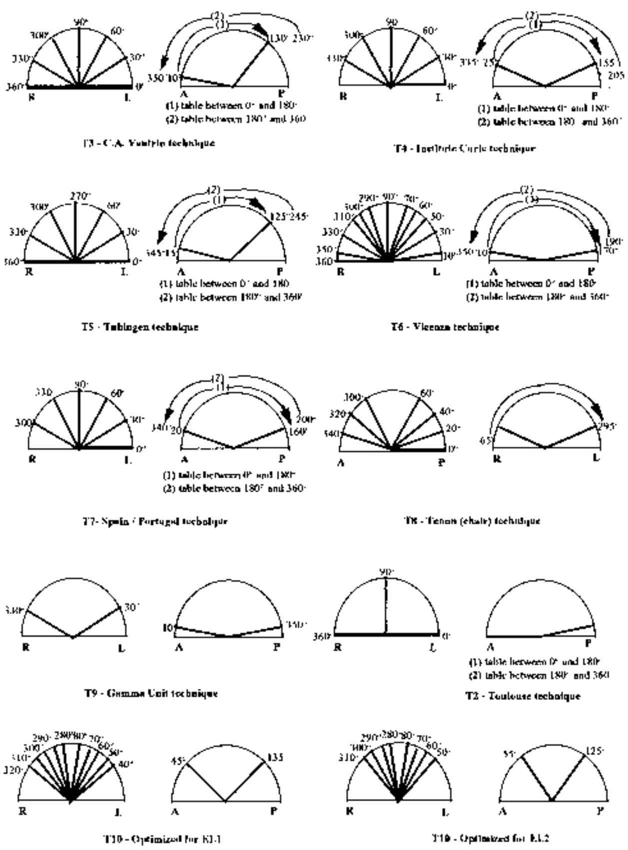

Fig. 2. Schematic diagram of the different beam configurations used for this study.

results, we chose in this case the 50% isodose as the enveloping reference isodose and the treatment was designed to deliver 18 Gy to the reference isodose.

DVHs were plotted (Fig. 3) for the target and the surrounding tissue, for each applied technique. For the normal tissue DVH calculation, we considered a cubic space with total dimensions $100 \times 100 \times 100$ mm^3, from which the volume of the target was excluded. Various regions of interest (ROIs) have been studied.

For the lesion, we calculated the volume covering the lesion, defined as the fraction of the lesion receiving a dose equal or superior to the prescribed dose (reference isodose). For the normal tissues we studied the region situated between the isodoses 10% and lesion surface ($D_{L,s}$) and the region situated between 30% isodose and the lesion surface. Finally, we studied the overdosed normal tissue volume, defined as the volume of the normal tissue included in the reference isodose surface.

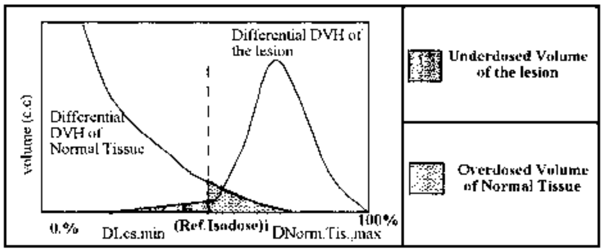

Fig. 3. Differential dose-volume histograms inside and outside the lesion.

Considering that the standard multi-arc techniques (T3–T9) are an optimized configuration for spherical targets, and the techniques T10 and T11 are optimized configurations for the EL_1 and EL_2, respectively, we examined the dose-volume parameters for each ROI as a function of the target shape. Based on the two previous studies, we investigated the variation of the dose-volume parameters for each ROI as a function of the target shape.

RESULTS

Differential DVHs were plotted for each target volume and beam arrangement. The comparison between the irradiation techniques was made using the above quantitative parameters, which were derived from the calculated DVHs.

Lesion

The calculated quantitative parameters for the lesional volumes are presented in Table 1 for the lesions and for all the irradiation techniques studied. For the standard multi-arc techniques (T3–T9), the minimum, maximum and the mean values of all the parameters are presented.

The lesional coverage volume. The coverage volume provides a quantitative indication of the capability of each technique to treat the whole target volume. Standard multi-arc techniques and the limited 3-arc technique showed a coverage capability of more than 98% of the target volume for all the target shapes. The majority of the techniques produced spherical isodose curves, with exception of the Linac sitting patient technique, which produced slightly elliptical isodoses. The single-arc technique (T1), compared with the multi-arc techniques showed a 2% decrease of the coverage volume for the two ellipsoids. The technique T10 (the optimized technique for the EL_1) showed a 6.5% decrease, from the mean value of the multi-arc techniques, of the coverage volume, whereas the technique T11 (the optimized technique for the EL_2) showed an 11.3% decrease.

Mean and integral doses to the whole lesion. For the nine techniques (T1–T9), as the target volume decreases, the mean dose in the whole lesion increases as the target receives higher doses. For the multi-arc techniques, the variation in the mean dose of the whole lesional area between the SPH and the EL_2 is 2.02 Gy. We could not, however, detect any significant difference between these techniques.

Considering the whole target volume, the average value of the mean dose for the multi-arc techniques is 32.13 Gy for the SPH, 33.36 Gy and 34.15 Gy for the EL_1 and the

Table 1

Dosimetric results to the lesion for all the techniques

	T1	T2	T3–T9			T10	T11
			Min	Mean	Max		
SPH							
Coverage Vol. (cc)	3.763	3.808	3.775	3.799	3.824	–	–
Mean Dose (Gy)	32.31	32.22	32.06	32.13	32.18	–	–
Integral Dose (gr*Gy)	123.6	123.3	122.9	123.0	123.2	–	–
EL$_1$							
Coverage Vol. (cc)	2.286	2.324	2.345	2.355	2.365	2.202	–
Mean Dose (Gy)	33.05	33.22	33.31	33.36	33.43	30.76	–
Integral Dose (gr*Gy)	78.26	78.64	78.85	78.98	79.33	72.82	–
EL$_2$							
Coverage Vol. (cc)	1.134	1.148	1.152	1.160	1.178	–	1.029
Mean Dose (Gy)	33.6	33.85	34.02	34.15	34.60	–	29.72
Integral Dose (gr*Gy)	38.52	39.3	38.54	39.50	40.27	–	34.92

EL$_2$, respectively. The limited 3-arc and single-arc techniques for the SPH showed 0.28% and 0.56% relative deviation from the standard techniques, respectively. In the case of EL$_1$ the deviations for the two techniques are 0.42% and 0.93%, respectively, whereas in the case of EL$_2$ the relative deviations were 0.88% and 1.61%, respectively. For the two optimized techniques T10 and T11, the decrease from the mean value obtained with the standard techniques was 7.8% and 13% for the EL$_1$ and EL$_2$, respectively. For the multi-arc techniques, the decrease in the integral dose from the SPH to EL$_2$ (123 to 39.5 gr*Gy) is due principally to the decrease in the target volume. The relative deviation rates between the optimized techniques T10 and T11 and the standard techniques are 7.8% and 13%, respectively.

Normal tissues

The calculated quantitative parameters for the different normal tissue areas are presented in Table 2 for all the targets and for all the irradiation techniques studied. For the multi-arc techniques, the minimum, maximum and the mean value of all the parameters are presented.

Volumes of the global region (10%-$D_{L,s}$) and the (30%-$D_{L,s}$) subregion. We calculated the corresponding volumes for the regions (10%-$D_{L,s}$) and (30%-$D_{L,s}$) for the three target shapes. The values of the (30%-$D_{L,s}$) region for the EL$_2$ were greater than those for the SPH. A higher degree of increase was presented for the (10%-$D_{L,s}$) region. Most of the techniques produced the same results, except the single-arc technique and the limited 3-arc technique, which presented slightly increased regions of high doses (30%-$D_{L,s}$). The volume included in the global normal tissue area (10%-$D_{L,s}$) showed a small variation in multi-arc techniques with a mean value of 80.76 cc for the SPH. The variation was more significant for the limited 3-arc and single-arc techniques. By using these techniques the increase in the irradiated normal tissue volume was 50.81% and 106.04%, respectively. However, the volume of the normal tissues irradiated has been significantly decreased with the two optimized techniques T10 and T11. For the EL$_1$, the decrease was 30.4% for the (10%-$D_{L,s}$) region and 40.46% for the (30%-$D_{L,s}$) region, whereas for the EL$_2$ the decrease was 56.02% for the (10%-$D_{L,s}$) and 67.9% for the (30%-$D_{L,s}$) region.

Mean and integral doses. The mean doses delivered to 10%-$D_{L,s}$ and 30%-$D_{L,s}$ regions and for all target shapes were calculated (Table 2). The difference between the techniques was minor, but there was still a small deviation for the limited 3-arc and single-arc techniques. Nevertheless, the degree of the increase of the EL$_2$ values for the 30%-$D_{L,s}$ area is more important than this one for the 10%-$D_{L,s}$ region.

Most techniques produced the same integral dose to the corresponding volume of the area 10%-$D_{L,s}$ for the three target shapes, except the single-arc and the limited 3-arc technique where there was a slight increase in the region of high doses (30%-$D_{L,s}$). The integral dose into the global normal tissue area (10%-$D_{L,s}$) showed small variation in multi-arc techniques with a mean value of 608.6 gr*Gy for the SPH. This variation became important for the limited 3-arc and single-arc technique. For those techniques the increase in the integral dose was 35.44% and 91.12%, respectively.

In both the mean and integral dose to the global normal tissue, a significant difference between the standard and the optimized techniques was observed for the two ellipsoids.

Normal tissue overdosed volume

The calculated quantitative parameters for the overdosed area of the normal tissues are presented in Table 3 for all the lesions and for all the irradiation techniques studied. For the multi-arc techniques, the minimum, maximum and the mean value of all the parameters are presented.

Normal tissue overdosed volume. The overdosed volume of the normal tissues has been calculated. Standard multi-arc techniques and the limited 3-arc technique produced similar results for the SPH with 1.120 cc and 1.127 cc, respectively. The single-arc technique (T1), compared with the multi-arc techniques, showed a 19% increase of the overdosed volume for the EL_1 and 12% for the EL_2. The technique T10 (the optimized technique for the EL_1) showed an 83.7% decrease from the mean value of the multi-arc techniques, whereas the technique T11 (the optimized technique for the EL_2) showed a 96% decrease.

Mean and integral dose. The mean dose to the overdosed region was calculated for all target shapes and the results were almost the same for all the techniques. The mean dose to the overdosed normal tissue using the standard techniques and for the smallest ellipsoid is 30.1 Gy, which is important if we consider that its corresponding volume is more than three times the target volume. For the EL_1 the mean dose was decreased to 28.85 Gy and for the SPH it was 27.07 Gy. The difference between the standard multi-arc and the optimized techniques was 6.9% for the EL_1 and 13.2% for the EL_2. The integral dose to the overdosed volume increases with a decrease in the target volume for the multi-arc techniques. The significant difference observed for the optimized techniques was due to the important decrease in the overdosed volume using the corresponding beam configuration.

DISCUSSION

Within the framework of the Dynarad project, we had the opportunity to study and process several SRT techniques used by seven different institutions. These irradiation techniques represent the actual regimens used in Europe. Furthermore, they cover the minimum (C. A. Vautrin technique) and maximum (Vicenza technique) irradiation volumes as well as some of intermediate stages. To our knowledge, this is the first time the isodoses used at different centers by varying techniques are directly compared between institutions assessed in the same treatment planning system. The fact that all the techniques have been processed with the same calculation algorithm has made the results more consistent for clinical comparison.

For all the described regions (ROIs) we studied dosimetric parameters such as the mean and the integral doses. Concerning the multi-arc techniques, it has been already demonstrated that they give similar results for simple spherical lesions (9). We will present for the seven multi-arc techniques (T3–T9) of the DYNARAD participating centers the minimum, the maximum and the mean values of the dose-volume parameters into the above volumes.

Table 2

Dosimetric results to the healthy tissue areas for all the techniques

	T1	T2	T3–T9			T10	T11
			Min	Mean	Max		
Healthy tissue area 10%–$D_{L,s}$							
SPH						SPH	
Volume (cc)	166.4	121.8	76.54	80.76	83.78	–	–
Mean Dose (Gy)	7.020	6.790	7.440	7.526	7.600	–	–
Integral Dose (gr*Gy)	1167.0	827.4	581.8	608.6	630.5	–	–
EL_1						EL_1	
Volume (cc)	167.8	123.3	78.77	82.17	85.24	57.18	–
Mean Dose (Gy)	7.230	7.070	7.840	7.918	8.020	7.219	–
Integral Dose (gr*Gy)	1213.0	872.4	626.0	653.4	674.7	412.8	–
EL_2						EL_2	
Volume (cc)	169.0	124.5	79.22	83.40	86.45	–	36.68
Mean Dose (Gy)	7.410	7.320	8.190	8.278	8.400	–	6.93
Integral Dose (gr*Gy)	1251.0	911.7	670.9	693.7	714.2	–	254.1
Healthy Tissue area 30%–$D_{L,s}$							
SPH							
Volume (cc)	22.56	16.59	14.45	14.90	15.42	–	–
Mean Dose (Gy)	15.90	16.10	16.23	16.26	16.28	–	–
Integral Dose (gr*Gy)	359.0	267.1	235.1	241.5	250.8	–	–
EL_1							
Volume (cc)	24.03	18.05	15.92	16.32	16.88	9.717	–
Mean Dose (Gy)	16.83	17.27	17.48	17.50	17.54	15.622	–
Integral Dose (gr*Gy)	404.5	311.8	279.3	286.2	295.0	151.8	–
EL_2							
Volume (cc)	25.22	19.26	17.13	17.58	18.09	–	5.460
Mean Dose (Gy)	17.57	18.23	18.49	18.54	18.61	–	15.19
Integral Dose (gr*Gy)	443.2	351.2	323.8	325.3	334.4	–	82.89

Table 3

Dosimetric results to the overdosed healthy tissue area for all the techniques

	T1	T2	T3–T9			T10	T11
			Min	Mean	Max		
SPH							
Volume (cc)	1.592	1.127	1.080	1.120	1.207	–	–
Mean dose (Gy)	27.22	27.00	27.01	27.07	27.13	–	–
Integral dose (gr*Gy)	43.34	33.40	29.64	30.49	32.60	–	–
EL_1							
Volume (cc)	3.067	2.721	2.535	2.578	2.660	0.421	–
Mean dose (Gy)	29.00	28.87	28.82	28.85	28.88	26.86	–
Integral dose (gr*Gy)	88.92	78.57	73.17	74.19	76.72	11.31	–
EL_2							
Volume (cc)	4.219	3.897	3.735	3.768	3.853	–	0.150
Mean dose (Gy)	30.07	30.08	30.05	30.09	30.10	–	26.11
Integral dose (gr*Gy)	126.8	117.2	112.5	113.4	115.8	–	3.920

Those data will be compared with those obtained with the limited arc techniques, the one 360° rotation (T1) and the 3-arc (two transverse and one sagittal) (T2) to determine whether a possible improvement could be obtained. The comparison will be realized taking into account the lesion shape, spherical and different ellipsoidal degree (ratio between the maximum and the minimum target dimension).

All the techniques used for this study produced very similar dose distributions, whereas for the limited 3-arc (T2) and single-arc (T1) techniques the deviation becomes evident. For the standard multi-arc techniques (T3–T9) and the limited arc techniques (T1 and T2), we observe that the mean dose inside the lesion is almost independent of the technique. However, it increases slightly as the target shape becomes more ellipsoidal. The integral dose follows the variation in the mean dose as a function of the technique, but it is drastically decreased, as the target shape becomes more ellipsoidal (Table 1).

On examining the global normal tissue region 10%-$D_{L,s}$ we noticed an important increase in the volume for the limited 3-arc (an increase of 49.9%) and single-arc (an increase of 104.7%) techniques in respect of the multi-arc techniques (mean value 80.76 cc). The calculated mean dose in this region did not present significant differences. Similar variations were observed for the two ellipsoid targets. According to the above, the integral dose variation follows the volume variation (Table 2).

The region 30%-$D_{L,s}$ is of clinical interest, as the dose-volume parameters can be indexes for complication probability. The mean dose in this area did not present significant differences. However, an important variation in the integral dose was observed, as the target volume is relatively small. Considering the sphere, the single-arc technique presents an increase of 48.6% compared with the standard techniques, whereas the limited 3-arc technique presents an increase of 10.6%. For the two ellipsoids EL_1 and EL_2, the increased volumes compared with the standard techniques are 41.3% and 36.2%, respectively, for the single-arc technique, whereas for the limited 3-arc technique an increase of 9% and 8%, respectively, was observed. This shows the necessity of using multi-arc techniques.

The effect of the different techniques on the overdosed normal tissue volume was similar, except for the single-arc technique, which seems to produce a larger overdosed normal tissue volume (Table 3). The overdosed normal tissue volume presents small variations for all the target shapes as a function of the technique. Nevertheless, the variations as a function of the target shape show an important increase as we pass from the sphere to the ellipsoid. This result clearly shows that the planning of the ellipsoidal targets with standard techniques is unacceptable. The mean dose for each target shape is the same from T1 to T9. As we move from SPH to ellipsoids, the mean dose increases. According to the above data, the integral dose increases drastically.

For the spherical lesion, the multi-arc techniques (T3–T9) have been considered as the optimum configuration. For presenting the need of conformation, following the target shape, we have calculated the absolute difference between the standard and the optimized techniques. We have observed that as the target shape becomes more ellipsoidal, the greater the need for an optimized configuration. Furthermore, the differences between the two ellipsoidal targets increase into the four regions of interest as we move from the exterior (10% isodose curve) to the center of the lesion.

Our results are compatible with those of Graham (10) who states that ‘there is no significant benefit for an arrangement of more than 3 arcs for the spherical target sizes’. Serago (19) uses arcs technique for most radiosurgical cases: ‘Although the dose volume histogram for 4 vs. 6 arcs is essentially identical, we feel, there is a minor safety advantage of using more arcs.’ He also adds that the differences between techniques are only appreciated at the lower isodose levels that are not generally clinically significant. These conclusions are also in agreement with the results of Schell (17): 'Differences were seen in the irradiated volumes of normal tissue mainly at clinically in significant levels.'

According to the above information, for more complex target shapes than the sphere there is a need of a more conformal treatment using variable numbers of arcs, angular apertures, collimator opening, or multi-isocentric treatments. This became more evident with the improved results presented for the two optimized techniques. Nevertheless, before executing any optimization procedure by modifying the irradiation parameters, it is helpful to examine the effects of the standard beam configuration using 3-D quantitative parameters.

CONCLUSION

The results presented show a high degree of compatibility between the techniques from mono-isocentric stereotactic irradiation between seven institutions with small deviations for the technique using the 3-arc and a single-arc techniques. The homogeneity of tissue coverage will permit multi-institutional clinical studies by different centers.

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