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Physics Investigation

Evaluation of multiple factors affecting normal brain dose in single-isocenter multiple target radiosurgery

Yu Yuan, PhD[1], Evan M. Thomas, MD, PhD[1], Grant A. Clark, MD[1], James M. Markert, MD, MPH[2], John B. Fiveash, MD[1] and Richard A. Popple, PhD[1]

[1]Department of Radiation Oncology, University of Alabama at Birmingham, Birmingham, Alabama 35294, USA
[2]Department of Neurosurgery, The University of Alabama at Birmingham, Birmingham, Alabama, USA

Correspondence to: Richard A. Popple, PhD, Department of Radiation Oncology, University of Alabama at Birmingham, 1720 2nd Ave South, Birmingham, AL 35294, USA. Email: rpopple@uabmc.edu

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ABSTRACT

We investigated the effects of multiple planning factors on normal brain dose for single-isocenter VMAT stereotactic radiosurgery (SRS). Ten patients were retrospectively planned using a standardized objective function and all 16 combinations of 2 versus 4 arcs, collimator angle 45° versus selected per beam to minimize area of normal brain exposed in the beams-eye-view, fixed jaw versus following the trailing MLC leaf, and a 2 Gy mean dose objective for healthy brain versus no low dose objective. Limiting the normal brain mean dose in the optimization objective function significantly reduced the low dose spill into the normal brain without changing target coverage. Jaw tracking and appropriate selection of collimator also reduced the low dose volume, but to a lesser extent. To reduce low dose spill into normal brain for single isocenter VMAT radiosurgery of multiple targets, it is important to incorporate a limit on low dose spill into the objective function. This study has implications beyond single-isocenter VMAT radiosurgery. When comparing different inverse-planned treatment techniques, metrics that are important for evaluation of plan quality must be included the objective function.

Keywords: radiosurgery, VMAT, linac, SRS, brain metastases

INTRODUCTION

Medical linear accelerator (linac) based stereotactic radiosurgery (SRS) has been of interest in the radiation oncology community for many years.[1, 2] With the advent of intensity modulated arc therapy[3] and volumetric modulated arc therapy (VMAT),[4] linac-based SRS can achieve improved plan quality and high delivery efficiency.

For intracranial multiple metastatic diseases, a multi-isocenter setup, i.e., one isocenter for each individual lesion, is typically applied in conventional linac based SRS. However, treatment of multiple lesions with a single isocenter approach has been described,[5] with recent interest in using VMAT.[6-8] The use of VMAT technique for single isocenter multiple lesion SRS introduces the issue of dose limitation to normal brain dose. One concern is the so-called "island-blocking" problem, in which leaf gaps irradiate normal brain while in transition between lesions. Kang et al.[9] proposed a method to minimize the island-blocking prob-

lem by optimizing the collimator and couch angles. However, island-blocking is not the only factor that influences normal brain dose. For example, variable secondary collimator size (often referred to as jaw tracking) has been shown to reduce spinal cord dose for stereotactic radiosurgery of the spine.[10] Other factors, including number of arcs and construction of the objective function, will also influence normal brain dose. Therefore, a comprehensive study on the effects of various factors on normal brain dose in clinical setting is needed. In this paper, we present such a study to evaluate the effects of number of arcs, collimator angle, variable secondary collimator size, and optimization objectives on normal brain dose.

MATERIALS AND METHODS

Patient selection

Ten intracranial multi-target patients previously treated at our institution were selected for study. The number of planning target volumes (PTVs) for these patients ranged from 3 to 11, with a mean number of 5.4. The PTV volumes of the targets were within a range of 0.03 to 29.06 cc, with a mean volume of 3.91 cc.

Planning

The cases were retrospectively planned for volumetric modulated arc therapy (VMAT) using the Eclipse treatment planning system (TPS) (Varian Medical Systems, Palo Alto, CA) for treatment with a TrueBeam linear accelerator (Varian Medical Systems, Palo Alto, CA) following the procedure described by Clark et al.[6] The linac was equipped with a multi-leaf collimator having 2.5 mm leaf width in the central 8 cm and 5 mm in the periphery, with a total field length of 22 cm. All plans used a 10 MV flattening filter free beam with a dose rate of 2400 monitor units per minute. The isocenter was placed at the geometric center of the PTVs. The prescription dose was 18 Gy in one fraction, and plans were normalized to deliver 100% of prescription dose to 99% of the total target volume. Dose was calculated using the Eclipse Analytic Anisotropic Algorithm using a 2.5 mm grid size.

Number of arcs

It has been reported that multiple-arc plans had superior plan quality compared to single-arc plans.[7] Based on these findings, two-arc plans and four-arc plans were generated. In the two-arc plans, a transversal arc and a vertex arc were utilized, and in the four-arc plans, two additional oblique vertex arcs were utilized. The arc geometries are given in Table 1 and are illustrated in Figure 1.

Table 1. Arc geometry in IEC 61217 coordinate system. The arc geometries are illustrated in Figure 1.

Arc	Plan	Gantry start angle	Gantry stop angle	Gantry rotation direction	Table angle
1	2-arc, 4-arc	181	179	CW	0
2	2-arc, 4-arc	181	10	CW	90
3	4-arc	10	181	CC	45
4	4-arc	179	350	CC	315

Collimator angle selection

For multiple target treatment planning, it has been proposed that collimator angle selection can influence plan quality.[9] Briefly, a pair of targets will share MLC leaf pairs when they are aligned along the direction of the MLC leaf travel. As a consequence, delivering radiation to both targets requires undesired irradiation of the normal tissue between them. Kang et al. refer to this issue as the "island-blocking problem." [9] They proposed an algorithm to minimize this "island blocking" area by selecting the optimal couch and collimator angles during the gantry rotation in the VMAT delivery to minimize leaf-pair sharing between targets. They concluded that minimizing the sharing of MLC leaves between lesions improves plan quality with respect to the volume receiving 12 Gy and the homogeneity of dose within the target. A similar algorithm, Projection Summing Optimization, has been implemented by Wu et al. using treatment planning scripting.[11] Wu et al. found reductions in mean and low dose volume to normal brain. However, neither group investigated other factors influencing low dose spill.

In our work, we modified the approach of Kang et al.[9] to directly minimize the "island area" between the targets. For two targets, the further apart in the beams-eye-view, the larger the potential island area. For each arc, we generated an MLC aperture that irradiated all targets at each control point (a conformal arc), as illustrated in Figure 2a. For each control point, we calculated the island area, given as the open area of the aperture in the beam's-eye-view that did not include the target volume, as shown in Figure 2b. For a given collimator angle, the average island area for each arc was given by

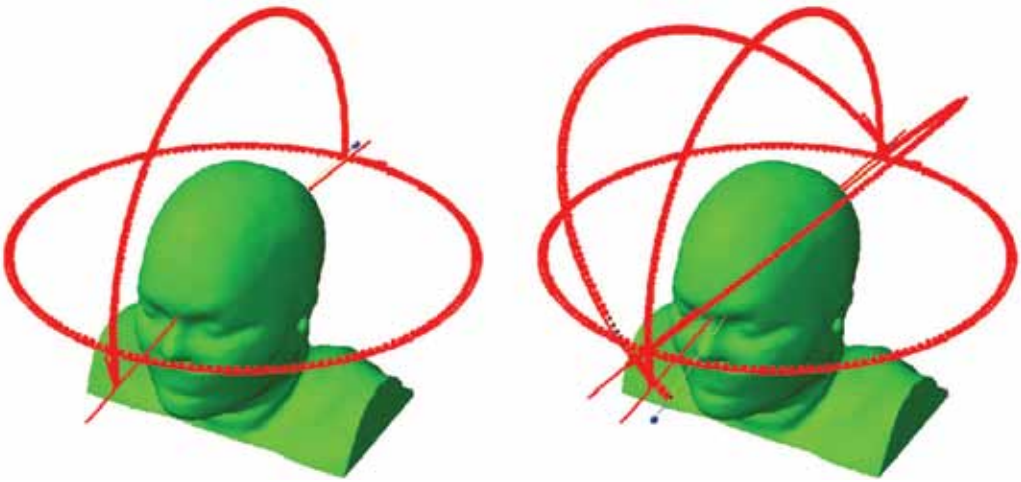

Figure 1. Two and four arc geometries.

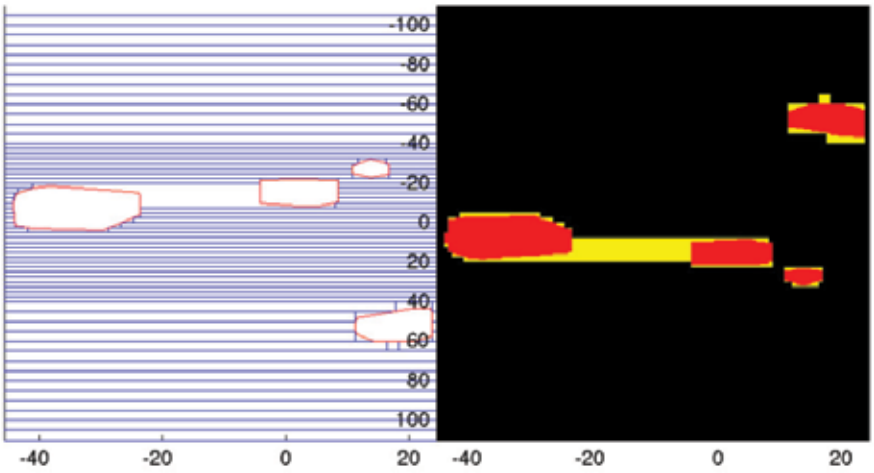

Figure 2. Conformal MLC aperture for four targets. The yellow area is the island area.

$$A_{mean}(\theta) = \frac{1}{N}\sum_{i=1}^{N} A(\varphi_i, \theta) \qquad (1)$$

where $A(\varphi,\theta)$ is the island area for gantry angle φ and collimator angle φ, j_i is the gantry angle of control point i, and N is the number of control points. The number of control points was determined by the optimizer such that the control point spacing was approximately 2 degrees. For each arc, A_{mean} was computed in one degree increments of collimator angle and the collimator angle that minimized A_{mean} selected. We hypothesized that minimizing the island blocking area would result in reduced dose spill into normal tissue. We compared plans that used the collimator angle having the minimal island area with plans using a 45-degree collimator angle.

Jaw tracking

Jaw tracking dynamically conforms the photon jaws to the MLC aperture during delivery to provide more shielding to normal tissues.[12] To investigate the effect of jaw tracking on low dose spill, plans were generated with and without the jaw tracking enabled. It was expected that irradiation to normal tissues would be decreased for the jaw tracking plans.

Low dose constraint

In addition to the dosimetric goals given in Clark et al.[6], we investigated further constraining low dose spill to normal tissue. We created a normal brain region-of-

interest by excluding the PTVs from the brain. A mean dose constraint of 2 Gy was used for the normal brain, with a priority weight of 100.

Analysis

To evaluate effects of multiple factors, i.e. the number of arcs, collimator angle selection, jaw tracking, and normal brain low dose constraint, a total of 16 (2^4, in which 4 represents the number of factors, and 2 represents the status for each factor) plans were generated for each case. We calculated several metrics of plan quality.

The conformity index, defined as the ratio of 100% of prescription isodose volume to the target volume[13], was calculated for each individual PTV. The gradient index, used to evaluate the dose fall-off from the edges of targets, and defined as the volume encompassed by the 50% isodose surface to the total prescription isodose volume[14], was calculated for each plan.

For reporting dose-volume metrics, we used the nomenclature described by Mayo et al[15]. We evaluated several measures of low dose spill: V10%[cc] and V25%[cc], the volumes of healthy brain receiving more than 10% and 25% of the prescribed dose, respectively, and the mean dose received by normal brain. Additionally, we report the volume of healthy brain receiving more than 12 Gy, V12Gy[cc], which has been shown to be a predicator of risk for brain necrosis in radiosurgery for AVMs.[16]

To evaluate the hypothesis that appropriate selection of collimator angle reduces the island area, we calculated the island area for each plan. To account for the dose-rate variations inherent to VMAT, we calculated the monitor unit weighted island area, given by

$$A_{Weighted} = \sum_{i=1}^{N} MU_i A_i \qquad (2)$$

where MU_i is the monitor unit setting for control point i and A_i is the island area exposed by control point i. As described above, A_i is calculated by calculating the area of the MLC aperture for control point I and subtracting the area of the PTVs, as projected into the beams-eye-view, that are exposed within the aperture.

RESULTS

The mean normal brain volume was 1269 cm^3 (range 1041 cm^3 to 1590 cm^3). Mean difference between the normal brain dose-volume histograms (DVHs) are shown in Figure 3. The plans were superior with collimator angle selected, jaw tracking, and low dose constrained.

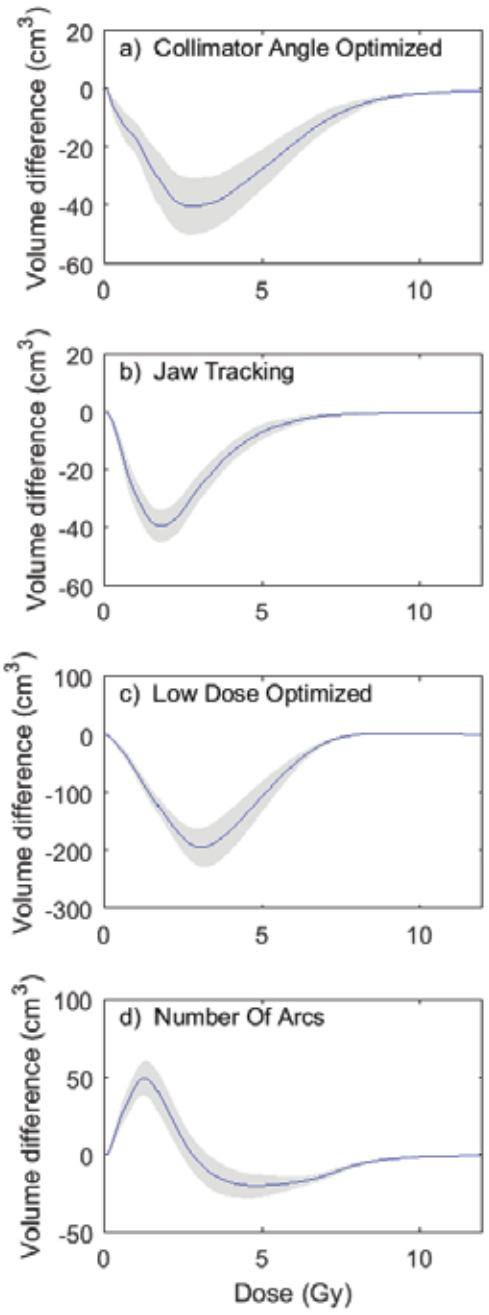

Figure 3. Mean difference between dose volume histograms for normal brain. Each curve (a-c) represents the difference between the DVH with and without collimator angle optimized, jaw tracking, and a low dose objective, and for (d) the difference between 4 arcs and 2 arcs. Negative numbers indicate that collimator angle optimization, jaw tracking, a low dose objective, or 4 arcs reduces the volume of normal brain at the given dose. The gray bands indicate the 95% confidence intervals.

The volume difference with collimator angle selected and with low dose constrained was largest around 3 Gy, whereas with jaw tracking the difference was largest slightly below 2 Gy. The demonstrated improvements of plans in the low dose range were not surprising, since selected collimator angle and jaw tracking were designed to provide more shielding to normal tissues by MLCs and jaws, respectively. It was also easily understandable that the plans with low dose constrained had better quality only in the low dose range since a mean dose objective of 2 Gy was put on normal brain tissues. The DVH difference between 4 arcs and 2 arcs resulted in slight improvement in the range 3 to 10 Gy, but at the expense of increased volume below 3 Gy.[7, 17]

To further illustrate the differences in the effect of the parameters on normal brain low dose volumes, the DVH difference for collimator angle selection, jaw tracking, and low dose constraint are plotted together in Figure 4. Figure 4 shows that the reduction in low dose volume achieved by jaw tracking or collimator angle selection is modest, whereas constraining the low dose spill during optimization results in more substantial improvement.

Scatter plots for the effects number of arcs, collimator angle selection, jaw tracking, and low dose constraint on normal brain V10%[cc], V25%[cc], V12Gy[cc], and mean dose are shown in Figures 5-8. Each point on a scatter plot corresponds to the value of the plan quality metric for two plans having different values of one plan parameter with all other parameters the same. If a given parameter has no effect on the specified endpoint, then all points will fall along a line with slope of 1. The further the points are from the line, the more effect the parameter has on the endpoint. It can be seen from Figures 5-8 that the largest effect on low dose volumes in the normal brain is the low dose constraint. The other parameters have a significantly smaller effect.

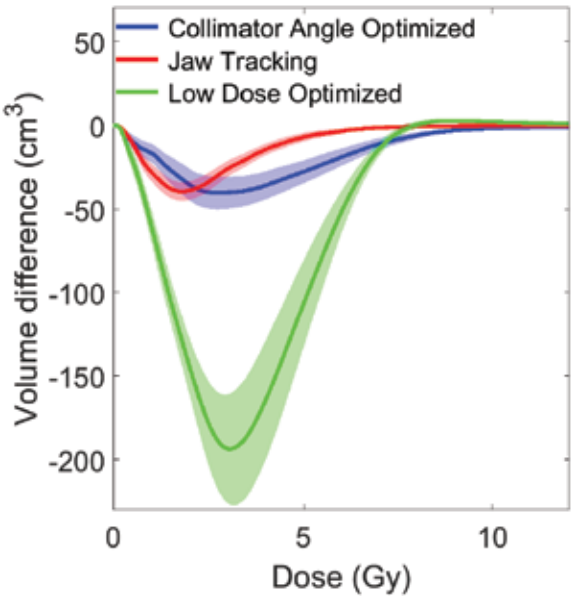

Figure 4. Mean difference between dose volume histograms for normal brain for each parameter. Negative numbers indicate that collimator angle optimization, jaw tracking, or a low dose objective reduces the volume of normal brain at the given dose. The bands indicate the 95% confidence intervals.

Normal brain V10%[cc], V25%[cc], V12Gy[cc] and mean dose are shown in Tables 2-5 for all 16 combinations of number of arcs, collimator angle selection, jaw tracking, and low dose constraint. Also tabulated are the median differences with the combination having the lowest mean value of V10%[cc], V25%[cc], V12Gy[cc] or mean dose, along with the p-value for a one-sided Wilcoxon signed rank test. Not surprisingly, for V10%[cc], V25%[cc], and mean dose the minimum value was obtained for plans having low dose constrained, jaw tracking, and collimator angle selected. Furthermore, for V10%[cc], V25%[cc], and mean dose the low dose constraint resulted in the lowest values independent of the values of the other parameters. A low dose constraint increased V12Gy[cc] by approximately 1 cc relative to the same combination of number of arcs, collimator angle selection, and jaw tracking.

Figure 9 shows paired comparison plotting for relative importance of number of arcs, collimator angle selected, jaw tracking, and low dose constrained on the monitor unit weighted island area. It was expected that plans with selected collimator angle would decrease the island area, and this was observed, as shown in Figure 9. However, it can also be seen that this reduction of island area can be achieved for only some of the cases, and that the reduction is small in comparison with to plans with a low dose constraint, for which reduction of island area was be achieved for a majority of the cases. Jaw tracking and number of arcs had no effect on island area, as would be expected.

Jaw tracking and low dose constraint are parameters of the optimization system selected by the planner and require no additional effort. Collimator angle selection, however, requires a separate calculation. For the subgroup of plans having jaw tracking and low dose constraint, the reduction benefit of collimator selection is minimal. The mean reduction in brain volume receiving more the 2.5 Gy, for example, was only 20 cm^3.

Finally, median conformity index and gradient index for plans with and without collimator angle selected, jaw tracking, low dose constrained, or with 4 arcs vs. 2 arcs are shown in Table 6. For each factor, the 16 plans per patient were divided into two groups of 8 and the mean values for the 10 patients were calculated for each group. Also calculated was the median difference between the two groups and the p-value for a two-sided Wilcoxon signed rank test.[17]

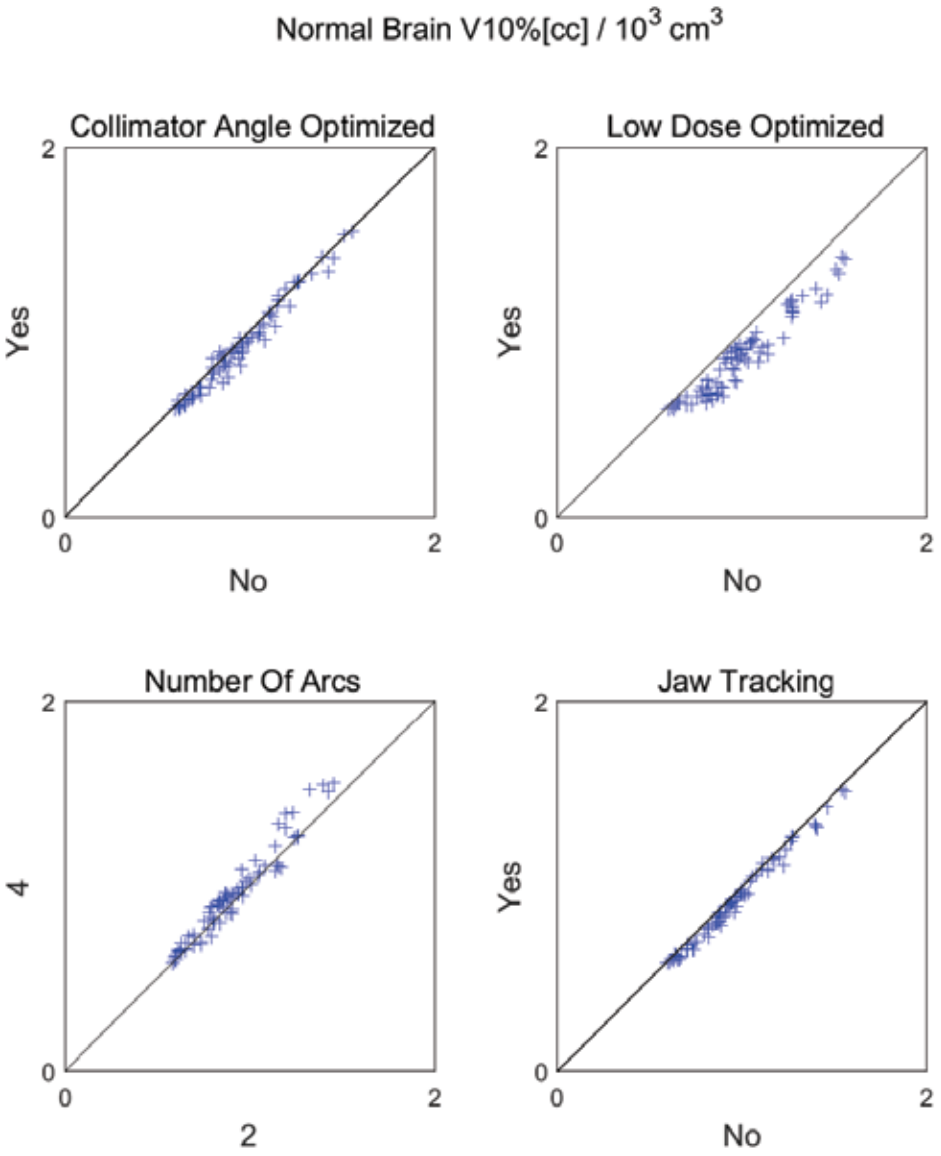

Figure 5. Scatter plots of normal brain V10%[cc] for each parameter. Each point represents the V10%[cc] for a pair of plans with different values of the planning parameter and all other planning parameters the same. Points falling on the line have the same V10%[cc] for both plans.

DISCUSSION

Number of arcs

Table 2 shows that the 2-arc configuration has the minimum value of V10%[cc], whereas Table 3 demonstrates that the 4-arc configuration has the minimum value of V25%[cc]. This effect is evident in Figure 4(d), which shows that the 4-arc plans irradiate more normal brain volume in the range 0 to 2.8 Gy, but irradiate less normal brain volume above 2.8 Gy. This redistribution of dose occurs because the additional arcs distribute the entrance dose over a larger volume, resulting in less volume at intermediate dose levels, but more at lower dose levels. The marginal improvement for plans with more arcs observed in our study also agrees with the findings of Clark et al and Thomas et al.[7, 17]

Collimator angle selection and Jaw tracking

In 2010, Kang et al.[9] reported the results of their investigation into the utility of couch and collimator angle optimization in mitigating the shared MLC leaf problem for multiple targets. They observed that optimizing couch and

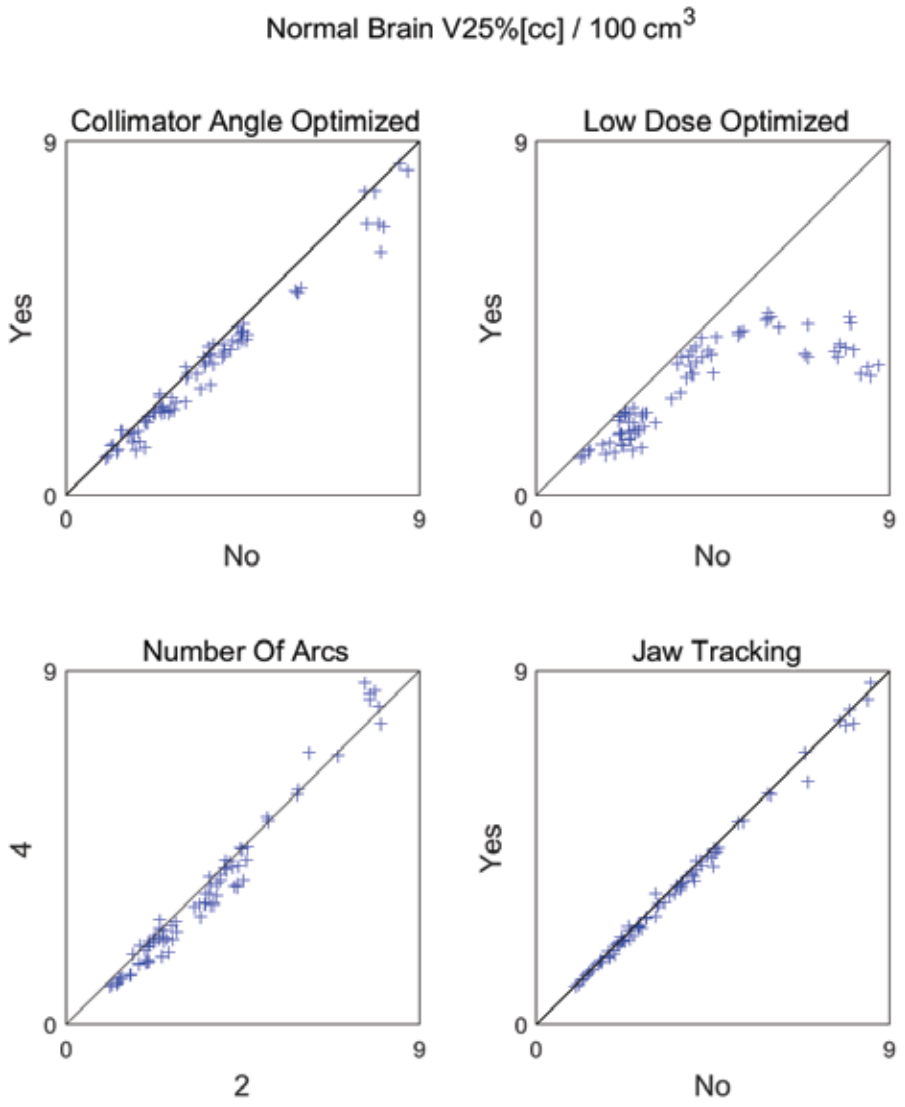

Figure 6. Scatter plots of normal brain V25%[cc] for each parameter. Each point represents the V25%[cc] for a pair of plans with different values of the planning parameter and all other planning parameters the same. Points falling on the line have the same V25%[cc] for both plans.

collimator angle reduced the V12Gy[cc] in each of the three cases they tested. Recently, Wu et al.[11] reported similar results, observing reduction in normal brain dose metrics over the entire dose-volume range. Our results also showed that collimator angle selection reduces V12Gy[cc], across a large array of cases independent of other factors.

For multiple-target irradiation, the collimator angle selection and jaw tracking play two distinct roles in normal tissue sparing. For optimal collimator angle selection, the island blocking area is minimized, thus the irradiation of normal tissue is minimized. For jaw tracking, the jaw size is optimized to fit the aperture, thus to reduce unnecessary irradiation to normal tissues. However, in essence, these two techniques have the same goals: to provide maximum shielding to normal tissues. The differences between them can be viewed from two aspects. First, the regions of the normal tissue sparing: for collimator selection, it is the region surrounded by multiple targets that are spared, and for jaw tracking, it is the region surrounding the multiple targets that is spared. Second, the means of normal tissue sparing: for collimator selection, the normal tissue is spared by MLC shielding, while for jaw tracking, it is spared by jaw shielding.

In current linear accelerator systems, the MLC direction is aligned with X jaws in the treatment head. However, optimal collimator selection is in nature the optimal MLC angle selection, and this angle does not necessarily provide the best jaw angle for the optimal aperture conformance. Therefore, it is

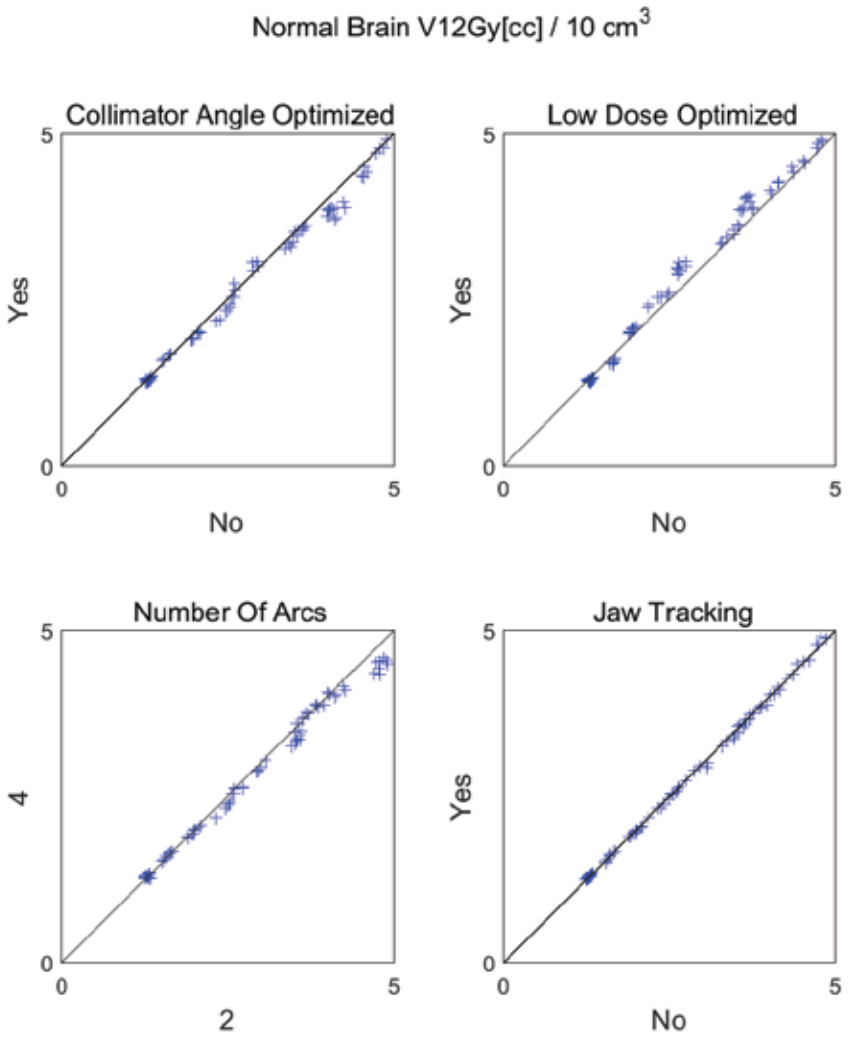

Figure 7. Scatter plots of normal brain V12Gy[cc] for each parameter. Each point represents the V12Gy[cc] for a pair of plans with different values of the planning parameter and all other planning parameters the same. Points falling on the line have the same V12Gy[cc] for both plans.

not feasible for current treatment head to achieve both multi-target inner and outer normal tissue sparing simultaneously. A separate MLC system and jaw system, i.e. the rotation of the MLC system is independent of the jaw system (collimator angle), would have more degrees of freedom and could potentially achieve simultaneous inner and outer normal tissue sparing for multi-target radiation therapy.

Collimator optimization during gantry rotation

In our work, one optimal collimator angle was obtained for each arc in the plan, and this collimator angle was fixed during the arc delivery. This collimator select may not be optimal at every gantry angle, since for multi-target, the BEVs vary with gantry rotation, and at each gantry angle, there is an optimal collimator angle. To obtain the best normal tissue sparing, the collimator angle should be optimal at each gantry position. The research on collimator optimization during gantry rotation is ongoing at our institution and will be tested on Varian TrueBeam/Edge machines in the future.

Low dose objective

The initial motivation of this work was to evaluate the effect of the optimal angle collimator on the low dose spill improvement for multi-target radiation therapy, based on the principle from Kang et al. that the island block area could be reduced by optimally selecting the collimator angle.[9] This low dose spill improvement was confirmed by the result shown in Figure 3a. Following this low dose spill improvement

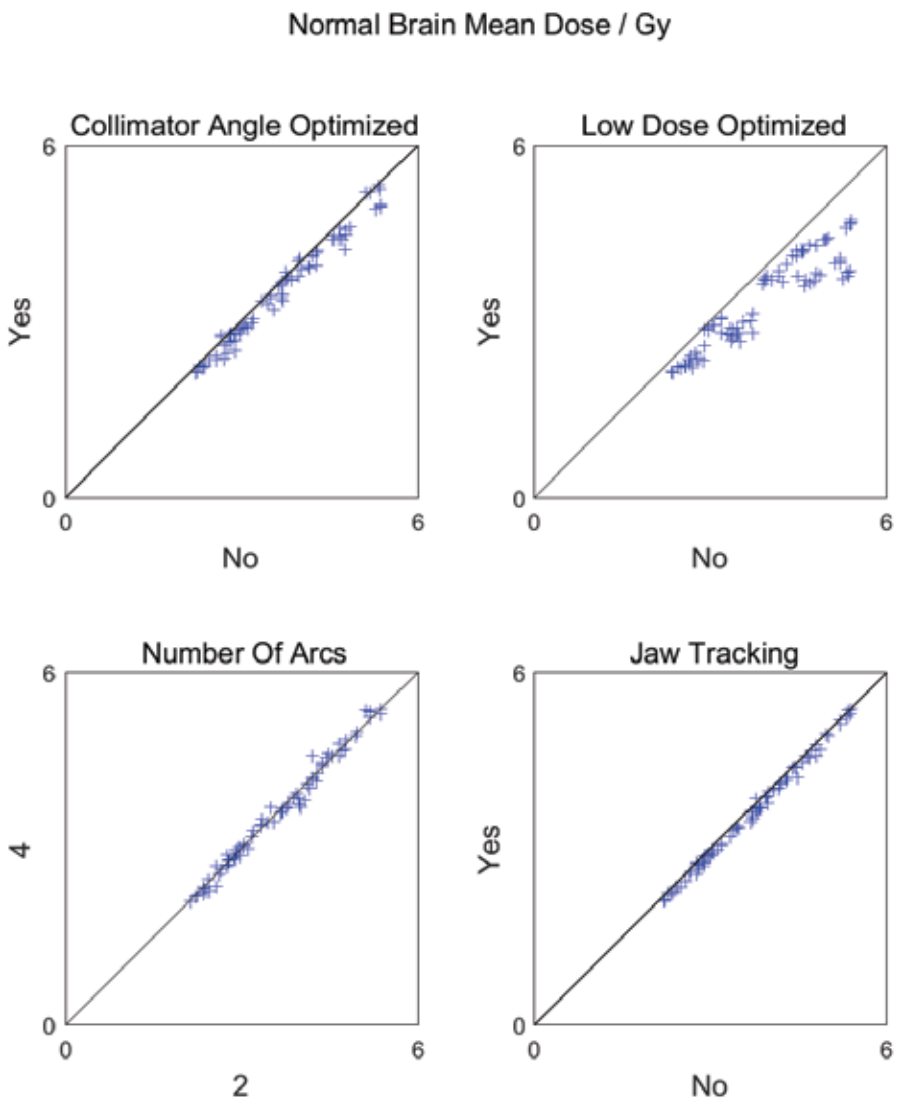

Figure 8. Scatter plots of normal brain mean dose for each parameter. Each point represents the mean dose for a pair of plans with different values of the planning parameter and all other planning parameters the same. Points falling on the line have the same mean dose for both plans.

by collimator angle selection, it was natural to consider putting low dose constraints on normal brain tissue. A mean low dose constraint instead of conventional maximum dose limit was added in order to reduce the overall dose in normal brain tissue, rather than only the maximum dose near the targets. Although we expected that the both collimator angle optimization and a low dose objective would improve the low dose spill, we were surprised to find that the reduction was substantially larger for plans with low mean dose optimized as compared to in plans with optimal angle collimator selection, as shown in Figure 3. It was shown in Figure 9 that the calculated MU weighted MLC island area reduction in plans with low dose optimized was substantially less than that in plans with collimator angle optimized, and this accounted for the low dose spill improvement. Therefore, the low dose spill improvement is in essence achieved by MLC island area reduction, which was the main objective of selecting the optimal angle collimator. However, incorporating a low dose spill constraint into the objective function does a better job of achieving this goal.

Including a low dose objective is more effective at reducing the low dose spill than indirect means of controlling the low dose spill through manipulation of plan geometry, such as collimator angle selection. However, the addition of a low dose spill objective resulted in a small degradation in the conformity index, as shown in Table 6. Similarly, there was a small increase in the

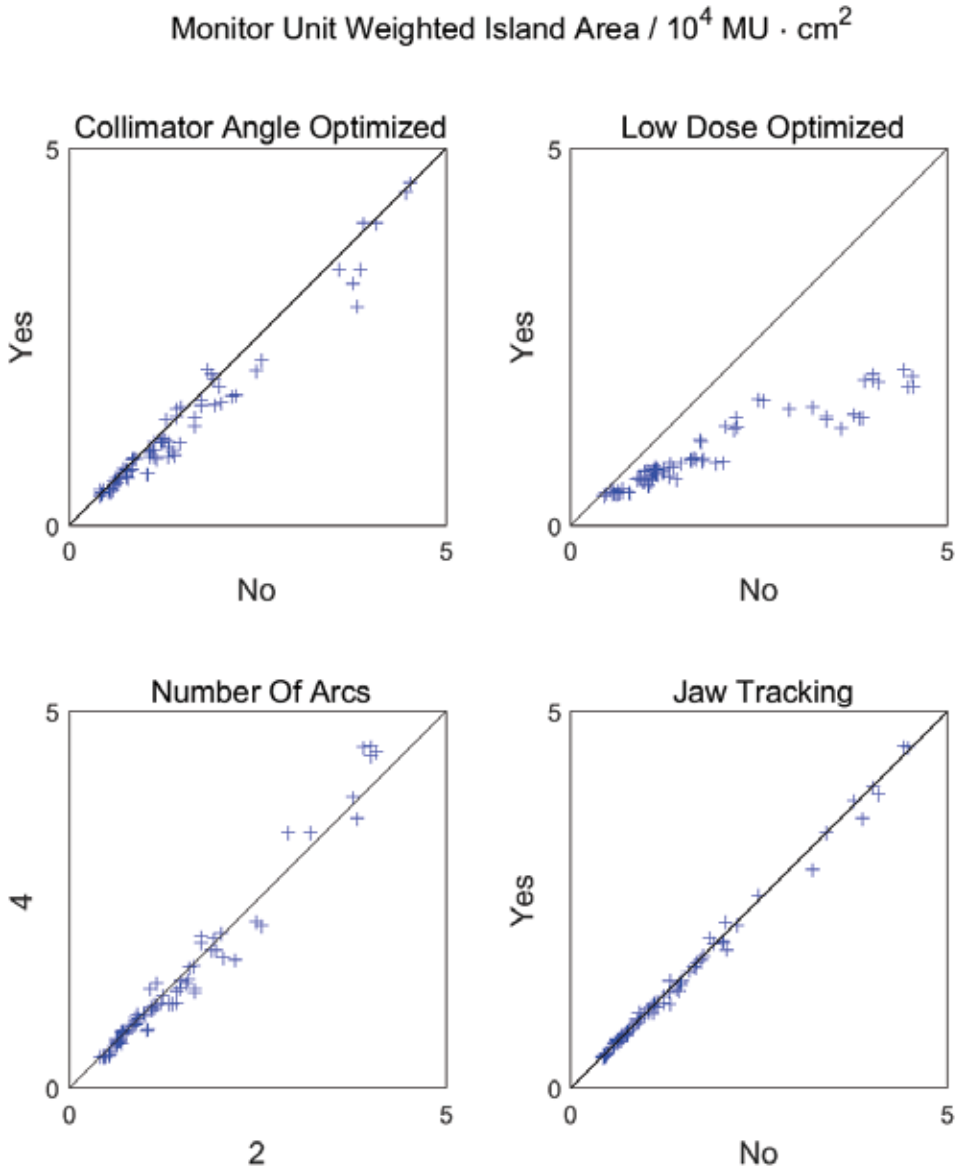

Figure 9. Scatter plots of monitor unit weighted island area (Equation 2) for each parameter. Each point represents the monitor unit weighted island area for a pair of plans with different values of the planning parameter and all other planning parameters the same. Points falling on the line have the same monitor unit weighted island area for both plans.

volume receiving more than 12 Gy. This suggests that improvement in low dose spill comes at the expense of a small increase of volume in the moderately high dose region. If necessary, adjusting the priority of the dose objective would control this trade-off depending on the clinical goals of the plan.

Clinical impact

We incorporated a low dose objective into our standard planning protocol in April 2014. Rather than a mean dose objective, our clinical implementation was that no more than 1% of the normal brain to receive greater than 1/6 of the prescription dose (priority = 125). This formulation was based on the observation of the typical location of the inflection point of the normal brain DVH and achieves similar results to those reported here. Before April 2014, the average mean brain dose was 18% of the prescription dose, with a standard deviation of 9%. After April 2014, the average mean brain dose decreased to 12%, with a standard deviation of 7%. As multiple randomized trials have now demonstrated that whole brain radiation therapy impairs cognitive function and QOL,

Table 2. Mean normal brain V10%[cc] for the ten cases planned using each combination of number of arcs, low dose constraint, jaw tracking, and collimator angle selection. The median difference with the combination having the smallest mean normal brain V10%[cc], the range of the differences, and the p-value for a one-sided Wilcoxon signed rank test are also shown.

Number of arcs	Low dose constraint	Jaw tracking	Collimator angle selected	Mean	Median difference	Range	p
2	+	+	+	828	0	-	-
2	+	+	-	840	12	-52 to 88	0.63
4	+	+	+	850	15	-56 to 118	0.38
2	+	-	+	857	34	1 to 49	0.00
4	+	+	-	868	39	-94 to 139	0.08
2	+	-	-	878	40	4 to 109	0.00
4	+	-	+	885	57	-35 to 205	0.05
4	+	-	-	913	91	-40 to 198	0.02
2	-	+	+	928	110	17 to 171	0.00
2	-	-	+	962	137	31 to 239	0.00
2	-	+	-	972	138	32 to 293	0.00
4	-	+	+	979	123	44 to 329	0.00
4	-	+	-	1009	169	52 to 319	0.00
4	-	-	+	1015	163	57 to 350	0.00
2	-	-	-	1016	188	69 to 347	0.00
4	-	-	-	1062	191	111 to 428	0.00

Table 3. Mean normal brain V25%[cc] for the ten cases planned using each combination of number of arcs, low dose constraint, jaw tracking, and collimator angle selection. The median difference with the combination having the smallest mean normal brain V25%[cc], the range of the differences, and the p-value for a one-sided Wilcoxon signed rank test are also shown.

Number of arcs	Low dose constraint	Jaw tracking	Collimator angle selected	Mean	Median difference	Range	p
4	+	+	+	244	0	-	-
4	+	-	+	252	5	2 to 19	0.00
4	+	+	-	258	11	-11 to 44	0.03
4	+	-	-	263	15	-6 to 66	0.01
2	+	+	+	279	30	0 to 76	0.00
2	+	-	+	283	37	-9 to 84	0.00
2	+	+	-	291	42	15 to 88	0.00
2	+	-	-	303	56	18 to 104	0.00
4	-	+	+	377	71	18 to 517	0.00
2	-	+	+	381	98	24 to 464	0.00
4	-	-	+	384	86	24 to 534	0.00
2	-	-	+	393	103	36 to 464	0.00
4	-	+	-	421	109	38 to 561	0.00
2	-	+	-	427	120	39 to 451	0.00
4	-	-	-	441	144	50 to 541	0.00
2	-	-	-	441	136	59 to 478	0.00

Table 4. Mean normal brain V12Gy[cc] for the ten cases planned using each combination of number of arcs, low dose constraint, jaw tracking, and collimator angle selection. The median difference with the combination having the smallest mean normal brain V12Gy[cc], the range of the differences, and the p-value for a one-sided Wilcoxon signed rank test are also shown.

Number of arcs	Low dose constraint	Jaw tracking	Collimator angle selected	Mean	Median difference	Range	p
4	-	+	+	26.1	0.0	-	-
4	-	-	+	26.1	0.0	-0.1 to 0.3	0.85
2	-	-	+	26.8	0.0	-0.6 to 3.7	0.43
4	-	+	-	26.8	0.6	-0.3 to 2.8	0.06
2	-	+	+	26.9	0.0	-0.2 to 4.5	0.49
4	-	-	-	27.0	0.8	-0.3 to 2.5	0.06
4	+	+	+	27.1	1.1	-0.8 to 2.9	0.04
4	+	-	+	27.3	1.1	-0.8 to 4.1	0.04
2	-	-	-	27.5	0.7	-0.8 to 3.9	0.05
2	-	+	-	27.5	0.6	-0.5 to 4.6	0.06
2	+	+	+	27.8	1.8	-1.2 to 5.6	0.05
4	+	+	-	27.8	1.9	-1.5 to 4.5	0.04
2	+	-	+	28.0	2.3	-1.1 to 4.4	0.04
4	+	-	-	28.0	2.3	-1.4 to 4.7	0.03
2	+	+	-	28.5	3.3	-1.7 to 5.5	0.04
2	+	-	-	28.6	3.4	-1.5 to 5.1	0.02

Table 5. Mean of the normal brain mean dose for the ten cases planned using each combination of number of arcs, low dose constraint, jaw tracking, and collimator angle selection. The median difference with the combination having the smallest mean of the normal brain mean dose, the range of the differences, and the p-value for a one-sided Wilcoxon signed rank test are also shown.

Number of arcs	Low dose constraint	Jaw tracking	Collimator angle selected	Mean	Median difference	Range	p
4	+	+	+	3.23	0.00	-	-
2	+	+	+	3.29	0.03	-0.00 to 0.30	0.00
4	+	-	+	3.30	0.07	0.04 to 0.12	0.00
4	+	+	-	3.30	0.08	-0.08 to 0.20	0.01
2	+	-	+	3.35	0.11	-0.00 to 0.36	0.00
2	+	+	-	3.37	0.13	-0.07 to 0.28	0.00
4	+	-	-	3.40	0.18	0.05 to 0.28	0.00
2	+	-	-	3.48	0.26	0.07 to 0.34	0.00
2	-	+	+	3.72	0.39	0.05 to 1.49	0.00
4	-	+	+	3.78	0.43	0.12 to 1.54	0.00
2	-	-	+	3.80	0.48	0.11 to 1.49	0.00
4	-	-	+	3.85	0.53	0.17 to 1.61	0.00
2	-	+	-	3.93	0.57	0.18 to 1.41	0.00
4	-	+	-	3.95	0.63	0.22 to 1.66	0.00
2	-	-	-	4.05	0.71	0.33 to 1.48	0.00
4	-	-	-	4.09	0.83	0.34 to 1.63	0.00

Table 6. Median conformity index and gradient index. For each factor number of arcs, low dose constraint, jaw tracking, or collimator angle selection, all combinations of the remaining factors are included, resulting in comparison of two groups of 80 plans. The median difference and the p-value for a two-sided Wilcoxon signed rank test are also shown

		Conformity index	Gradient index
Number of arcs	2	1.20	3.95
	4	1.18	3.88
	Median difference	-0.01	-0.08
	p	0.00	0.00
Collimator angle selected	No	1.20	3.92
	Yes	1.19	3.92
	Median difference	0.00	-0.10
	p	0.02	0.00
Jaw tracking	No	1.19	3.93
	Yes	1.19	3.91
	Median difference	0.00	-0.02
	p	0.02	0.00
Low dose constrained	No	1.15	3.85
	Yes	1.24	3.94
	Median difference	0.09	-0.08
	p	0.00	0.00

patients with larger numbers of metastases will elect radiosurgery alone rather than whole brain RT. As some of these patients will require multiple course of radiosurgery, it will be clinically important to minimize the whole brain dose with each course of radiosurgery.

Better planning or better technique?

It was found from our work that the improvement of plan quality by collimator selection and jaw tracking was modest when compared to the improvement by adding an additional mean dose constraint for the healthy brain. Are collimator selection and jaw tracking worth the effort? Regarding this issue, we have two perspectives that can be complementary to each other. First, it is important to make full use of the planning optimizer to achieve maximal quality plans. It is important to explicitly include planning goals in the objective function, rather than rely on geometry or other planning technique to achieve an implicit goal not incorporated into the objective function. Second, even though the improvement was modest for jaw tracking and collimator angle selection, new techniques and careful geometry selection can still improve the plan quality. The approach of Wu et al.[11] demonstrates the feasibility of efficiently incorporating automated geometry selection using scripting of the treatment planning system. Because scripts are portable, automated geometry selection tools can be rapidly disseminated.

CONCLUSIONS

To reduce low dose spill into normal brain for single isocenter VMAT radiosurgery of multiple targets, it is important to incorporate a limit on low dose spill into the objective function. Jaw tracking and collimator selection further reduce the low dose spill, but to a much lesser extent. Ideally, all three strategies would be employed to reduce the low dose spill; however, selecting the collimator angle requires the most effort by the planner in return for the least reduction. A low dose spill objective and jaw tracking are options easily configured in the planning software, whereas selection of the collimator angle requires software tools not currently available in treatment planning systems, although work is purportedly underway by vendors that may make this feature natively available and integrated into treatment planning systems.

This study has implications beyond single-isocenter VMAT radiosurgery. When comparing different inverse-planned treatment techniques, metrics that are important for evaluation of plan quality must be included the objective function.

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Author contributions
Conception and design: Grant A. Clark, John B. Fiveash, Richard A. Popple
Data collection: Grant A. Clark, Yu Yuan
Data analysis and interpretation: Richard A. Popple, Evan M. Thomas, Yu Yuan
Manuscript writing: Richard A. Popple, Yu Yuan
Final approval of manuscript: Grant A. Clark, John B. Fiveash, James M. Markert, Richard A. Popple, Evan M. Thomas, Yu Yuan

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