Received:
26 January 2016

Revised:
15 March 2016

Accepted:
12 April 2016

<http://dx.doi.org/10.1259/bjr.20160093>

Cite this article as:

Ruschin M, Sahgal A, Iradji S, Soliman H, Leavens C, Lee Y. Investigation of two linear accelerator head designs for treating brain metastases with hypofractionated volumetric-modulated arc radiotherapy. *Br J Radiol* 2016; **89**: 20160093.

FULL PAPER

Investigation of two linear accelerator head designs for treating brain metastases with hypofractionated volumetric-modulated arc radiotherapy

^{1,2}MARK RUSCHIN, PhD, ^{2,3}ARJUN SAHGAL, MD, ¹SARA IRADJI, MSc, ^{2,3}HANY SOLIMAN, MD, ¹CLAUDIA LEAVENS, PhD and ^{1,2}YOUNG LEE, PhD

¹Department of Medical Physics, Sunnybrook Odette Cancer Centre, Toronto, ON, Canada

²Department of Radiation Oncology, University of Toronto, Toronto, ON, Canada

³Department of Radiation Oncology, Sunnybrook Odette Cancer Centre, Toronto, ON, Canada

Address correspondence to: Dr Mark Ruschin

E-mail: Mark.Ruschin@sunnybrook.ca

Objective: To investigate brain radiation dose in complex cases arising from two stereotactic linear accelerator designs and to present a method for comparing brain dose to published data.

Methods: Two head designs were considered: Beam Modulator (BM) and Agility (AG). 12 patients treated on BM were replanned with AG. Planning objectives were: minimize brain dose and satisfy target coverage and organs at risk dose constraints. Each of the 36 targets was analyzed for conformance index (CI Paddick), gradient index (GI) and homogeneity index (HI). Total volume of tissue receiving 80% (V80) of the prescription dose down to 25% (V25) was evaluated. Similarly the volume of brain minus planning target volume receiving 80% (BMP80) down to 25% (BMP25) was evaluated. The mean brain dose and BMP dose were also evaluated. System differences were statistically evaluated using Wilcoxon signed-rank test. Power-law models for total volume (V) and brain minus planning target volumes (BMP) were generated based on BM data.

Results: The median CI Paddick was 0.74 and 0.76 for BM and AG, respectively ($p = 0.04$). The median GI was 5.5 and 6.1 ($p < 0.01$) and the median HI was 1.17 and 1.16 for BM and AG, respectively ($p < 0.01$). Neither V or BMP receiving doses of 80% down to 40% exhibited statistically significant difference between the two systems, whereas the volume of brain minus PTV receiving 25% (BMP25) was weakly different ($p = 0.02$). AG exhibited a lower mean BMP dose (4.1 Gy) than BM (4.6 Gy) ($p < 0.01$). Power-law models for V/BMP showed excellent ($R^2 > 0.80$) agreement for the dose levels studied and comparable results with published data.

Conclusion: Treatment plans of equivalent quality were attained with AG compared with BM.

Advances in knowledge: The AG system involves a novel collimation design. The present article demonstrates equivalent or improved brain dose for complex, multi-target cases using AG vs an older stereotactic system.

INTRODUCTION

The use of intensity-modulated radiotherapy or volumetric-modulated arc radiotherapy (VMAT) using multileaf collimators (MLCs) for stereotactic radiosurgery and radiotherapy is becoming increasingly popular, as this technique affords efficient delivery with a high degree of target conformity.^{1–3} In particular, for multiple targets, the use of VMAT has been implicated in yielding shorter treatment times while providing comparable plan quality to intensity-modulated radiotherapy and three-dimensional conformal treatments.¹ Initial experiences with VMAT were with multi-isocentre plans,^{4,5} followed by a series of studies investigating the feasibility of a single-isocentre approach.^{2,6}

Unlike for single-fraction stereotactic radiosurgery, there is limited evidence for optimal prescription and normal tissue

tolerances for hypofractionated stereotactic radiotherapy (HF-SRT). HF-SRT uses 3–5 fractions to mitigate radiation-induced harm to the normal tissue, in particular for large or recurrent disease, while delivering a clinically effective dose to the target. Therefore, evaluation and evidence-based implementation of emerging technology that can minimize normal tissue dose is warranted.

The recently developed Elekta Agility™ (AG; Elekta AB, Stockholm, Sweden) 160-leaf system⁷ has been proposed for treating multiple brain metastases with radiosurgery.⁶ The AG system was designed to minimize interleaf leakage as well as provide full-jaw shielding perpendicular to the MLC motion. A dynamic leaf guide capable of producing leaf speeds up to 6.5 cm s^{-1} was also added. In the present work, we hypothesized that the AG system could lead to

lower integral dose to the healthy brain tissue than an older system with 4-mm leaves called the Beam Modulator (BM)⁸ owing to the AG's decreased leakage, increased leaf speed and perpendicular diaphragm. As the number of patients being treated with multiple brain metastases is increasing,⁹ including the number of retreatments, increasing evidence is needed to support new technologies such as AG in order to minimize brain dose. The focus of the present article was on cases involving multiple brain metastases that were considered challenging to plan.

METHODS AND MATERIALS

Two linear accelerator head models were considered in the present study. BM was the Elekta Synergy® model "S" linear accelerator (Elekta AB, Stockholm, Sweden) equipped with the BM treatment head. The BM MLC consists of 40 leaf pairs, each 4-mm wide, projected at the isocentre.⁸ AG was the Elekta AG (Elekta AB, Stockholm, Sweden) beam model: 80 leaf pairs, each 5-mm wide, projected at the isocentre and full jaws perpendicular to the MLC.⁷ The AG system involved a complete redesign of the treatment head and MLC system, in order to minimize radiation leakage, as detailed in the study by Thompson *et al.*⁷ The leakage is minimized by reducing the interleaf gap to 90 µm and defocusing the gap from the source, thereby avoiding direct beam radiation through the leaf tip. A brief overview of some of the major differences between BM and AG is given in Table 1, including how the various differences may contribute to a lower normal brain dose. Apart from add-on devices such as the Apex system (Elekta AB),¹⁰ the AG system has replaced the BM as the primary stereotactic radiosurgery MLC-based system sold by the vendor.

12 patient cases were included in the present study, each treated with HF-SRT using 5 fractions with target characteristics summarized in Table 2. 10 of the 12 cases involved multiple targets and were deemed highly challenging by expert planners and physicists (MR, YL) with over 5 years' experience in SRS planning. Two cases (Cases 10 and 12) involving a single target were chosen to ensure that the findings were not unique to challenging cases only. All patients were initially planned and treated using the BM system. All patients were immobilized using a thermoplastic mask (Orfit Industries, Wijnegem, Belgium) on a six-degree-of-freedom treatment couch (Hexapod™; Elekta

AB, Stockholm, Sweden). Setup accuracy was confirmed using online cone-beam CT, which undergoes daily quality assurance (QA) for kilovoltage/megavoltage isocentre calibration.

Each case was replanned using the AG system. All treatment planning (original and replanned) was performed using the Pinnacle³ treatment planning system (TPS) v. 9.2 (Philips Healthcare, Andover, MA) with the SmartArc option. The specifics of our dose calculation and QA process follows the approach taken by Ruschin *et al.*¹¹ Treatment planning for multiple targets consisted of placing isocentres such that the maximum off-axis distance of any leaf would be <5 cm, thereby limiting the susceptibility of plan deliverability to rotational setup errors, leaf speed accuracy and off-axis small-field beam modelling.^{1,12} The arc configurations used for a total of 28 arcs are shown in Table 2. Pre-treatment verification measurements were conducted for all cases using the ArcCHECK® cylindrical diode array (Sun Nuclear Corporation, Melbourne, FL) using the system's gamma analysis with a 3% per 2-mm global limit. The default low-dose threshold is set at 10% but can be increased to 15% for a given case to limit diodes to the clinically relevant region. In the present article, the same low-dose threshold per case was used for AG and BM. Treatment planning for a given case can take up to 7 or 8 h for complex cases. Total treatment time is around 10–15 min per isocentre with 1–2 min of beam-on time and the remaining time is devoted to patient setup and cone-beam CT-based image verification. For each plan, the arc segments generated by the TPS were qualitatively assessed by looking at each segment's beam's eye view to detect if any unwanted gaps appeared over the normal tissue.

The gross tumour volume (GTV) and organs at risk (OARs) consisting of the brainstem, globes, lens, optic nerves and chiasm were contoured on the axial volumetric T₁ post-gadolinium MRI scan fused to the treatment planning CT. No additional expansion to the GTV was made to define a clinical target volume (CTV), *i.e.* CTV = GTV. A planning target volume (PTV) margin of 2 mm was then applied around each CTV. The brain was contoured on CT and a "normal brain" contour was generated as the brain contour excluding all PTVs and the brainstem. We refer to normal brain as brain minus planning target volume (BMP) in the current article. The mean dose to the brain and BMP was evaluated for all patients, as well as the

Table 1. Summary of relevant machine specifications for the Beam Modulator (BM)⁸ and Agility (AG)⁷ systems

Parameter	BM system ⁸	AG system ⁷	Potential for lower brain dose
Leaf thickness	4 mm	5 mm	No
Field of view	21 × 16 cm	40 × 40 cm	No
Maximum interleaf leakage	1.7%	0.44%	Yes
Average transmission	0.6–0.8%	0.35%	Yes
Jaws	None	Perpendicular to MLC	Yes (shield out leaf gaps)
Maximum leaf speed	2 cm s ⁻¹	6.5 cm s ⁻¹	Yes (leaves can cover gaps more efficiently)
Penumbra (80–20%)	4.2–4.8 mm	3.7–4.8 mm	No

MLC, multileaf collimator.
Parameters are for 6-MV beams.

Table 2. Summary of relevant plan details

Case number	Number of targets	Prescribed dose	Volumes (cm ³)	Prescription as % of max	Arc configuration
1	3	30 Gy each	4.3, 3.9, 3.5	87, 87, 87	1 iso; 1 arc
2	4	25 Gy each	1.0, 2.9, 1.4, 1.8	84, 83, 84, 84	1 iso; 1 arc
3	4	27.5 Gy to 3 targets; 25 Gy to 1 target	56.8, 15.6, 3.6, 3.7	87, 88, 88, 87	Iso 1: 1 arc; iso 2: 3 partial arcs; iso 3: 1 arc
4	3	30 Gy each	1.8, 4.2, 11.1	89, 88, 85	Iso 1: 1 arc; iso 2: 2 partial arcs
5	5	25 Gy each	2.2, 5.6, 2.0, 3.2, 3.3	84, 72, 78, 73, 73	Iso 1: 1 arc; iso 2: 1 full, 1 partial
6	6	20 Gy to 3 targets; 15 Gy to 3 targets	8.0, 0.7, 1.5, 2.1, 14.3, 17.2	97, 97, 86, 79, 73, 78	Iso1: 1 arc; iso 2: 1 arc; iso 3: 1 arc; iso 4: 1 arc
7	2	30 Gy each	5.7, 5.0	84, 84	1 iso; 1 arc
8	3	30 Gy each	1.2, 4.6, 2.9	87, 86, 86	3 iso; 1 full arc each
9	5	25 Gy each	2.9, 5.9, 5.7, 4.6, 4.2	81, 84, 81, 87, 90	Iso 1: 1 full; 1 partial; iso 2: 1 arc
10	1	30 Gy	4.9	86	1 iso; 1 arc
11	2	30 Gy each	12.7, 2.6	86, 92	Iso 1: 1 arc; iso 2: 1 arc
12	1	30 Gy	7.0	93	1 iso; 1 arc
Total	39 ^a	–	–	–	28 arcs

Iso, isocentre; Max, maximum.

^aThere were 39 targets planned; 36 targets were included in statistical analysis.

total volume and BMP receiving 80%, 70%, 60%, 50%, 40% and 25% of the prescription dose.

The planning objectives were to minimize normal brain dose while maintaining target coverage and conformality and respecting the OAR dose limits. Treatment plans were normalized for target coverage, with the aim to have the volume of each PTV receiving 100% of the prescription dose (V100) to be >98%. Importantly, attempts were made both clinically and in replanning to constrain the maximum dose within the PTV to be <130% of the prescription dose. Target homogeneity was measured using the homogeneity index, defined as the ratio of the maximum dose in the PTV to the prescription dose. Conformality is given by the Paddick¹³-defined conformality index (CI). The gradient index (GI) for the present study was defined by first identifying the isodose line covering at least 98% of each target (D98). The GI was calculated as the ratio of the volume of tissue receiving 50% of D98 to the volume receiving D98. This method of calculating GI is suggested to be more accurate, since it explicitly accounts for which isodose line is covering the target.¹⁴

Statistical significance of differences in all metrics between the systems was determined using a two-sided Wilcoxon signed-rank test. Of the original 39 targets planned, 3 targets were excluded from statistical analysis, since the plan normalization resulted in a V100 difference of >20% between the AG and BM systems. To facilitate comparison between BM and AG and to other studies in the literature, a model for tissue and normal tissue volume receiving specified isodoses was made based on the clinical BM data as a function of total PTV volume.

According to Ruschin et al,¹¹ a power-law fit was made to the data. The 95% prediction band was generated around each fit to establish a range of expected outputs for any given PTV volume made from the given set of cases. We first took the natural logarithm of PTV volume and total volume/BMP data and performed linear regression analysis on the results to obtain logarithmic versions of best fit and prediction bands. We then

Figure 1. Planning target volume (PTV) parameters for 36 targets analyzed: (a) volume of each PTV receiving 100% of the prescription dose (V100); (b) homogeneity index (HI); (c) conformality index (CI) Paddick; and (d) gradient index (GI). AG, Agility; BM, Beam Modulator.

inverted the natural logarithm operation to obtain the prediction bands for the original unlogarithmic data.

RESULTS

All plans generated for AG met the clinical OAR and target objectives and were delivered to the ArcCHECK diode array with equivalent pass rates to the BM system at the 3% per 2-mm level using either local or global gamma analysis. For the 36 cases analyzed, the V100 measured on AG was greater than or within 1% of the corresponding BM plan. As seen in [Figure 1a](#), the 95% confidence interval (notches) overlap, indicating that the difference in median values was not statistically significant ($p = 0.21$). The median homogeneity index was lower for the AG plans by 1% (1.17 vs 1.16) and although the confidence intervals overlapped ([Figure 1b](#)), the Wilcoxon signed-rank test indicated a difference of statistical significance ($p < 0.01$). The AG plans trended towards higher median conformity index Paddick values than BM plans (0.76 vs 0.74, $p = 0.04$) ([Figure 1c](#)). The GI ([Figure 1d](#)) was on an average 0.6 higher in the AG plans ($p < 0.01$). The exclusion of the two single-target cases did not affect the statistical significance reached in any of the target metrics. The OAR doses were on an average minimally

higher (<60 cGy on average, maximum difference on any OAR was 260 cGy) for BM than for AG, but none of the differences were statistically significant, and all plans satisfied clinical objectives.

Qualitatively, subtle differences were observed in dose distributions between the BM and AG plans. A representative sagittal slice of a distribution is shown in [Figure 2a,b](#) for a five-target case (Case 5, [Table 2](#)). For 7/12 cases (Cases 1, 2, 4, 5 and 7–9), the volume of BMP receiving higher dose was greater for AG plans, while the volume receiving lower dose was lower for AG plans. The exact percent prescription dose for which the BMP dose–volume histogram (DVH) of the AG dropped below the BM plan for the seven cases was: 35%, 24%, 36%, 41%, 23%, 30% and 50%, respectively. An example is shown in [Figure 2c](#) (Case 5).

The data for volume of each PTV receiving 60% of the prescription dose (V60), volume of each PTV receiving 50% of the prescription dose, volume of each PTV receiving 25% of the prescription dose, BMP receiving 60% of the prescription dose, BMP receiving 50% of the prescription dose and BMP receiving 25% of the prescription dose (BMP25) are plotted against the total PTV, as shown in [Figure 3a–f](#). There was no statistically significant difference between AG and BM for all comparisons, except for BMP25 ($p = 0.02$). The two single-target cases follow the same trend as the multitarget cases with respect to the volumes of tissue and BMP receiving specific doses. Exclusion of the two single-target cases did not affect the statistical significance reached for any dose fall-off metric, although it was observed that the AG plans yielded lower volumes of BMP at every point along the DVH curve. The mean dose to the brain and mean dose to BMP are also shown in [Figure 3g,h](#); the mean dose was lower in all 12 cases for the AG plans than for the BM plans, with a median reduction of 0.5 Gy ($p < 0.01$).

The coefficients of the best-fit power curve based on the BM data are shown on [Figure 3a–f](#) together with the R^2 value, which was lowest for BMP25 ($R^2 = 0.80$) but can still be considered as an excellent fit to the data. As seen in [Figure 3](#), all the AG data except one case (V60 and BMP receiving 60% of the prescription dose for Case 2) fall within the 95% prediction band generated by the BM data, indicating that the model encompasses both systems well. The equations and prediction band in [Figure 3](#) can then be used to compare the present study to similar published studies in the literature.

The arc segments were generally conformal to the targets, but two qualitative limitations were observed ([Figure 4](#)): (1) unwanted gaps appeared in between targets exposing the normal tissue; (2) the perpendicular jaws of the AG remained open to the largest extent to cover all targets for the entire arc span. The first limitation occurred in both BM and AG; during planning, attempts were made to minimize gaps *via* utilizing different collimation rotations but with limited success.

DISCUSSION

The AG system was a novel design by the vendor for enhancing radiation delivery and, as indicated in [Table 1](#), potentially reducing dose to the healthy tissue. The results of the present study

Figure 2. Example of sagittal dose distribution for Case 5. (a) Beam Modulator (BM) plan, (b) Agility (AG) plan and (c) dose–volume histogram (DVH) of both plans. Three of the five targets are displayed; the other two targets are on different slices. The isodose lines shown are the prescription dose (innermost), 80%, 50% and 25% (outermost) respectively. The middle target was proximal to the brainstem and not fully covered by the prescription isodose to respect organ at risk tolerance. (c) DVH showing two planning target volumes (PTVs) (for ease of reading figure) and BMP for BM (solid) and AG plan (dashed). The DVH for the BMP is higher for the AG plan down to 10.2 Gy below which the BM DVH is higher. cGy, centigray; norm, normal.

indicated that within the Pinnacle TPS, AG produced treatment plans of equivalent quality to BM for treating 1–6 targets with a modest reduction in the mean dose to the normal brain.

Dose spillage outside of the targets, assessed using dose to the tissue and BMP, has been an area of active research in the last few years, with competing technologies being investigated for potential dosimetric advantages.^{15–17} Although the selected cases in the present article were challenging by design, as shown in Table 3, we found reasonable agreement with other published data reported on radiation therapy delivery to multiple targets.^{1,2,15,16,18} As seen in Table 3, the literature results generally fell within or very close to the 95% prediction band based on the model presented in Figure 3. Of particular note were the results by Ma et al¹⁵ and McDonald et al,¹⁶ which indicated for specific cases a volume of normal brain receiving 60% and 50% of the prescription dose higher than the upper limit of our model's 95% prediction band. In the case of Ma et al,¹⁵ 12 targets

were planned, which is consistent with a higher normal tissue dose, given the complexity of the case. It should be noted that our clinical practice for hypofractionated brain radiotherapy tends to limit the maximum dose allowed within the target to <130% and is frequently (26 out of 36 cases analyzed here) <120%. In the aforementioned SRS literature, the maximum dose permitted within the targets often extends to 160% (or higher) of the prescription dose. The discrepancy in the prescription practice may partially explain the differences between the present article and published data. Hypofractionated cases involve larger targets than those treated with SRS, and since we use a 2-mm PTV margin to account for the interfraction setup variability, the hotspots are constrained owing to concern over radiation-induced brain necrosis within the margin.

Although the results of the present study indicate that mean brain and BMP doses were lower with AG, caution must be taken in the interpretation. The DVH curves for the BMP were

Figure 3. Total tissue volume and brain minus planning target volume (BMP) receiving 60%, 50% and 25% of the prescription dose plotted as a function of total planning target volume (PTV) (a–f). Best-fit curves based on Beam Modulator (BM) data are shown as solid lines together with their coefficients and R^2 values. The 95% prediction band around each fit is shown as a dashed line. (g, h) Mean dose to the brain and mean dose to BMP for all 12 cases. AG, Agility; cm³, cubic centimetre; Gy, gray; V25, volume of each PTV receiving 25% of the prescription dose; V50, volume of each PTV receiving 50% of the prescription dose; V60, volume of each PTV receiving 60% of the prescription dose.

Figure 4. Example of arc segments exhibiting treatment planning system limitations in beam's eye view (BEV). Solid arrows indicate regions where perpendicular jaws (in this case X2) of the Agility system do not close in to shield open segments over normal tissue. Dashed arrows indicate where unnecessary large/long leaf gaps occur over normal (non-target) tissue for multiple segments. CP, control point.

often higher with the BM system in the low-dose region (<50% of the prescription dose) and similar in the high-dose region. The fact that the AG system has lower interleaf and intraleaf transmission and perpendicular jaws (Table 1) could translate to an overall lowering of the normal tissue dose across the entire field.⁷ On the other hand, a slight reduction in volume receiving high doses may be possible with the BM owing to its finer MLC width, which may confer a dose-sculpting advantage around and in between targets. MLC width was investigated by Serna *et al*,¹⁹ who found that a 2.5-mm leaf thickness yielded a somewhat improved GI compared with a 5.0-mm leaf thickness around targets <10cm³.

Another factor that may affect BMP dose distribution is beam arrangement. Huang *et al*¹⁸ investigated dynamic conformal arcs *vs* single-isocentre, multiple-arc VMAT and found that VMAT yielded lower intermediate-to-high doses and higher lower isodoses. Although it is outside the scope of the present study to conclude what technical factors influence most the normal brain dose, the results of Ma *et al*¹⁵ indicate that the apparatus itself [Gamma Knife™ (Elekta AB) *vs* CyberKnife® (Accuray Inc., Sunnyvale, CA) *vs* linear accelerator] plays a role. Based on our results, and evidence presented in Table 3, the TPS itself likely plays an influential role in determining brain dose.

Table 3. Literature review of tissue and normal brain doses received from linear accelerator-based radiosurgery and radiotherapy to multiple targets

Reference	Target volume/number of targets	Parameter reported	Parameter results (cm ³)	Present study fit (95% prediction band) (cm ³)
Clark <i>et al</i> ^{2 a}	6.5 cm ³ /3	V60 (total)	21.7–37.6	28 (18.7–42cm ³)
Ma <i>et al</i> ^{15 a}	5.4 cm ³ /12	V60 (normal brain)	24.9	16.4 (10.9–24.6)
Huang <i>et al</i> ^{18 a}	2.84 cm ³ /5	V50 (normal brain)	14–16	14.3 (9.6–21.6)
Audet <i>et al</i> ^{1 a}	2.6 cm ³ /2, 11.3 cm ³ /4	V50 (normal brain)	5.1–7.1, 47.8–85.1	13.3 (7–25), 46.4 (31–70)
McDonald <i>et al</i> ^{16 b}	3.71 cm ³ /2, 6.57 cm ³ /2, 21.28 cm ³ /3, 9.29 cm ³ /3, 41.70 cm ³ /4, 1.63 cm ³ /5, 1.56 cm ³ /5	V50 (normal brain)	33.7, 50.8, 161.9, 69.6, 205, 121.5, 57.7	18 (12–27), 29.3 (19–44), 79.5 (53–119), 39.3 (26–59), 140.7 (94–211), 9.0 (4.5–18), 8.6 (4.3–17)

V50, volume receiving 50% of the prescription dose; V60, volume of each PTV receiving 60% of the prescription dose.

^aIndicates Eclipse Varian HD120™ (Varian Medical Systems, Palo Alto, CA) treatment planning system (TPS) and linear accelerator combination.

^bIndicates Pinnacle Varian iX TPS (Philips Healthcare, Andover, MA) and linear accelerator combination.

In the present study, we observed that the TPS optimization engine produced undesirable segments for multiple targets (Figure 4). For example, the perpendicular jaws in the AG system were not used to modulate the beam and provide shielding to uninvolved brain. Furthermore, the large gaps between targets in both BM and AG enhanced the dose spillage to the normal brain for this TPS. The limitations in the TPS for planning multiple targets were discussed with the vendor and may be resolved in future version releases. The limitations for planning multiple targets could partially explain the findings of McDonald et al,¹⁶ who reported larger normal tissue doses using the same TPS as in the present study. Within the TPS used, these limitations could be overcome by assigning an isocentre/arc to each target, but these approaches result in prohibitively long planning and delivery times. Our clinical practice involves adjusting the collimator and couch angles in the TPS to ensure that the MLC can adequately shield tissue between targets. Future work involves comparing the performance of the current TPS with other TPS in terms of minimizing dose to tissue.

One potential limitation of the present article is that measured differences between planning metrics are only as accurate as the beam models within the TPS. Although all treatment plans were measured, subtle differences in beam model accuracy could translate to differences in the brain dose being presented. Another limitation is in the ArcCHECK system itself. Although the diode-sensitive volume is sufficiently small (0.019 mm³), the fixed spacing (1 cm) may limit the accuracy of the dose distribution for small targets. A film would provide a higher spatial resolution and is used for dose verification in several studies.^{1,6,20} However, ArcCHECK has been demonstrated to be sensitive to errors in patient-specific QA for radiosurgery, including radiosurgery to multiple targets.^{21–24} Another advantage

of ArcCHECK is that the measurement and analysis is integrated in the same software.²⁵

The present study is of retrospective nature and therefore the comparison may be unfair or biased, given *a priori* knowledge of the BM plans and the fact that there was no time restriction on planning. However, it should be noted that the purpose of the present study was to demonstrate that equivalent or improved plans were feasible while following institutional protocols. Although a limited number of cases ($N = 12$) were included, 10 challenging cases were selected involving complex arrangement of multiple targets suitable for testing the limits of the AG and BM systems. Two single-target cases were also included to ensure nothing unusual occurred in the dose distributions towards the easier end of the planning spectrum. Nevertheless, additional complex cases involving different patterns of targets would have served to improve the statistical analysis. Since the number of patients being treated with multiple targets is increasing, including the frequency of retreats, increasing evidence is needed to support emerging technologies such as AG in order to minimize brain dose.

CONCLUSIONS

In conclusion, the results of the present study indicate that the beam model based on AG provides equivalent quality plans to the Synergy BM, with potential reductions in mean brain dose. A method for comparing results of the present study to published literature was produced. Caution must be exercised when considering multiple targets, as TPS limitations may result in exposure of unwanted normal tissue.

FUNDING

The present study was sponsored in part by the Brain Tumour Foundation of Canada.

REFERENCES

- Audet C, Poffenbarger BA, Chang P, Jackson PS, Lundahl RE, Ryu SI, et al. Evaluation of volumetric modulated arc therapy for cranial radiosurgery using multiple noncoplanar arcs. *Med Phys* 2011; **38**: 5863–72. doi: <http://dx.doi.org/10.1118/1.3641874>
- Clark GM, Popple RA, Young PE, Fiveash JB. Feasibility of single-isocenter volumetric modulated arc radiosurgery for treatment of multiple brain metastases. *Int J Radiat Oncol Biol Phys* 2010; **76**: 296–302. doi: <http://dx.doi.org/10.1016/j.ijrobp.2009.05.029>
- Lagerwaard FJ, Meijer OW, van der Hoorn EA, Verbakel WF, Slotman BJ, Senan S. Volumetric modulated arc radiotherapy for vestibular schwannomas. *Int J Radiat Oncol Biol Phys* 2009; **74**: 610–5. doi: <http://dx.doi.org/10.1016/j.ijrobp.2008.12.076>
- Mayo CS, Ding L, Addesa A, Kadish S, Fitzgerald TJ, Moser R. Initial experience with volumetric IMRT (RapidArc) for intracranial stereotactic radiosurgery. *Int J Radiat Oncol Biol Phys* 2010; **78**: 1457–66. doi: <http://dx.doi.org/10.1016/j.ijrobp.2009.10.005>
- Wolff HA, Wagner DM, Christiansen H, Hess CF, Vorwerk H. Single fraction radiosurgery using Rapid Arc for treatment of intracranial targets. *Radiat Oncol* 2010; **5**: 77. doi: <http://dx.doi.org/10.1186/1748-717X-5-77>
- Iwai Y, Ozawa S, Ageishi T, Pellegrini R, Yoda K. Feasibility of single-isocenter, multi-arc non-coplanar volumetric modulated arc therapy for multiple brain tumors using a linear accelerator with a 160-leaf multileaf collimator: a phantom study. *J Radiat Res* 2014; **55**: 1015–20. doi: <http://dx.doi.org/10.1093/jrr/rru042>
- Thompson CM, Weston SJ, Cosgrove VC, Thwaites DI. A dosimetric characterization of a novel linear accelerator collimator. *Med Phys* 2014; **41**: 031713. doi: <http://dx.doi.org/10.1118/1.4866228>
- Patel I, Glendinning AG, Kirby MC. Dosimetric characteristics of the Elekta Beam Modulator. *Phys Med Biol* 2005; **50**: 5479–92. doi: <http://dx.doi.org/10.1088/0031-9155/50/23/004>
- Yamamoto M, Serizawa T, Shuto T, Akabane A, Higuchi Y, Kawagishi J, et al. Stereotactic radiosurgery for patients with multiple brain metastases (JLGK0901): a multi-institutional prospective observational study. *Lancet Oncol* 2014; **15**: 387–95. doi: [http://dx.doi.org/10.1016/S1470-2045\(14\)70061-0](http://dx.doi.org/10.1016/S1470-2045(14)70061-0)
- Godwin GA, Simpson JB, Mugabe KV. Characterization of a dynamic multi-leaf collimator for stereotactic radiotherapy applications. *Phys Med Biol* 2012; **57**: 4643–54. doi: <http://dx.doi.org/10.1088/0031-9155/57/14/4643>
- Ruschin M, Lee Y, Beachey D, Yeboah C, Wronski M, Babic S, et al. Investigation of dose falloff for intact brain metastases and surgical cavities using hypofractionated volumetric modulated arc radiotherapy. *Technol Cancer Res Treat* 2016; **15**: 130–8. doi: <http://dx.doi.org/10.1177/1533034614567277>

12. Kang J, Ford EC, Smith K, Wong J, McNutt TR. A method for optimizing LINAC treatment geometry for volumetric modulated arc therapy of multiple brain metastases. *Med Phys* 2010; **37**: 4146–54. doi: <http://dx.doi.org/10.1118/1.3455286>
13. Paddick I. A simple scoring ratio to index the conformity of radiosurgical treatment plans. Technical note. *J Neurosurg* 2000; **93**(Suppl 3): 219–22. doi: <http://dx.doi.org/10.3171/jns.2000.93.supplement>
14. Ohtakara K, Hayashi S, Hoshi H. Dose gradient analyses in Linac-based intracranial stereotactic radiosurgery using Paddick's gradient index: consideration of the optimal method for plan evaluation. *J Radiat Res* 2011; **52**: 592–9. doi: <http://dx.doi.org/10.1269/jrr.11005>
15. Ma L, Petti P, Wang B, Descovich M, Chuang C, Barani IJ, et al. Apparatus dependence of normal brain tissue dose in stereotactic radiosurgery for multiple brain metastases. *J Neurosurg* 2011; **114**: 1580–4. doi: <http://dx.doi.org/10.3171/2011.1.JNS101056>
16. McDonald D, Schuler J, Takacs I, Peng J, Jenrette J, Vanek K. Comparison of radiation dose spillage from the Gamma Knife Perfexion with that from volumetric modulated arc radiosurgery during treatment of multiple brain metastases in a single fraction. *J Neurosurg* 2014; **121**: 51–9. doi: <http://dx.doi.org/10.3171/2014.7.GKS141358>
17. Thomas EM, Popple RA, Wu X, Clark GM, Markert JM, Guthrie BL, et al. Comparison of plan quality and delivery time between volumetric arc therapy (RapidArc) and Gamma Knife radiosurgery for multiple cranial metastases. *Neurosurgery* 2014; **75**: 409–17; discussion 417–8. doi: <http://dx.doi.org/10.1227/NEU.0000000000000448>
18. Huang Y, Chin K, Robbins JR, Kim J, Li H, Amro H, et al. Radiosurgery of multiple brain metastases with single-isocenter dynamic conformal arcs (SIDCA). *Radiother Oncol* 2014; **112**: 128–32. doi: <http://dx.doi.org/10.1016/j.radonc.2014.05.009>
19. Serna A, Puchades V, Mata F, Ramos D, Alcaraz M. Influence of multi-leaf collimator leaf width in radiosurgery via volumetric modulated arc therapy and 3D dynamic conformal arc therapy. *Phys Med* 2015; **31**: 293–6. doi: <http://dx.doi.org/10.1016/j.ejmp.2015.01.011>
20. Lagerwaard FJ, van der Hoorn EA, Verbakel WF, Haasbeek CJ, Slotman BJ, Senan S. Whole-brain radiotherapy with simultaneous integrated boost to multiple brain metastases using volumetric modulated arc therapy. *Int J Radiat Oncol Biol Phys* 2009; **75**: 253–9. doi: <http://dx.doi.org/10.1016/j.ijrobp.2009.03.029>
21. Gray T, Pearson D. SU-E-T-738: the limit of detectability and resolution of a cylindrical diode array phantom for VMAT and SRS quality assurance. *Med Phys* 2015; **42**: 3506. doi: <http://dx.doi.org/10.1118/1.4925102>
22. Lin MH, Veltchev I, Koren S, Ma C, Li J. Robotic radiosurgery system patient-specific QA for extracranial treatments using the planar ion chamber array and the cylindrical diode array. *J Appl Clin Med Phys* 2015; **16**: 5486.
23. Maurer J, Liu H, Wiant D, Koch K, Manning M, Sintay B. SU-E-T-197: comparing quality assurance strategies for single isocenter treatments of multiple brain metastases. *Med Phys* 2015; **42**: 3377. doi: <http://dx.doi.org/10.1118/1.4924558>
24. Vieilleveigne L, Molinier J, Brun T, Ferrand R. Gamma index comparison of three VMAT QA systems and evaluation of their sensitivity to delivery errors. *Phys Med* 2015; **31**: 720–5. doi: <http://dx.doi.org/10.1016/j.ejmp.2015.05.016>
25. Létourneau D, Publicover J, Kozelka J, Moseley DJ, Jaffray DA. Novel dosimetric phantom for quality assurance of volumetric modulated arc therapy. *Med Phys* 2009; **36**: 1813–21.