5-1-2020

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Nels C Knutson

William R Kennedy

Francisco J Reynoso

Jiayuan Peng

Lauren E Henke

See next page for additional authors

Authors

Nels C Knutson, William R Kennedy, Francisco J Reynoso, Jiayuan Peng, Lauren E Henke, Eric Laugeman, Michael Watts, Jessica Hillard, Ana Heermann, Geoffrey D Hugo, Sasa Mutic, and Bin Cai

Scientific Article

Intracranial Stereotactic Radiation Therapy With a Jawless Ring Gantry Linear Accelerator Equipped With New Dual Layer Multileaf Collimator

Nels C. Knutson, PhD,* William R. Kennedy, MD,
Francisco J. Reynoso, PhD, Jiayuan Peng, MS, Lauren E. Henke, MD,
Eric Laugeman, MS, Michael Watts, MS, Jessica Hillard, MS,
Ana Heermann, AS, Geoffrey D. Hugo, PhD, Sasa Mutic, PhD and
Bin Cai, PhD*

Department of Radiation Oncology, Washington University School of Medicine, St. Louis, Missouri

Abstract

Purpose: To test the feasibility of a simplified, robust, workflow for intracranial stereotactic radiation therapy (SRT) using a ring gantry linear accelerator (RGLA) equipped with a dual-layer stacked, staggered, and interdigitating multileaf collimator.

Materials and Methods: Twenty recent clinical SRT cases treated using a radiosurgery c-arm linear accelerator were anonymized. From these data sets, a new planning workflow was developed and used to replan these cases, which then were compared to their clinical counterparts. Population-based dose-volume histograms were analyzed for target coverage and sparing of healthy brain. All plans underwent plan review and quality assurance and were delivered on an end-to-end verification phantom using image guidance to simulate treatment.

Results: The RGLA plans were able to meet departmental standards for target coverage and organ-at-risk sparing and showed plan quality similar to the clinical plans. RGLA plans showed increases in the 50% isodose in the axial plane but decreases in the sagittal and coronal planes. There were no statistically significant differences in the homogeneity index or number of monitor units between the 2 systems. There were statistically significant increases in conformity and gradient indices, with median values of 1.09 versus 1.11 and 2.82 versus 3.13, respectively, for the c-arm versus RGLA plans. These differences were not believed to be clinically significant because they met clinical goals. The population-based dose-volume histograms showed target coverage and organ-at-risk sparing similar to that of the clinical plans. All plans were able to meet the departmental quality assurance requirements and were delivered under image guidance on an end-to-end phantom with measurements agreeing within 3% of the expected value. RGLA plans showed a median reduction in delivery time of $\approx 50\%$.

Conclusions: This work describes a simplified and efficient workflow that could reduce treatment times and expand access to SRT to centers using an RGLA.

Introduction

Stereotactic radiosurgery (SRS) is an established modality in the management of brain metastases, providing local control and survival comparable to whole brain radiation therapy with decreased potential for neurocognitive decline in both the definitive and postoperative settings.[1-3] As the incidence of brain metastases steadily increases due to increased utilization of magnetic resonance imaging and improvements in systemic therapy, both the need for and utilization of SRS have increased accordingly.[4-6]

Historically, SRS has been delivered in a single fraction, with dosing typically as per The Radiation Therapy Oncology Group 90-11 study.[7] Brain radiation necrosis (RN) is an important late complication of SRS that may lead to irreversible neurologic symptoms in some patients. Tumor size, prescription dose, and the volume of normal brain exposed to 12 Gy (V12) >10 cm^3 are all factors implicated in the development of RN.[8,9] Therefore, the use of single-fraction SRS for treating large or irregular intracranial volumes is limited by concerns of RN. Furthermore, SRS requires high accuracy of the setup, treatment planning, and delivery process. This comes at the cost of requiring increased complexity and precision of the immobilization devices, imaging guidance modalities, and mechanical accuracy of the linear accelerator (linac). This is often accomplished by the use of rigid immobilization stereotactic frames or, in frameless SRS cases, 6 degrees of freedom couches with surface monitoring or intrafractional imaging systems.

Multifraction SRS or stereotactic radiation therapy (SRT), typically given in 3 to 5 fractions to doses of 24 to 35 Gy, is an emerging alternative to single-fraction SRS, particularly for metastases greater than 2 cm in size or for large, irregular postoperative cavities that would otherwise prove challenging to treat with single-fraction SRS. The goal of this approach is to minimize the risk of RN while maintaining high local control rates. Early retrospective comparisons of multiple versus single-fraction regimens have had promising results, with at least equivalent local control rates and lower neurologic adverse events in both the upfront and postoperative settings.[10,11] However, no randomized comparisons have been published to date, and the optimal dose and fractionation scheme has yet to be established.

To address the global need for image guided radiation therapy, a new-generation ring gantry linac, the Halcyon (Varian Medical System, Palo Alto, CA), recently was released. Halcyon is capable of providing a 6 MV flattening filter free beam with rapid gantry rotation up to 4 rotations per minute. It has a compact jawless treatment head equipped with double stack multileaf collimator (MLC). Previous studies have shown promising results in terms of superior imaging quality, improved treatment efficiency, simplified operations, and acceptable plan quality.[12-15] However, to our knowledge, there is no study focusing on the evaluation and implementation of fractioned brain SRS study using this new device.

In this study, we test the feasibility of treatment planning and delivery for intracranial stereotactic radiation therapy on this novel ring gantry linear accelerator. We evaluate (1) the dosimetric performance of the coplanar beam Halcyon plans compared with traditional plans using noncoplanar beams, (2) the feasibility of standardizing planning procedures to reduce planning variations and improve efficiency, and (3) the simulated treatment delivery performance (end-to-end testing) on an anthropomorphic phantom to test plan deliverability, accuracy under image guidance, and operational efficiency gain.

Methods and Materials

After review from the Human Research Protection Office at our institution, our retrospective institutional review board–exempt review of patients was approved (HRPO #201901143).

Twenty patients who had undergone stereotactic radiation therapy who were clinically treated on a c-arm linac (Edge, Varian Medical Systems) equipped with a 6 degrees of freedom couch and high-definition MLC were selected for inclusion. Eclipse V13.7 (Varian Medical Systems) was used for the clinically delivered plans in all cases. Each case used volumetric modulated arc therapy (VMAT)[16] with 1 to 2 axial half arcs and 2 to 4 noncoplanar half arcs using 6 flattening filter free beam with a dose rate of 1400 monitor units per minute. All cases were prescribed 30 Gy in 5 fractions to the planning target volume (PTV). In each case the gross tumor volume (GTV) was defined on the T1 weighted magnetic resonance imaging post contrast by the MD. A 2 mm PTV expansion was used in each case. The median GTV was 14.4 mL (range, 5.7-43.7 mL), and the median PTV was 23.5 mL (range, 11.1-55.2 mL).

For each case, the clinical data sets were anonymized by a third-party honest broker and imported into a

Table 1   Volumetric modulated arc therapy optimization objectives

Optimization object	Optimization specification	Typical relative weight
OAR	Upper: Whatever is required to meet constraints	Whatever is required
NTO	Start distance = 0 mm, start dose = 101%, end dose = 20%, fall off = 0.25	150
GTV	Lower: V32 Gy = 100%; upper: V42.5 Gy = 0%	120 and 100, respectively
PTV	Lower: V30.5 Gy = 100%	110
PTV-GTV	Upper: V36 Gy = 0%	100
Ring touching PTV	Upper: V30 Gy = 0%	80
Ring 5 mm from PTV	Upper: V15 Gy = 0%	80
MUR	Max MU <1800	80

Abbreviations: GTV = gross tumor volume; NTO = normal tissue objective; OAR = organ at risk; PTV = planning target volume; MUR = monitor unit ratio.

nonclinical treatment planning station. The original clinical plan data was then confirmed and recorded. A new treatment plan was then created using the Halcyon. Each plan was calculated using the analytical anisotropic algorithm[17-19] beam model with a 1 mm dose grid, as used in the original clinical plans. A single isocenter and 4 full arc beam geometry was set up, using the arc geometry tool allowing the treatment planning system to select the optimal collimator angles and fine tune the isocenter location. The 4 arcs with unique collimator angles were chosen to match our clinical experience and follows similar experiences from the literature.[14,20] VMAT was used with the photon optimizer (PO v15.6) using convergence mode, which enforces stricter criteria for convergence between multiresolution levels in the

optimization process. All optimizations were restarted after intermediate dose calculation at the third multi-resolution level. This version of the Halcyon allows for full interdigitating and independent travel of stacked and staggered MLCs. In each case, a ring structure touching the PTV, a ring structure 5 mm from the PTV, and a contour covering the patients face were used for optimization. The normal tissue objective and maximum monitor unit objectives were also used in each case. In all cases, organ-at-risk (OAR) tolerances from American Association of Physicists in Medicine Task Group 101[21] were respected and included in the optimization in needed. A minimum PTV coverage of the prescription isodose >98% of the PTV was used. In each case the plan was normalized to match the clinical plan while respecting OAR doses. A maximum dose to the ring touching the PTV of 3050 cGy, a max dose to the ring 5 mm from the PTV of 1500 cGy, and a maximum dose of 200 cGy to the patient's face were used for VMAT optimization. In all cases, we optimized on the GTV to force the hotspot to be within the GTV and not on the edges of the PTV. The optimization parameters used can be seen in Table 1.

In each case, plans were evaluated qualitatively by reviewing isodose lines and dose-volume histograms (DVHs)[22] and quantitatively by collecting plan quality metrics and DVH data. For all cases the conformity index (CI = V30 Gy/volume of PTV), gradient index (GI = V15 Gy/V30 Gy), gradient measure (GM = distance between equivalent spheres of the 30 Gy isodose to the 15 Gy isodose), homogeneity index (HI = max dose/30 Gy), R50 = V15 Gy/volume of PTV, and monitor unit ratio (MUR = total MU/3000 cGy) were collected. A summary of these metrics and our departmental standards is given in Table 2. Box and swarm plots of each parameter for both the original clinical plans and the ring gantry plans were created. Wilcoxon signed-rank testing was used to compare the 2 paired data sets. In all cases, DVH data was exported for comparison using in-house developed software to compare groups of patients by calculating the median and inner fences of the DVH distributions across groups of plans. This

Table 2   Plan quality metrics and organ at risk constraints

Quantity	Definition	Clinical goal (acceptable variation)
CI	V_{30Gy}/V_{PTV}	1-1.2 (1-1.5)
GI	V_{15Gy}/V_{30Gy}	<3 (<4)
R50	V_{15Gy}/V_{PTV}	<4 (<4.5)
HI	Max dose/30 Gy	1.1-1.55
GM	Distance between 30 Gy and 15 Gy equivalent spheres	<0.8 cm (<1.2 cm)
MUR	No. of monitor units/3000 cGy	<4 (<5)

Organ at risk	Volume (mL)	Dose constraint (Gy)
Brain stem	0.5	23
	0.03	31
Spinal cord and medulla	1.2	14.5
	0.35	23
	0.03	30
Optics	0.2	23
	0.03	25
Cochlea	0.03	25

Abbreviations: CI = conformity index; GI = gradient index; GM = gradient measure; HI = homogeneity index; MUR = monitor unit ratio; R50 = relative ratio of the 50 isodose volume hetero.
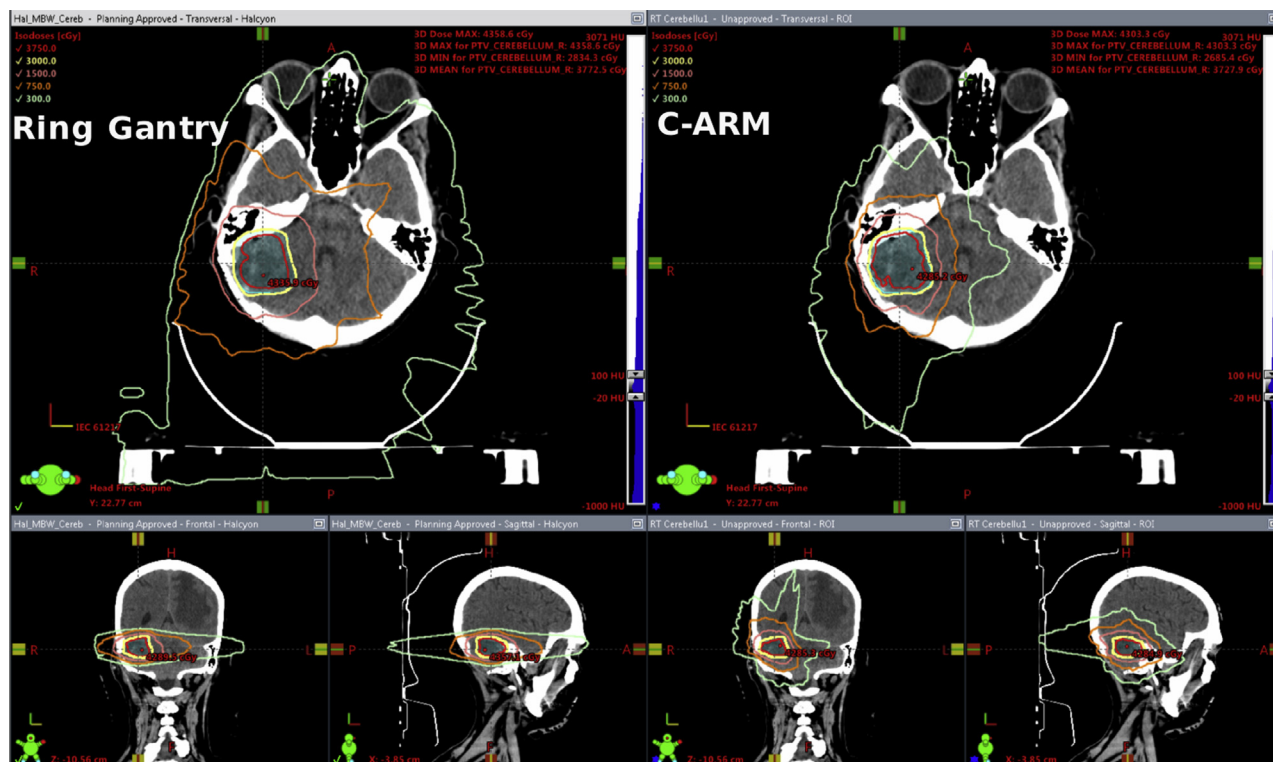
Figure 1   Visual comparison of stereotactic radiation therapy plans with c-arm and ring gantry linear accelerators.

was completed for all clinical plans and ring gantry plans for the PTV and brain structures to compare the 2 sets of plans.

Each case followed our clinical workflow and was reviewed by a physicist and radiation oncologist. Each plan was reviewed for plan quality and deliverability issues by a physicist in a formal precheck. Any issues seen at this step were resolved before radiation oncologist review. Once each precheck was approved, each plan was reviewed by a radiation oncologist and approved. Once approved, each case underwent quality assurance (QA) measurements using portal dosimetry for a 2-dimensional fluence map QA and ion chamber measurements for 1-dimensional absolute dose measurement. A 2-dimensional gamma analysis[23,24] with a 2%/2 mm criterion was used for the portal dosimetry data. A 3% dose difference criterion was used for the ionization chamber measurements. Upon completion of the clinical workflow steps, for each case, a stereotactic end-to-end testing phantom was set up, imaged using kilovoltage cone beam computed tomography, and then treated. The total treatment time from beam on to beam off and dose reading from an ionization chamber inside the phantom were recorded in each case.

Results

All plans were deemed to meet departmental clinical standards by a physicist and radiation oncologist for target coverage and OAR sparing. Sample visual comparison of

a clinical c-arm linac plan and the corresponding ring gantry linac plan are shown in Figure 1. Overall, we observed an increase in the distance between PTV and the isodose lines below 1500 cGy in the axial plane for the ring gantry plans. However, in the superoinferior plane, there was a reduction in the distance from the PTV to isodose lines at and below 1500 cGy for the ring gantry plans compared with the clinical c-arm plans. Isodose lines above 1500 cGy line were similar between the 2 plans types.

Box plots and swarm plots for plan quality metrics between the clinical plans and the ring gantry plans across all patients are shown in Figure 2. There was no statistically significant difference in the number of monitor units used or the homogeneity index. There were slight but statistically significant increases in CI, GI, R50, and GM. The median values of CI, GI, R50, and GM were 1.09 versus 1.11, 2.82 versus 3.13, 3.13 versus 3.53, and 0.72 versus 0.80 cm, respectively, for the c-arm versus ring gantry plans. Although these differences were statistically significant, they were not believed to be clinically significant in this patient cohort, given that all plan parameters for all plans fell within the clinically acceptable range.

Population-based DVHs results for the brain and PTVs for the c-arm and ring gantry linacs are shown in Figure 3. The median of the populations is shown by bold lines and the corresponding inner fences (first quartile minus 1.5 times the interquartile range and the third quartile plus 1.5
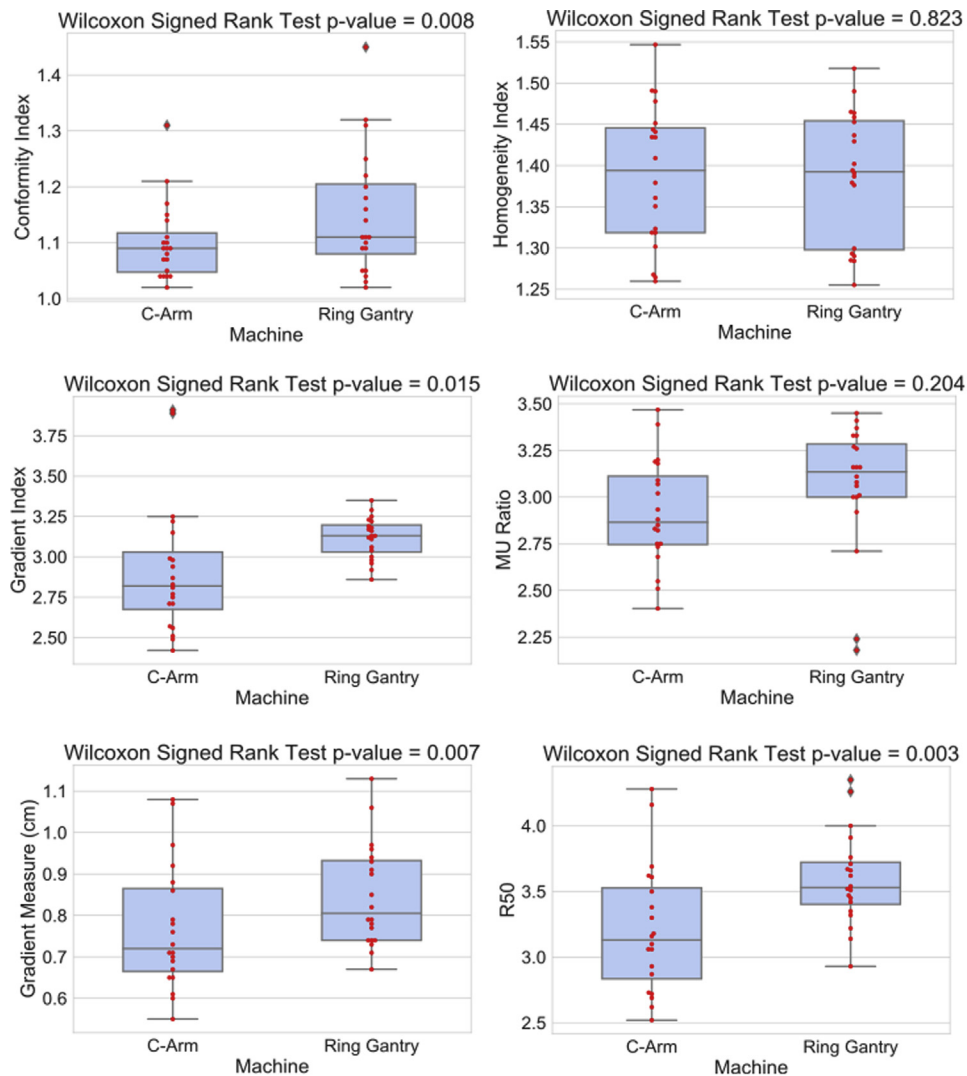
Figure 2   Box and swarm plots of plan quality parameters for Halcyon stereotactic radiation therapy plans and the clinical plans.

times interquartile range) are shown by dashed lines for the ring gantry (black) and the c-arm (red) plans. All plans have clinically acceptable dose to the normal brain, as shown in Figure 3a. The median brain volume for ring gantry plans was slightly reduced compared with c-arm for doses under 150 cGy and slightly increased for doses above 150 cGy to 1500 cGy. Volumes receiving doses above 1500 cGy are nearly identical because these are dictated by the target coverage. Figure 3B shows very similar target coverage achieved between the 2 systems, with the ring gantry having slightly more coverage from 3000 to 3700 cGy and slightly less from 3800 cGy to 4100 cGy. Note that the sharp changes in the median (Fig 3b) are caused from the variation in homogeneity index of the individual plans. When an individual PTV coverage metric goes to zero, it is no longer included in the population calculation; however, right before reaching zero it is included, thus causing rapid changes in the median. All plans had clinically acceptable coverage.

All plans met current clinical QA standards for treatment: being within 3% of expected for an ionization chamber measurement and having a minimum of 90% of points, yielding a gamma value of 1 with a 2%/2 mm criterion. The median ion chamber−measured percent difference from expected was 1.6% (range, −2.7% to 2.9%) for the ring gantry system versus 0.01% (range, −2.5% to +2.9%) for the clinical c-arm system. Similarly, the portal dosimetry results yielded a median pass rate of 100% (range, 98.8%-100%) with a 2%/2 mm gamma criterion per field. By comparison, the clinical c-arm plans yielded 99.4% (range, 95.4%-100%).

Ion chamber measurements completed under kilo-voltage cone beam computed tomography image guidance in the end-to-end phantom agreed within 3% of the expected dose. The median percent difference of the expected to measured dose was +0.7% (range, −2% to +3%). Treatment times for all cases were reduced by almost 50% using the ring gantry delivery. The median
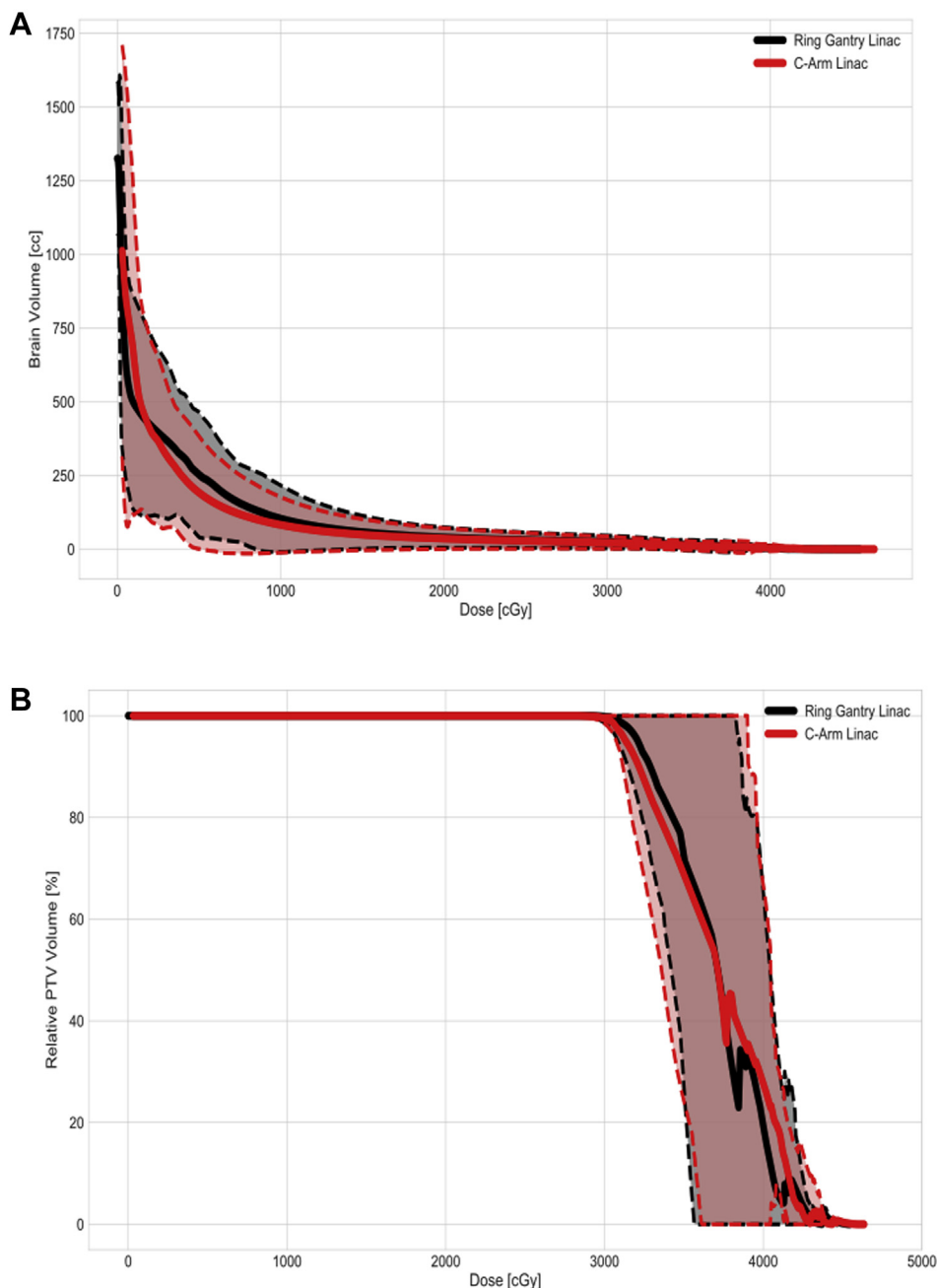
Figure 3 Planning target volume (PTV) and brain dose-volume histogram data for Halcyon stereotactic radiation therapy plans and the clinical plans.

time for the treatment delivery using the ring gantry was 2 minutes and 46 seconds (range, 2 minutes 36 seconds to 3 minutes 14 seconds), whereas clinical plans had a median delivery time of 4 minutes 43 seconds (range, 3 minutes 13 seconds to 6 minutes 21 seconds). Figure 4 summarizes of the QA results.

Discussion

In this study, we evaluated the feasibility of fractionated intracranial stereotactic radiation therapy planning and delivery using a novel ring-gantry system. We found that plans made on the Halcyon system had similar dosimetric plan quality to standard clinically deliver plans. The Halcyon system also enabled a simplified, robust, and accurate workflow with reduced treatment delivery times.

The Halcyon is one of the latest ring gantry systems; however, previous ring gantry systems such as Tomo-Therapy (Accuray, Sunnyvale CA), the Vero (BrainLab, Munich DE), and the MRidian (ViewRay, Oakwood Village, OH) have all been proposed for use in inter-cranial SRT or SRS. This work showed plan quality
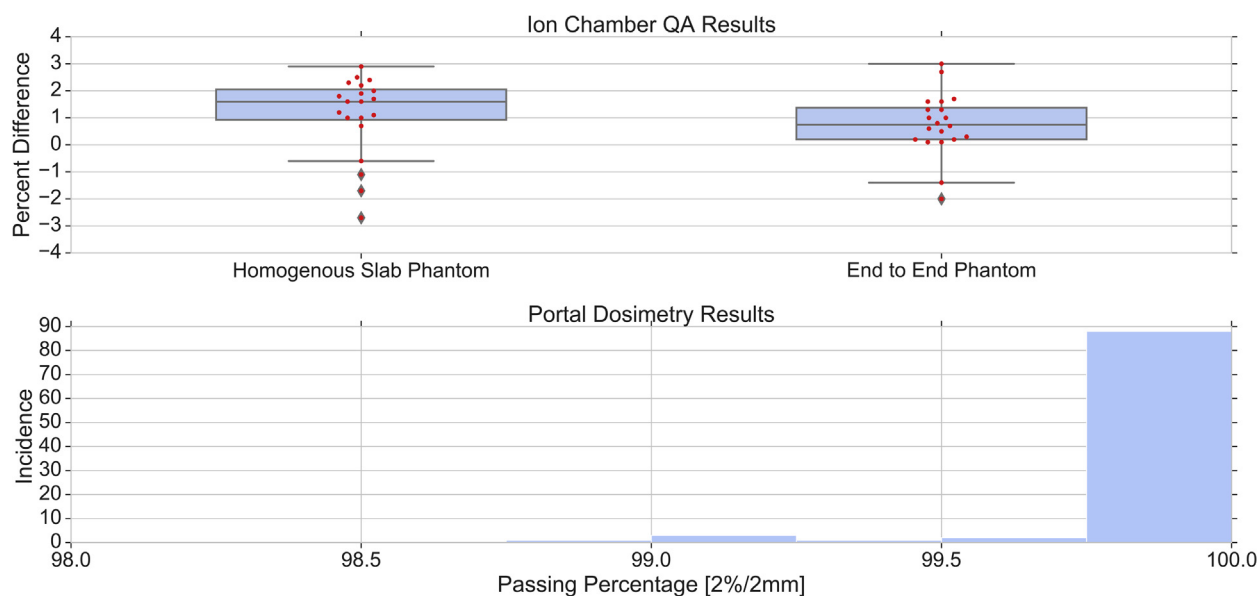
Figure 4 Summary of quality assurance (QA) results for stereotactic radiation therapy plans with the ion chamber results shown on top and portal dosimetry pass rates per field shown on bottom.

metrics similar to or better than reported in the literature for these other ring gantry delivery systems.[25-29]

In addition to being faster in delivery, the Halcyon also has several benefits with the ring-gantry design. There are no risks of the rotating gantry colliding with the patient with the ring gantry geometry, potentially improving patient safety. Any potential collisions with ring and the patient or couch are modeled directly in the treatment planning system. Given the 1-m bore, lack of couch rotation, and relatively small size of the head relative to the bore size, the likelihood of a collision issue is very low and did not occur in any of the cases in this study. Given the lack of couch rotations, there is also no couch walkout (ie, a shift in the couch isocenter with rotation with respect to the radiation isocenter due to couch rotation), which simplifies the QA needed before the SRT procedures. This increase in standardization in the treatment planning of these SRT cases could reduce potential errors that can occur in the planning process.

The lack of 6 degrees of freedom corrections is a limitation of the current generation of Halcyon. Treating with the isocenter at the center of rotation of the target will minimize the effects of setup rotation on the plan.[30,31] Fractionation used in SRT also allows for this uncertainty to be spread over a few fractions and blur the dose instead of making a single systematic shift in the dose, as seen in SRS. Thus, SRT is the more appealing option for the Halcyon in its current form.

This study is a proof of principle study and was completed in a limited patient population set with limited statistical analysis due to the relatively small sample size. Given these limitations it is difficult to draw strong statistical conclusions of equivalency to an SRS c-arm linac. However, we have shown in our patient population with our clinical guidelines that the Halcyon was able to meet our goals, often with reduced variability of our current clinical practice. The Halcyon could be promising and viable option if access to an SRS linac is limited. Additional work would need to be completed to ensure this methodology could be applied to a different patient population with different clinical goals, although these results are promising for future clinical use.

The Halcyon offers reduced cost of purchase and maintenance and comes preconfigured, reducing the time and cost for commissioning. Even if one concedes that the Halcyon only provides noninferior clinical plan quality, this would still represent a potential value increase. In particular as described by Porter et al, value to the patient should be measured as clinical outcome per cost to the achieve them.[32] Assuming the clinical outcomes could be noninferior, and given the reduced cost of the Halcyon, this would represent a higher value to the patient. Future work will show if this is in fact true; however, this work seems to indicate it is at least feasible. Even if one concedes the Halcyon could be slightly inferior to traditional c-arm linear accelerators in some aspects, the fact that there could still be increased value to patients and given that the Halcyon could lead to more access to SRT in resource-limited areas of the market could indicate a potential disruptive innovation occurring, as described by Christensen et al and Hwang et al.[33,34] Again, time will tell the full impact of the Halcyon on the radiation therapy market, but increasing access to SRT at reduced costs could potentially be a large innovation to the field.

Conclusions

This work has demonstrated the feasibility and accuracy of a simplified, robust workflow for intracranial stereotactic radiation therapy using a ring gantry linac. This could increase access to a standardized and robust approach to SRT for a larger patient population.

References

1. Sahgal A, Aoyama H, Kocher M, et al. Phase 3 trials of stereotactic radiosurgery with or without whole-brain radiation therapy for 1 to 4 brain metastases: Individual patient data meta-analysis. *Int J Radiat Oncol Biol Phys*. 2015;91:710-717.
2. Brown PD, Jaeckle K, Ballman KV, et al. Effect of radiosurgery alone vs radiosurgery with whole brain radiation therapy on cognitive function in patients with 1 to 3 brain metastases a randomized clinical trial. *JAMA*. 2016;316:401-409.
3. Brown PD, Ballman KV, Cerhan JH, et al. Postoperative stereotactic radiosurgery compared with whole brain radiotherapy for resected metastatic brain disease (NCCTG N107C/CEC·3): A multicentre, randomised, controlled, phase 3 trial. *Lancet Oncol*. 2017;18:1049-1060.
4. Johnson JD, Young B. Demographics of brain metastasis. *Neurosurg Clin N Am*. 1996;7:337-344.
5. Kann BH, Park HS, Johnson SB, Chiang VL, Yu JB. Radiosurgery for brain metastases: Changing practice patterns and disparities in the United States. *J Natl Compr Canc Netw*. 2017;15:1494-1502.
6. Modh A, Doshi A, Burmeister C, et al. Disparities in the use of single-fraction stereotactic radiosurgery for the treatment of brain metastases from nonsmall cell lung cancer. *Cureus*. 2019;11:e4031.
7. Shaw E, Scott C, Souhami L, et al. Single dose radiosurgical treatment of recurrent previously irradiated primary brain tumors and brain metastases: Final report of RTOG protocol 90-05. *Int J Radiat Oncol Biol Phys*. 2000;47:291-298.
8. Nedzi LA, Kooy H, Alexander E, Gelman RS, Loeffler JS. Variables associated with the development of complications from radiosurgery of intracranial tumors. *Int J Radiat Oncol Biol Phys*. 1991;21:591-599.
9. Korytko T, Radivoyevitch T, Colussi V, et al. 12 Gy Gamma Knife radiosurgical volume is a predictor for radiation necrosis in non-AVM intracranial tumors. *Int J Radiat Oncol Biol Phys*. 2006;64:419-424.
10. Fokas E, Henzel M, Surber G, et al. Stereotactic radiosurgery and fractionated stereotactic radiotherapy: Comparison of efficacy and toxicity in 260 patients with brain metastases. *J Neurooncol*. 2012;109:91-98.
11. Minniti G, Scaringi C, Paolini S, et al. Single-fraction versus multifraction (3 × 9 Gy) stereotactic radiosurgery for large (>2 cm) brain metastases: A comparative analysis of local control and risk of radiation-induced brain necrosis. *Int J Radiat Oncol Biol Phys*. 2016;95:1142-1148.
12. Cai B, Laugeman E, Mazur TR, et al. Characterization of a prototype rapid kilovoltage x-ray image guidance system designed for a ring shape radiation therapy unit. *Med Phys*. 2019;46:1355-1370.
13. Lim TY, Dragojević I, Hoffman D, Flores-Martinez E, Kim G. Characterization of the Halcyon™ multileaf collimator system. *J Appl Clin Med Phys*. 2019;20:106-114.
14. Cozzi L, Fogliata A, Thompson S, et al. Critical appraisal of the treatment planning performance of volumetric modulated arc therapy by means of a dual layer stacked multileaf collimator for head and neck, breast, and prostate. *Technol Cancer Res Treat*. 2018;17:153303381880388.
15. Li T, Irmen P, Liu H, et al. Dosimetric performance and planning/delivery efficiency of a dual-layer stacked and staggered MLC on treating multiple small targets: A planning study based on single-isocenter multi-target stereotactic radiosurgery (SRS) to brain metastases. *Front Oncol*. 2019;9:7.
16. Otto K. Volumetric modulated arc therapy: IMRT in a single gantry arc. *Med Phys*. 2008;35:310-317.
17. Tillikainen L, Helminen H, Torsti T, et al. A 3D pencil-beam-based superposition algorithm for photon dose calculation in heterogeneous media. *Phys Med Biol*. 2008;53:3821-3839.
18. Ulmer W, Harder D. A triple Gaussian pencil beam model for photon beam treatment planning. *Z Für Med Phys*. 1995;5:25-30.
19. Ulmer W, Pyyry J, Kaissl W. A 3D photon superposition/convolution algorithm and its foundation on results of Monte Carlo calculations. *Phys Med Biol*. 2005;50:1767-1790.
20. Clark GM, Popple RA, Prendergast BM, et al. Plan quality and treatment planning technique for single isocenter cranial radiosurgery with volumetric modulated arc therapy. *Pract Radiat Oncol*. 2012;2:306-313.
21. Benedict SH, Yenice KM, Followill D, et al. Stereotactic body radiation therapy: The report of AAPM Task Group 101. *Med Phys*. 2010;37:4078-4101.
22. Drzymala RE, Mohan R, Brewster L, et al. Dose-volume histograms. *Int J Radiat Oncol*. 1991;21:71-78.
23. Low DA, Harms WB, Mutic S, Purdy JA. A technique for the quantitative evaluation of dose distributions. *Med Phys*. 1998;25:656-661.
24. Low DA, Dempsey JF. Evaluation of the gamma dose distribution comparison method. *Med Phys*. 2003;30:2455-2464.
25. Wen N, Kim J, Doemer A, et al. Evaluation of a magnetic resonance guided linear accelerator for stereotactic radiosurgery treatment. *Radiother Oncol*. 2018;127:460-466.
26. Soisson ET, Hoban PW, Kammeyer T, et al. A technique for stereotactic radiosurgery treatment planning with helical tomotherapy. *Med Dosim*. 2011;36:46-56.
27. Burghelea M, Verellen D, Gevaert T, et al. Feasibility of using the Vero SBRT system for intracranial SRS. *J Appl Clin Med Phys*. 2014;15:90-99.
28. Kim B, Soisson E, Duma C, et al. Treatment of recurrent high grade gliomas with hypofractionated stereotactic image guided helical tomotherapy. *Clin Neurol Neurosurg*. 2011;113:509-512.
29. Tomita N, Kodaira T, Tachibana H, et al. Helical tomotherapy for brain metastases: Dosimetric evaluation of treatment plans and early clinical results. *Technol Cancer Res Treat*. 2008;7:417-424.
30. Roper J, Chanyavanich V, Betzel G, Switchenko J, Dhabaan A. Single-isocenter multiple-target stereotactic radiosurgery: Risk of compromised coverage. *Int J Radiat Oncol*. 2015;93:540-546.
31. Winey B, Bussiére M. Geometric and dosimetric uncertainties in intracranial stereotatctic treatments for multiple nonisocentric lesions. *J Appl Clin Med Phys*. 2014;15:122-132.
32. Porter ME. What is value in health care? *N Engl J Med*. 2010;363:2477-2481.
33. Christensen CM, Raynor ME, McDonald R. What is disruptive innovation. *Harv Bus Rev*. 2015;93:44-53.
34. Hwang J, Christensen CM. Disruptive innovation in health care delivery: A framework for business-model innovation. *Health Aff (Millwood)*. 2008;27:1329-1335.