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# Dosimetric Comparison of Two Linear Accelerator-Based Radiosurgery Systems for Intracranial Tumours with Rapidarc and Dynamic Conformal Arc Therapy

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**ABSTRACT**

***Introduction:*** The present study focused on the dosimetric evaluation of Edge and Novalis Tx (NTx) linear accelerator (LA)-based radiosurgery system by using RapidArc (RA) and dynamic conformal arc (DCA) planning techniques.

***Material and Methods:*** Forty patients with brain lesions of variable sizes (1.1-15.98 cc) were planned for Edge and NTx system by using the RA and DCA planning techniques on eclipse treatment planning system, version 13.6 (Varian Medical Systems, Palo Alto, CA, USA). All the plans were evaluated on the basis of paddick conformity index (PCI), homogeneity index (HI), and gradient index (GI). The maximum doses to organs at risk (OAR), V12Gy, V10Gy, and V5Gy for healthy brain tissue were also evaluated for all the plans. The treatment delivery efficiency for both systems was also evaluated.

***Results:*** The mean PCI and GI for both RA and DCA plans were found to be better in Edge as compared to NTx system (PCI Edge, RA=0.77±0.1, PCI NTx, RA=0.66±0.11, PCI Edge, DCA= 0.69±0.12, PCI NTx,DCA= 0.67±0.12). Significant differences in HI, doses to OAR, and V12Gy, V10Gy, and V5Gy brain volume were observed for both systems with p-value less than 0.05. Reduced treatment time was observed in Edge LA as compared to NTx LA.

***Conclusion:*** Edge LA produced clinically better target volume conformity, rapid dose fall-off, and reduced reduction in normal brain volume irradiation and treatment time compared to NTx. Thus, in the set of patient plans evaluated, it was noted that Edge stereotactic suite is more efficacious and diametrically suitable for intracranial radiosurgery.

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## Introduction

Intracranial radiosurgery is the process of administrating large amounts of radiation doses in a single fraction to well-defined small targets with a sharp dose fall off to avoid any complications associated with normal tissues. Several modalities are available that are used in actual practice for the delivery of hypofractionated intracranial radiation treatments using gamma knife, medical linear accelerators (LAs), or charged particle beams using external frame and frameless systems. Since its inception, gamma knife has been considered as the gold standard for the intracranial treatment of small lesions when compared with linear accelerator (LA)-based treatments due to its conformity and sharp dose fall off [1-3]. However, with the advent of volumetric modulated arc therapy (VMAT), fixed-field intensity-modulated therapy (IMRT) and dynamic conformal arcs (DCA) delivery techniques along with high-definition multi-leaf collimator (HD-MLC), on-board imager (OBI) for imaging and flattening filter-free (FFF) beams on LA has given new impetus to LA-based stereotactic radiosurgery (SRS) [4-10].

One of the most widely used LA-based systems in the past decade for cranial radiosurgery has been Novalis Tx (NTx) from Varian Medical Systems (Palo Alto, CA). It is equipped with HD-MLC (0.25 cm) and 6 MV SRS beam with a dose rate of 1000 MU/minute [11]. Several studies have explored and compared the use of NTx to gamma knife and cyber knife systems for SRS [12-14]. The newer platform available for LA-based SRS treatments is the Edge (Varian Medical Systems, Palo Alto, CA), which is equipped with FFF beams for facilitating faster treatment, HD-MLC (0.25 cm), treatment couch with 6 degrees of freedom (DOF), and jaw tracking technology for reduction in leakage and out-of-field dose [15]. At our radiation oncology unit, two advanced LAs have been commissioned that are capable of performing radiosurgical treatment, viz., NTx and Edge. Dynamic conformal arcs and RapidArc (RA) are the more often

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used planning techniques with both LAs. The DCA technique utilizes an arc rotational therapy in which the MLC leaves dynamically adapt the shape of the target volume during treatment delivery. On the other hand, RA technique with more degrees of freedom modulates the beam by simultaneously varying the speed of gantry, dose rate, and MLC to achieve conformal dose distribution [16,17].

For the SRS treatment, brain metastasis is a common indication, but our study focused on irregular-shape tumors, such as arteriovenous malformations (AVM's), acoustics neuromas (AN's), and single brain metastasis. There are no comparative studies on the use of RA and DCA techniques for intracranial tumors with the latest Linac-based technologies available for SRS treatments. In this study, we retrospectively evaluated plan quality and efficiency of treatment for various patients who received SRS for intracranial tumors. We planned each case employing different techniques of RA and DCA delivery for Edge and NTx and compared the plan quality, doses applied to the organs at risk, and the treatment efficiency achieved.

## Materials and Methods

### *Patients*

A total of 40 patients who were already treated with SRS were selected for this study. The cases included 14 patients with arteriovenous malformation, 15 with single metastatic lesion, and 11 with acoustic neuroma. The volume of the targets ranged from 1.1 to 15.98 $cm^3$ and the average volume was 4.78 $cm^3$. The treatment dose ranged from 15 Gy to 25 Gy at isocenter with the control dose of 80% prescription isodose line for all the patients.

### *Treatment Planning*

The patients were initially imaged by computed tomography (CT) on Siemens Biograph PETCT using a 1-mm slice thickness and different magnetic resonance imaging (MRI) sequences (T1-weighted and T2 flair), as per the department protocol. To generate the stereoscopic coordinate system, an external CT localizer (Brainlab) assembly was used. The images were directly transferred to the iPlan RT image (v.4.1, Brainlab AG Feldkirchen,Germany) treatment planning system. Contours such as gross tumour volume (GTV) and organs at risk (OAR), were outlined by a neurosurgeon and a radiation oncologist. Planning target volume (PTV) was created by giving a uniform margin of 1mm from GTV. Healthy brain was contoured by excluding the PTV as OAR. Localization of contoured images for stereotactic coordinates was performed on the iPlan planning system. All the contoured images were imported on treatment planning system (TPS) Eclipse v 13.6 (Varian Medical System, Palo Alto,CA) using DICOM enabled protocol for the DCA and RA plans creation. The isocenter for all the plans as generated by the stereotactic coordinate of iPlan planning system was kept the same in Eclipse. Identical DCA and RA plans were created for both NTx and Edge systems, leading to 160 dosimetric plans for our retrospective study.

The photon energy used for Edge LA was 6 MV flattening filter free (FFF) with a 1400 MU/min dose rate and 6 MV SRS with 1000 MU/min for NTx LA. The intensity of the beam was increased near the central axis after the removal of the flattening filter. The FFF beams have different characteristics when compared with normal conventional photon beam with minimal head scatter, sharper penumbra, higher dose rate, and minimum out-of-field dose and sharper penumbra. Also, the beam energy and profile can be slightly different.

Dose was calculated using analytic anisotropic algorithm (AAA) with a high-resolution calculation dose grid size of 1 mm. All the RA plans were generated using four non-coplanar and one coplanar arc, and all the DCA plans were generated with the same beam angle geometry using a 1-mm MLC margin to the planning target volume (PTV) during gantry rotation. All the planning and optimization parameters were kept the same for both RA and DCA techniques, as shown in Table 1. All the RA plans were optimized using the jaw tracking option enabled for Edge LA to reduce the dose due to leakage and transmission through the MLC leaves.

### *Plan comparison*

In this study, a comparison of both RA and DCA plans was performed using the dose volume histogram (DVH). The dosimetric parameters evaluated based on DVH included Paddick conformity index (PCI), homogeneity index (HI), and gradient index (GI).

The PCI [18], which takes into account the location of the prescription isodose volume (PIV) with respect to the target volume (TV), is defined as:

$$PCI = (TV_{PIV})^2 / (TV \times PIV)$$

The HI is defined as the ratio of the maximum dose (MD) to the prescribed dose (PD). It is a measure of dose homogeneity within the PTV volume.

Table 1. Beam arrangements for non-coplanar rapid arc therapy and dynamic conformal arc techniques.

| Arc | Table rotation | Initial angle | Final angle | Rotational direction |
|---|---|---|---|---|
| 1 | 60° | 0° | 181° | Anti-clockwise |
| 2 | 30° | 0° | 181° | Anti-clockwise |
| 3 | 0° | 181° | 179° | Clockwise |
| 4 | 330° | 179° | 0° | Anti-clockwise |
| 5 | 300° | 179° | 0° | Anti-clockwise |

A ratio of half of the prescribed dose to that of the prescribed dose is defined as the gradient Index [19]. A sharp fall-off dose can be evaluated with low spread of dose outside the lesion.

We evaluated the maximum dose received to lesion along with OARs for both systems. Further, the values of volumes, expressed in cubic centimetre (cc), receiving more than 12 Gy, 10 Gy, and 5 Gy ($V_{12Gy}$, $V_{10Gy}$ and $V_{5Gy}$) in the brain were also compared.

Besides the various dosimetric parameters, we compared the total monitor units delivered for RA and DCA techniques along with the actual beam on time and total treatment time for the completion of treatment for both LA systems. We excluded the time required for preparing the patient setup and imaging.

### *Statistical analysis*

SPSS version 22 was used to carry out the statistical analysis of the data, and a *P*-value<0.05 was considered statistically significant for Wilcoxon signed rank test.

## Results

Figures1-7 show the pictorial representation of the results of our complete study. Table 2 presents the summary of the plan evaluation on the basis of dosimetric parameters. The RA technique had higher PCI with a mean of 0.77±0.10 for Edge as compared to 0.66±0.11 for NTx LA. The HI for RA technique was found to be 1.09±0.03 for Edge and 1.17±0.04 for NTx LA. The HI for DCA technique was found to be 1.02±0.02 for Edge and 1.04±0.04 for NTx LA .The CI and HI were found to be statistically significant for both accelerators in the DCA technique. Significant difference in GI values was found for both accelerators for RA and DCA techniques. Statistically significant differences in dose to OARs and normal brain tissue volume receiving 12 Gy ($V_{12Gy}$), 10 Gy ($V_{10Gy}$), and 5 Gy ($V_{5Gy}$) in Edge and NTx LA for RA and DCA techniques were observed, as indicated in tables 3 and 4. As compared to NTx, RA and DCA plans on Edge LA were found to be more efficient to deliver, with less beam on time as shown in Table 5. The mean of the total treatment delivery time, excluding patient setup and imaging in RA for Edge, was found to be 10.02±0.85 minutes as compared to 14.37±0.73 minutes for NTx. For DCA technique, the treatment time was found to be 6.38±0.76 minutes for Edge, whereas it was found to be 10.08±0.75 minutes for NTx. Figures 1-3 show the variation between the dosimetric parameters PCI, GI, and HI with respect to PTV volumes in Edge and NTx machines for RA and DCA techniques. Based on the graphs, it is clear that the variation in all the dosimetric parameters is due to the type of machine and the treatment technique we used for the treatment rather than the PTV volumes.

Figures 4-5 show the variation of the dose received by OARs for DCA and RA techniques using Edge and NTx LA systems. Figure 6 pictorially demonstrates the control dose (80%) isodose distribution for Edge and NTx linac for the DCA and RA techniques. Figure 7 represents the brain volume receiving the 5 Gy dose for Edge and NTx linac for the DCA and RA techniques.

Table 2. Dosimetric indices for PCI, GI and HI for Edge and NTx.

| Dosimetric Parameter | | RA | | p-Value | DCA | | p-Value |
|---|---|---|---|---|---|---|---|
| | | Edge | NTx | | Edge | NTx | |
| PCI | Mean | 0.77 | 0.66 | 0.0001 | 0.69 | 0.67 | 0.0001 |
| | SD | 0.10 | 0.11 | | 0.12 | 0.12 | |
| HI | Mean | 1.09 | 1.17 | 0.0001 | 1.02 | 1.04 | 0.0001 |
| | SD | 0.03 | 0.04 | | 0.02 | 0.04 | |
| GI | Mean | 3.31 | 3.35 | 0.004 | 2.85 | 2.89 | 0.0001 |
| | SD | 0.54 | 0.55 | | 0.30 | 0.34 | |

Table 3. Normal brain tissue volume (in cc) receiving 5, 10 and 12 Gy for Edge and NTx.

| Brain volume in cc | | RA | | p-Value | DCA | | p-Value |
|---|---|---|---|---|---|---|---|
| | | Edge | NTx | | Edge | NTx | |
| 12 Gy | Mean | 5.08 | 6.20 | 0.0001 | 6.08 | 6.50 | 0.0001 |
| | SD | 5.25 | 5.95 | | 6.59 | 6.98 | |
| 10 Gy | Mean | 7.95 | 9.54 | 0.0001 | 8.87 | 9.49 | 0.0001 |
| | SD | 7.21 | 8.36 | | 8.86 | 9.39 | |
| 5 Gy | Mean | 29.15 | 34.29 | 0.0001 | 29.62 | 31.42 | 0.0001 |
| | SD | 23.33 | 26.53 | | 26.09 | 27.43 | |

Table 4. Maximum dose received by organs at risk for Edge and NTx.

| Maximum dose OAR's in Gy | | RA | | p-Value | DCA | | p-Value |
|---|---|---|---|---|---|---|---|
| | | Edge | NTx | | Edge | NTx | |
| Brainstem | Mean | 6.97 | 7.51 | 0.0001 | 7.19 | 7.35 | 0.0001 |
| | SD | 5.00 | 5.42 | | 5.88 | 5.96 | |
| Chiasm | Mean | 2.14 | 2.28 | 0.0020 | 1.93 | 2.00 | 0.002 |
| | SD | 2.67 | 2.82 | | 2.46 | 2.57 | |
| Rt optic nerve | Mean | 1.12 | 1.24 | 0.0010 | 1.03 | 1.10 | 0.002 |
| | SD | 1.21 | 1.35 | | 1.44 | 1.51 | |
| Lt optic nerve | Mean | 1.41 | 1.55 | 0.0050 | 1.33 | 1.37 | 0.038 |
| | SD | 1.80 | 1.92 | | 1.83 | 1.90 | |

Table 5. Monitor units and beam on time for Edge and NTx.

| Beam On time in minutes | | RA | | p-Value | DCA | | p-Value |
|---|---|---|---|---|---|---|---|
| | | Edge | NTx | | Edge | NTx | |
| BOT | Mean | 4.33 | 5.13 | 0.0001 | 3.11 | 3.92 | 0.0001 |
| | SD | 0.69 | 0.68 | | 0.10 | 0.12 | |
| Total Treatment Time | Mean | 10.02 | 14.37 | 0.0001 | 6.38 | 10.08 | 0.0001 |
| | SD | 0.85 | 0.73 | | 0.76 | 0.75 | |
| Monitor Units | Mean | 5831.25 | 5769.65 | 0.2190 | 2941.40 | 2697.45 | 0.0001 |
| | SD | 1366.20 | 1398.20 | | 408.33 | 374.03 | |

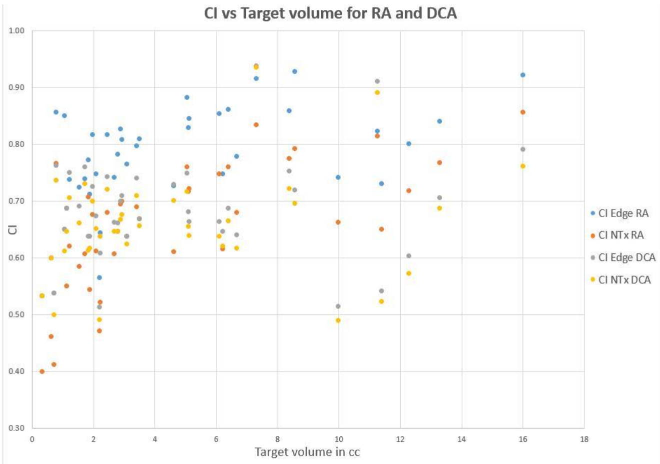



Figure 1. Paddick conformity index for Edge and NTx linac for DCAand RAplans.

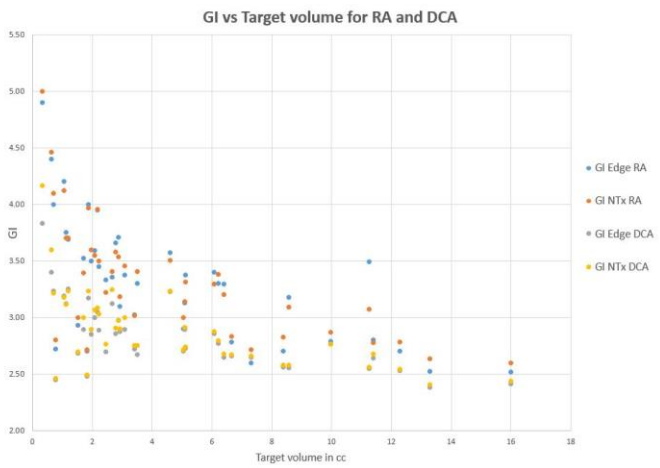



Figure 2. Gradient index for Edge and NTx linac for DCA and RA plans.

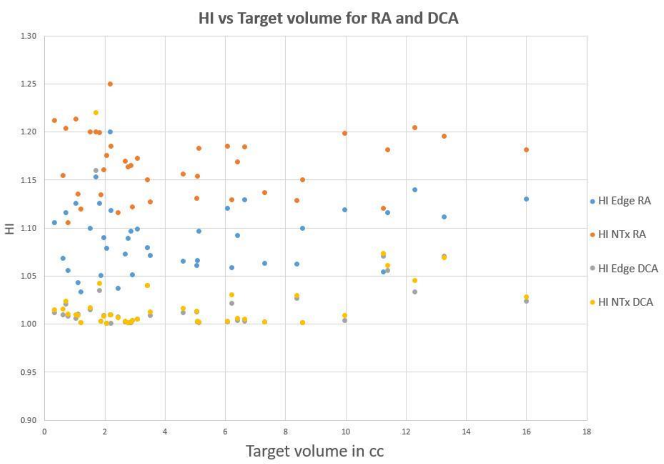
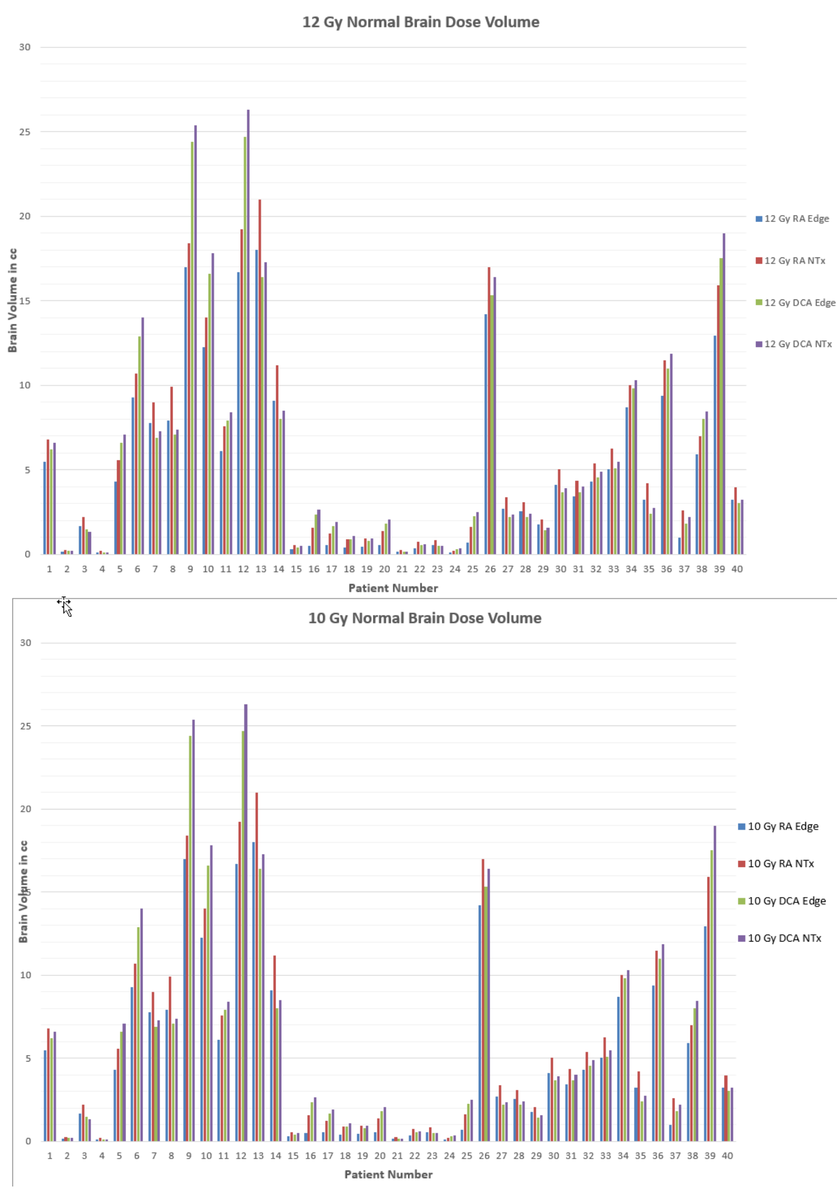



Figure 3. Homogeneity index for Edge and NTx linac for DCAand RAplans.



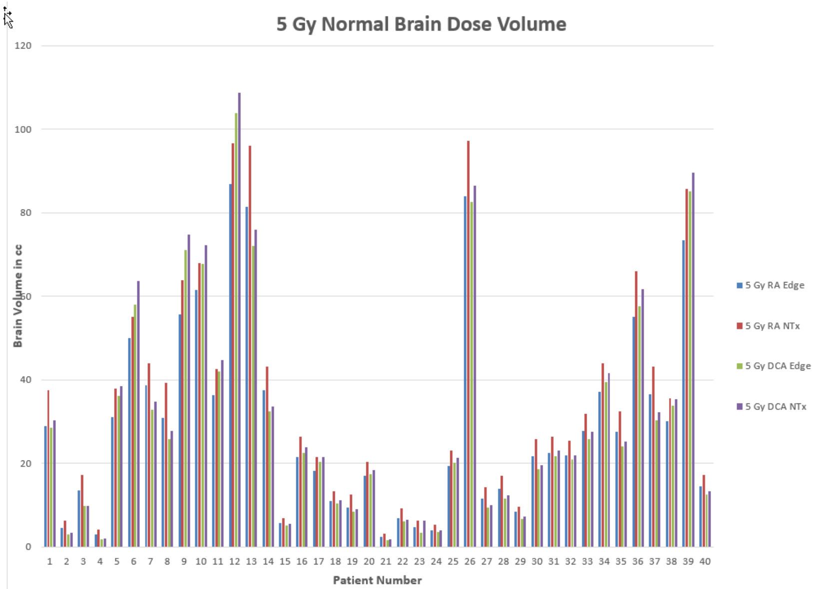
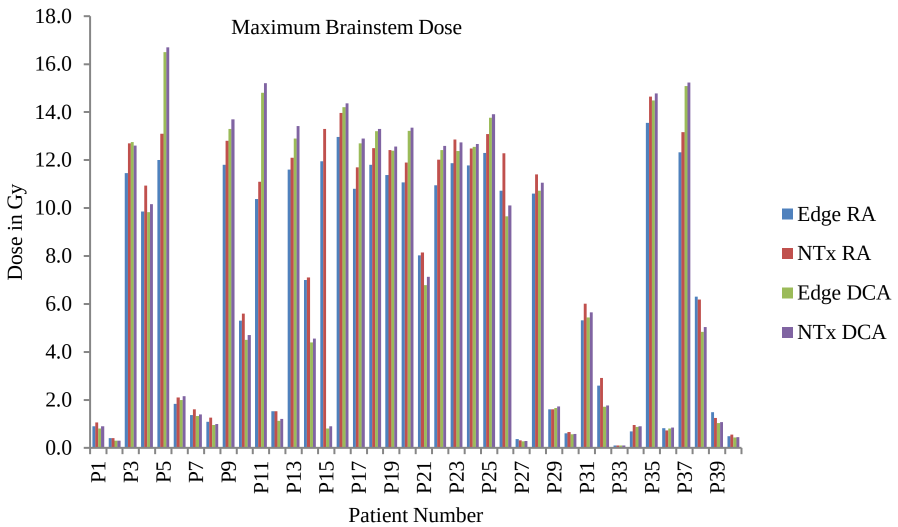
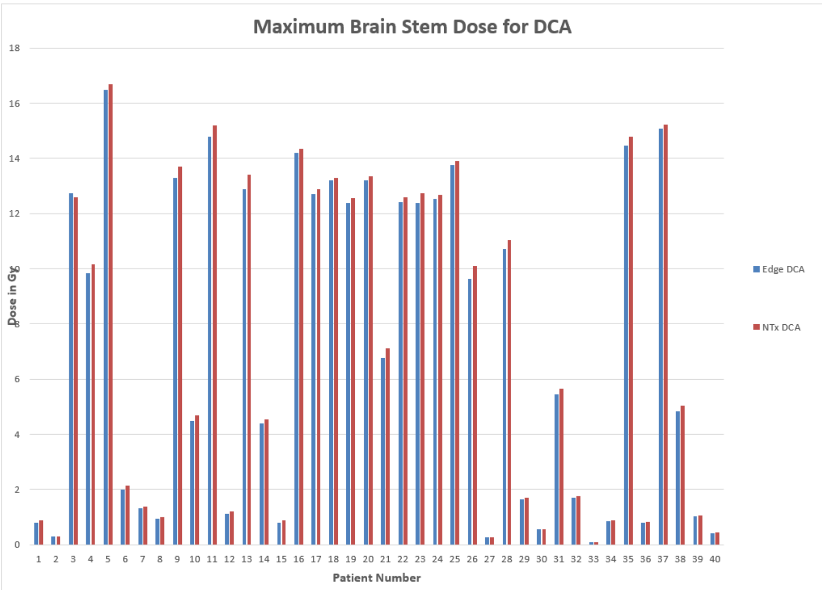



Figure 4. Normal brain dose 12Gy, 10Gy and 5Gy volume in cc for Edge and NTxlinac.



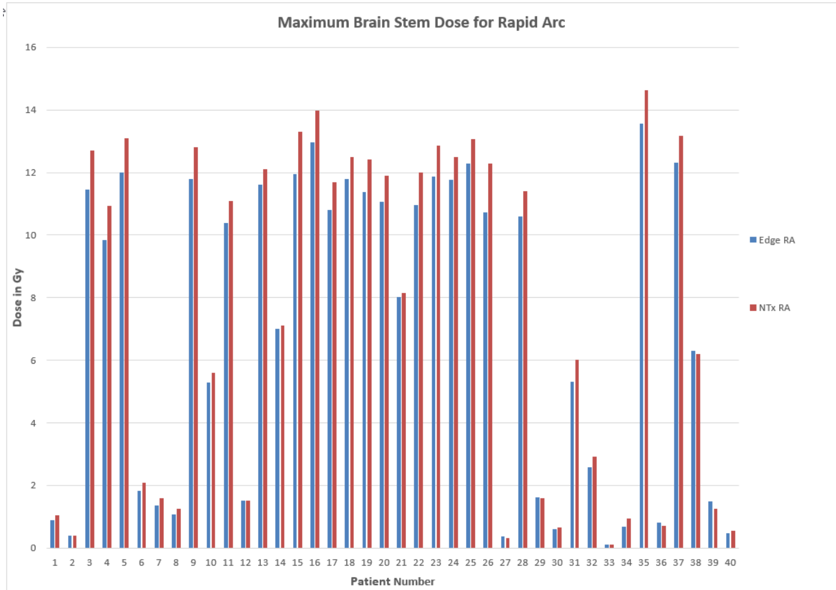



Figure 5. Maximum brainstem dose for Edge and NTx linac.

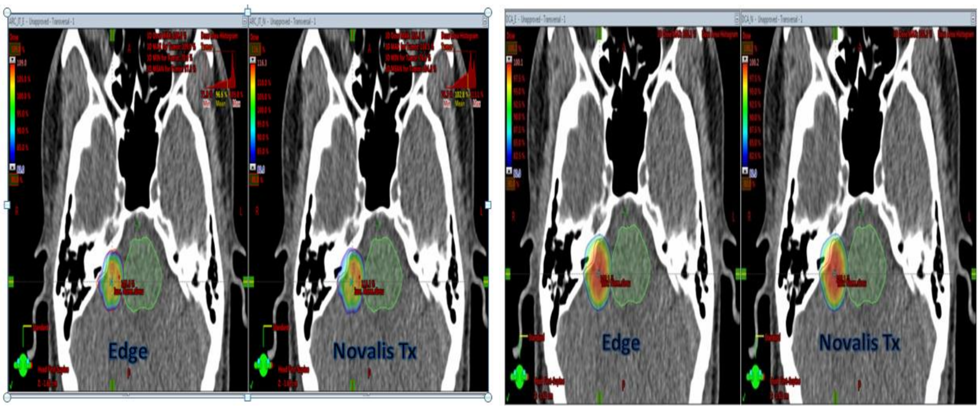



Figure 6. Control dose (80%) isodose distribution for Edge and NTx linac for RA technique (Left) and DCA technique (Right).

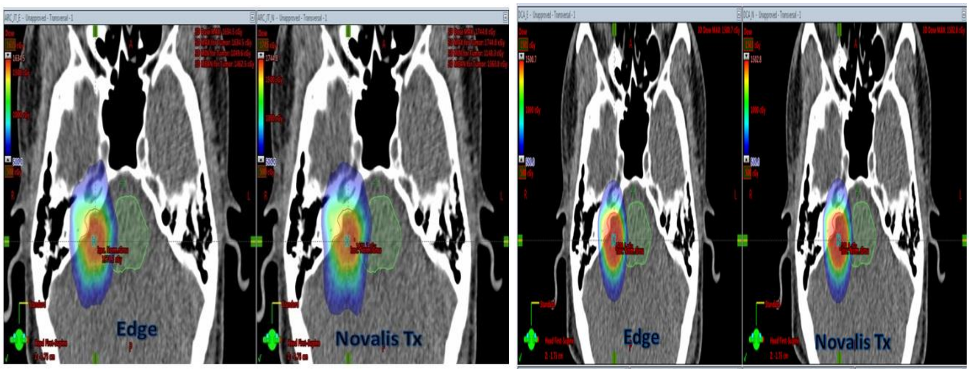



Figure 7. 5 Gy brain volume for Edge and NTx linac for RA technique (Left) and DCA technique (Right).

## Discussion

The Edge radiosurgery system is a novel linac-based SRS/SBRT treatment system allowing for faster and more accurate radiation delivery. Results of the present study indicate that the Edge system is capable of producing superior treatment plans to that of NTx system with significant reduction in dose to healthy tissues and treatment time.

In the present study, we assessed dose conformity, homogeneity, and fall-off for the two treatment techniques used in radiosurgery with the most widely used systems NTx and Edge LA. Dose conformity is a parameter that can help in delivering maximum dose to PTV; it is a measure of how well the prescribed dose conforms and covers the PTV volume. The ideal value of PCI is 1, which is an indication of achieving a high level of conformity within the given PTV volume. The PCI value more than 1 is an indication of over coverage of the target volume with the unnecessary high-dose regions beyond the target volume. A PCI value less than 1 implies that the target is under coverage. In our study, we observed a PCI value closer to 1 for Edge as compared to NTx with a significant difference ($p < 0.0001$) for both treatment techniques. Our results are in consonance with the published literature which demonstrated that inverse planning resulted in better conformity than forward techniques [20-22]. Higher PCI value also indicates that the dose fall-off outside the PTV is sharp, but it does not give any indication of distinctive levels of the dose received by the surrounding OARs.

Referring to the proposed guidelines of Radiation Therapy Oncology Group (RTOG) [23] for the routine evaluation of SRS plans based on several parameters, HI is considered as one of the key parameters for plan evaluation. The HI parameter is a measure of dose distribution homogeneity within the PTV. The HI values of less than 2, as per RTOG, balance the risk of local failure and neurologic injury. A value between 2 to 2.5 is considered with minor discrepancy, and a value above 2.5 is considered to be major discrepancy. Several studies indicate that HI tends to improve if we target a smaller tumor volume with high prescription dose. It also plays an essential role when the tumor is in close proximity with the critical structure.

In our study, we observed HI values$\leq$2 for both LA systems for both the treatment techniques. Thus, the observed value was in compliance with the RTOG protocol. A lower value of HI in Edge as compared to NTx with significant difference ($p < 0.0001$) for both treatment techniques indicates that for the same control dose we observed a higher value of hotspot in NTx as compared to Edge LA. To balance the risk of neurological injury and underdosing of the target, the maximum dose and the control dose must be optimized, which we observed more pronounced in case of Edge LA.

Excellent PCI alone cannot decide the quality of plan as it does not indicate the excessive dose received by normal tissues. An optimal dose reduction outside the target without compromising its coverage reduces the complications in normal tissues. In order to assess variation in OARs doses, the study of GI was done with regards to different LAs. It plays a central role in the prescribed ideal dose to target volume, such that the steepest dose fall-off can be achieved for a given treatment plan. The value of GI was found to be lower in Edge machine as compared to NTx with a significant difference ($p < 0.0001$). Lower GI value is an indication of reduced dose to normal brain tissue and OARs. The possible reason for lower GI in Edge is mainly its Jaw tracking technology which minimizes the inter and intra leaf leakage through MLC’s by keeping the jaws as close as possible to MLC apertures [24, 25]. Another reason behind the reduction could be the characteristic of FFF beams, which generate lower outside-field doses compared with those generated by flattened beams [26, 27].

It has been reported in the study published by Minniti, Clarke, Lanzetta et al. that radionecrosis development increases rapidly with the 5-10 cc volume of normal brain receiving 12 Gy or above [28]. It was also recommended by Blonigen et al. [29] that for $V_{10Gy}> 10.5\ cm^3$ or $V_{12Gy}> 8\ cm^3$ hypo-fractionation should be considered. To evaluate lower dose spillage, $V_{5Gy}$ brain volume was documented in our study. The normal brain tissue for all the measured criteria were lower for both LAs; however, a significant reduction in brain volume of around 16% for RA technique and around 6% for DCA technique was observed on Edge LA.

SRS is a time-consuming procedure, and the major challenges in it include having maximum dosimetric accuracy, minimum doses to nearby values of OARs, and limited treatment time. There was a significant reduction in overall treatment time excluding patient setup and imaging was found in case of Edge LA as compared to NTx due to the high dose rate and automated motion for both RA and DCA techniques. A 30% reduction in radiation time, which does not include imaging and patient set up time, was observed for RA plans, while a 37% reduction in DCA plan was noted as compared to NTx. Reduction in time plays a major role in SRS, especially when we need to treat multiple lesions, as the overall treatment time increases in such cases. The risk of intrafractional motion also increases in such patients, which leads higher doses to nearby OARs. The reduction of time is beneficial for both frame-based and frameless SRS, as it will reduce the intrafractional motion. In our previous study published on SRS, we compared the benefits of cone-based treatment for trigeminal neuralgia with FFF beams and concluded that there was a significant reduction in treatment time and doses to OAR [30].

Both systems were specifically commissioned at our centre to perform cranial SRS, hence rigorous measurement of all the parameters which could influence the dosimetric data such as leaf transmission and dosimetric leaf gap parameter for HDMLC was carried out. This has been the part of clinical mandatory acceptance protocol for both Edge and NTx accelerators to meet the eclipse treatment planning system beam data requirement. The Edge HDMLC has 0.9% transmission and 0.4 mm dosimetric leaf gap for six FFF beams as compared to 1.2% transmission and 0.7 mm dosimetric leaf gap for 6-MV SRS beam on NTx HDMLC. A detailed dosimetric study is needed for both HDMLCs, which is beyond the scope of the present study. However, a detailed study has been carried out in our institute by Sharma et.al on NTx HDMLC [31]. Therefore, the main limitation of our study is that the current work is purely a computer-based treatment planning retrospective study for two radiosurgery systems employing the same planning system.

There are few studies that have compared the use of FFF beams in SRS [32-35], and our findings are in conformity with the results of published studies. This study was aimed at dosimetric comparison and evaluation of the plan efficiency obtained from both systems: hence, efforts were made to understand the degree of flexibility of these systems in terms of dose gradients, target homogeneity, and OAR sparing. In order to make the dosimetric comparison between Edge and NTx systems more convenient and effective, RA and DCA plans were first optimized and generated by eclipse treatment planning for 6 MV SRS beam on NTx, and then the planning conditions were kept the same to avoid bias for 6 FFF beam on Edge LA. All the RA plans for Edge LA resulted in superior brain sparing as discussed earlier, although on a visual glance, it does not show any difference in dose distribution for 5 Gy volumes, as shown in Fig. 7. The reduction of 5 Gy brain volume may be of clinical significance in decreasing the brain toxicity.

With the developments in the linacs, including HDMLC and FFF beams, this study aimed to evaluate the relative advantages of delivery for SRS with the RA and DCA techniques. There are no comparative studies on the two stereotactic linac-based delivery systems for intracranial SRS. However, Ruschin et al. compared two stereotactic accelerator designs from Elekta to evaluate the brain dose for brain metastases [36].

## Conclusion

This study focused on two different linac-based SRS (Edge and NTx) systems along with the two advanced radiotherapy planning techniques (RA & DCA). A dosimetric analysis performed on the patient plans showed superior dose conformity in Edge LA as compared to NTx LA for both RA and DCA techniques. FFF beam associated with Edge LA had sharper penumbra, less head scatter, and less out-of-field dose as compared to 6X SRS beam of NTxLA, leading to higher conformity with the reduced normal brain tissue dose. The jaw tracking option associated with Edge also offers an additive advantage for the reduction of dose in normal brain tissue as compared to NTx LA. Higher dose rate delivery in a largely automated way in Edge LA enables a less treatment time as compared to NTx LA. Based on HI and GI, Edge LA is found to be superior to NTx LA. Based on planning technique, RA was found better in terms of CI and GI for both LA systems. However, in DCA technique, HI was found to be superior in terms of reduced number of MUs and treatment time for all patients. Dose to normal brain was found to be less in RA in comparison to DCA; however, both techniques were equally good based on dose received by OARs.

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