Clinical Implementation of HyperArc

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Abstract

The aim of this study was to present our experience on clinical implementation of HyperArc including dosimetric comparison between VMAT and HyperArc plans and dosimetric verification of HyperArc. In this study, eleven previously treated cases of brain metastasis were selected from our brain stereotactic radiotherapy program. The cases were retrospectively planned using HyperArc technique and the plan quality was evaluated. In addition, dosimetric effects of HyperArc plan with different energies and using jaw tracking technique were evaluated. Furthermore, dosimetric verification of HyperArc plans was performed using ion chamber and radiochromic film. Our results of dosimetric comparison shows that HyperArc technique improved both conformity index and gradient index compared to VMAT plans. We also found that using 6MV flattening filter free (6MV-FFF) beam improves gradient index in HyperArc plans compared to using 6MV flattening filter beam. Furthermore, our results show that jaw tracking technique reduces the size of low dose volume while maintaining similar target coverage, conformity index, and gradient index. In our dosimetric verification study, results of ion chamber and film measurement indicate no significant difference between VMAT and HyperArc plans. In conclusion, HyperArc simplifies planning of stereotactic treatment for brain and improves the dosimetry in treatment plans. Additionally, HyperArc provides safe and efficient treatment delivery to stereotactic treatment to brain.

Keywords

HyperArc; Stereotactic radiosurgery; Stereotactic radiotherapy

Declarations

Conflict of interest

The authors declare that they have no conflict of interest.

Introduction

Up to 30% of cancer patients develop brain metastases during the course of their diseases [1]. This represents a significant healthcare burden which is managed by a range of treatment modalities including surgical resection, radiation therapy (RT) and supportive care [2].

Multiple lesions are commonly found in patients who present with brain metastasis and postoperative whole brain radiotherapy (WBRT) has been the standard treatment of choice prior to advances in treatment techniques and treatment delivery systems [3, 4]. Stereotactic radiosurgery (SRS) is an alternative technique in RT but it is only appropriate to treat small solitary lesions or a small number of brain metastases. SRS requires rigid immobilization of the head to delivery high dose to the tumour in a single fraction. Traditionally, the immobilization is achieved by attaching stereotactic frame to the patient's skull and then fastened to the treatment table. However, frame-based SRS is invasive and is not suitable for fractionated treatment. More recently, frameless SRS has been exploited with the development and availability of image-guided radiation therapy (IGRT). Frameless SRS technique utilizes IGRT to actively monitor and correct patient position with respect to the treatment isocentre to deliver a highly accurate treatment.

Stereotactic radiotherapy (SRT) employs stereotactic techniques and applies to fractionated treatment (3 - 5 fractions). Instead of using a stereotactic frame, SRT treatment usually employs non-invasive fixation of the head, so it is more comfortable for patients at the cost of reducing setup accuracy. Therefore, PTV margin sizes from 1 to 3 mm are generally applied to the target [5-7]. In addition to patient comfort, the advantage of fractionated stereotactic treatment is the increase in tolerance to normal tissue. Studies have already shown SRT can improve local control and reduce the risk of developing severe radionecrosis to normal brain tissue compared to SRS for treating brain metastasis [5, 6, 8, 9]. With improved patient immobilization and treatment accuracy on standard linear accelerator, the efficacy of SRT is comparable to SRS but without the need to invest in specialised equipment.

At Waikato Regional Cancer Centre (WRCC), the brain SRT program has been running since March 2017. A total of 28 patients were treated in the first 27 months, and all these cases were brain metastases which occurred in cerebellum and cerebrum. VMAT approach with a mixture of coplanar and non-coplanar fields was adapted as the treatment technique in our brain SRT program. Also, a multi-isocentric technique was used, i.e. a treatment plan was designed for each lesion. In 2019, the department installed a new Truebeam linear accelerator (Varian Medical Systems) which is capable of HyperArc (HA) treatments. HA is a VMAT-based SRS solution introduced by Varian, which includes patient immobilisation, assisted treatment planning of intracranial targets, and automated treatment delivery.

Since HyperArc was introduced commercially in 2017, most publications focus on the comparison of plan qualities between HyperArc and other SRS treatment techniques such as standard VMAT [10-12], CyberKnife [13-15], and Gamma Knife [16]. These studies show that HyperArc can create similar plans dosimetrically compared to other SRS techniques, while CyberKnife and GammaKnife plans are better for very small lesions. In addition to brain lesions, other studies have also demonstrated HyperArc can be used to treat disease at the nasopharynx [17] or lesions at the scalp [18]. Despite the number of published articles on HyperArc, a technical note published by Popple and Snyder is the only source of information to provide details on HyperArc commissioning [19].

The aim of this article was to share our experience of implementing HyperArc clinically at Waikato Regional Cancer Centre in New Zealand. This article also included retrospective planning comparison between HyperArc and VMAT plans and dosimetric verification of HyperArc plans.

Materials and Methods

Our HyperArc treatment capable TrueBeam machine is equipped with Millennium 120 leaf MLC and PerfectPitch 6 DOF couch. Varian IsoLock procedure was completed during the new machine installation to determine whether the radiation isocentre radii (gantry/collimator/couch) is within 0.75 mm. This system is also able to use iterative cone-beam CT (iCBCT) reconstruction algorithm, which reduces noise and leads to improved CBCT image quality [20, 21]. Previous brain SRT treatments were delivered on another Truebeam machine with the same machine specifications as the new machine but without HyperArc capability. The two machines are beam-matched, and the same beam data was used on both machines in beam configuration of the treatment planning system (TPS).

HyperArc plans were created in Eclipse TPS version 15.6 (Varian Medical Systems) and all dose calculations were done with analytical anisotropic algorithm (AAA 15.6.04). Dose calculation of HA plan does not require a specific beam model in Eclipse TPS, so no additional beam data was collected and no "HA-specific" beam model was configured. Only 6MV flattening filter (6MV) and flattening filter free (6MV-FFF) photon beam are designated to be used in our brain SRT program. In the configuration of AAA algorithms, profiles and depth dose curves with field size down to 2 x 2 cm^2 are included in beam data for both energies. For 6MV-FFF beam data, output factors are available to field size from 1 x 1 cm^2; however, only output factors of 3 x 3 cm^2 and up are available in our 6MV beam data. A dimensionless effective source size is used for both energies in our AAA configuration, and dosimetric leaf gap (DLG) values were obtained using the sweeping gap technique.

Another integral part of HyperArc is the utilization of Encompass SRS immobilisation system (Qfix). This non-invasive fixation device consists of the Encompass Overlay on Varian IGRT Couch Top, and employs the "clam-shell" like Fibreplast mask to immobilise the head to the Encompass. Furthermore, the Encompass model was introduced as one of the support structure in Eclipse v15.6. This model includes two structures, "Encompass" and "Encompass base". The "Encompass" is the supporting frame part of the board, with default HU value of 400. "Encompass base" is the board itself, with default HU of -400. Synder et al demonstrated in detail on how to validate the HU values for the Encompass model [22] and the default HU values can be modified in Eclipse if needed. First, the Encompass device was configured in RT Administration to enable HA support in our TPS and treatment unit. To activate HA plan creation in Eclipse, the Encompass structures have to be inserted to the patient image. The structures are then used by the TPS as a reference to define a patient protection zone in the reference image, in which collision-free treatment is expected if isocentre is located inside the patient protection zone.

Verification of TPS calculated target quality metrics

Eclipse can calculate four commonly used SRS target quality metrics to the selected target in HA plan. These metrics are RTOG conformity index (RTOG CI), Paddick conformity index (Paddick CI), gradient index (GI), and ICRU83 homogeneity index (ICRU83 HI). To evaluate the difference between manual calculated and Eclipse calculated values, seven HyperArc plans with single target were created and these targets were contoured with high resolution segmentation in TPS. Isodose structures of 100% and 50% prescription were generated in each plan, and the overlapping structures of PTV and 100% isodose structure were created using Boolean operator in Eclipse. The indices were then calculated manually using the following equations:

RTOG CI is the ratio of prescription volume (PV) to target volume (PTV) [23].

$$\boldsymbol{RTOG\ CI = PV/PTV} \tag{1}$$

Paddick CI is a measure of how well the prescription dose conforms the target considering the overlapping between PTV and PV (PTV_{PV}) [24].

$$\boldsymbol{Paddick\ CI} = \boldsymbol{(PTV_{PV})^2/(PTV \times PV)} \quad (2)$$

GI is the ratio of 50% isodose volume to prescription volume [25].

$$\boldsymbol{GI = V_{50\%}/V_{100\%}} \quad (3)$$

ICRU83 HI indicates the uniformity of dose distribution within the target volume and it is expressed as the equation below [26].

$$\boldsymbol{ICRU83\ HI = (D_{2\%} - D_{98\%})/D_{50\%}} \quad (4)$$

The values of $D_{2\%}$, $D_{50\%}$, and $D_{100\%}$ were determined from DVH of each plan.

Dosimetric comparison of HyperArc plans

Eleven previously treated brain SRT cases were selected in this retrospective planning study and the details are listed in Table 1. Among the eleven cases, seven of them had single lesion, three of them had two lesions, and one had three lesions. Therefore, sixteen VMAT plans were created. Intact lesions and post-surgery cavity targets are found in these eleven cases, and the tumour sizes ranged from 0.2 to 28.3 cm^3. A PTV margin of 2 mm was applied and PTV sizes ranged from 1.0 to 42.6 cm^3. Initially, only 6MV photon beam was used and jaw tracking was disabled. All dose calculations in this study were with heterogeneity correction and 1 mm grid size. In VMAT planning, isocentre was manually placed in the centre of each target, with an occasional small off-centre treatment (< 2 cm) to avoid collision. Usually, three fields with the mixture of coplanar and non-coplanar arcs were used in each plan and there was no restriction on couch angle and arc trajectory as long as the plan was collision-free. Automatic normal tissue objective (NTO) was used in plan optimization. On the contrary, mono-isocentric technique was used in HA plan, so multiple brain metastases were irradiated simultaneously; hence, only eleven HA plans were created. Similar arcs as the VMAT plans were selected from the five half arcs (2 coplanar half arch at couch angle 0º, 3 non-coplanar half arc at couch rotation 45º, 315º, and 90º or 270º) that are available in HA planning. Isocentre location, collimator angle, and field size were optimized automatically in HA plans. In plan optimization, HA plans used the same objectives as the VMAT plans, but SRS NTO was used in HA plans. All HA plans were normalized to create similar $V_{100\%}$ coverage to the PTV as their corresponding VMAT plans. To compare the plan quality between VMAT and HA plans, several metrics were obtained from each plans: $V_{100\%}$ coverage to PTV, D_{max}, Paddick CI, GI, and V_{18Gy} to normal brain tissue (i.e., brain minus GTV or CTV). These values were analysed using paired t-test. All tests were two tailed with defined significance level of 0.05.

Additional comparison in plan quality was performed between HA plans using 6MV and 6MV-FFF. Seven HA plans created previously were planned again with 6MV-FFF selected (case 2, 3, 4, 7, 8, 9, and 11). All settings and optimization objectives were kept the same, and all 6MV-FFF plans were normalized to produce similar $V_{100\%}$ to PTV as the 6MV plans. In addition to the plan quality metrics mentioned above, number of MU required per gray (MU/Gy) in each plan was recorded. The dosimetric parameters of $V_{100\%}$ coverage to PTV, D_{max}, Paddick CI, GI, and V_{18Gy} to normal brain were analysed using paired t-test. All tests were two tailed with defined significance level of 0.05. Another planning study during our HA commissioning was to investigate how jaw tracking changes the volume of low dose in HA plans. Several 6MV and 6MV-FFF HA plans were optimized again with jaw tracking enabled. The aim was to achieve similar target coverage between HA plans using static jaw technique (SJT) and jaw tracking technique (JTT). Afterwards, the isodose volumes of 10%, 20%, and 30% on each plan were determined and compared. These isodose volumes, Paddick CI, and GI were analysed using paired t-test. All tests were two tailed with defined significance level of 0.05.

Dosimetric validation of HyperArc plans

Point dose and film measurement were employed in dosimetric verification of plans created for the eleven cases shown in Table 1. Dosimetric verification had already been done on those previously used VMAT plans during their patient specific QA. The measurements were done with the CIRS IMRT Head and Neck Phantom (HN Phantom) using IBA CC01 ion chamber and Gafchromic EBT-XD films. The HN Phantom consists of ion chamber and film section and they were used separately in our measurement. Each section is 15cm in length. For the ion chamber section, measurement point of the ion chamber was located at the centre of the phantom. In the film section of the phantom, slabs were arranged so that the film slab with 3 fiducials was located approximately in the middle of phantom. The film slab holds a 10 x 10 cm^2 film in transverse plane and imprints three pinpricks on the film for registration. Reference CT images of each section of the HN Phantom were obtained separately. Then, point dose and film verification plans were created in TPS for each VMAT plans. During the measurement, the phantom was rest on a customized foam that placed on a head and neck board overlaying on the IGRT couch top. CBCT match with six degree of freedom correction was performed before delivering the verification plan. The point dose results were then compared to the expected dose calculated by TPS and the percentage differences were determined afterwards. In addition to exposing application film, a set of calibration films was exposed on the same machine either before or after the exposure of application film.

Our in-house film dosimetry protocol was modified from the "One-scan" film dosimetry protocol described by Lewis et al [27]. All the films were stored in the dark for at least 12 hours before they were scanned together on an Epson 11000XL flatbed scanner. A new calibration curve was then determined on each scan image. The pixel values of the scan image were converted to dose using the specific calibration curve; hence, our film results were independent of daily output variation. To convert the film image to a dose image, this was done using an in-house ImageJ plugin. Subsequently, the dose image and the TPS exported dose plane were imported to OmniPro I'mRT (IBA Dosimetry) program to perform 2D gamma analysis. In our gamma analysis, both absolute and relative gamma analyses were performed using 3%, 1mm and 5%, 1mm criteria. In absolute gamma, both measurement and calculation were normalized by the prescribed dose in each case. In relative gamma, measurement and calculation were normalized by its own maximum dose in region of interest. In all gamma analysis, 10 % threshold was used.

When dosimetric verification was performed on HA plans, measurements were done with the same HN Phantom but on the Encompass Overlay. Since the size of ion chamber and film sections of HN Phantom are identical, only one Fibreplast shell was created to hold the phantom on Encompass. Reference CT images were acquired for each phantom on the Encompass with shell. The Encompass couch structures were inserted to the CT images of the phantoms after they were imported to the TPS. For each HA plan, point dose and film verification plans were created. If multiple targets were found in a single plan, multiple point dose verification plans were created and measurements were performed on each target. However, individual film measurement at each target was not necessary if a single film captured the dose distribution of multiple targets. Similarly, CBCT match was performed before point dose and film measurement. Percentage differences of point dose measurements were determined. Same film dosimetry protocol was used and gamma passing rates were recorded using the same absolute and relative gamma criteria. To compare VMAT and HA plans, percentage difference of point dose measurement and gamma passing rates were analysed using paired t-test. All tests were two tailed with defined significance level of 0.05.

Dosimetric verification were also performed on HA plans using 6MV-FFF beam. Point dose and film measurements were performed on the seven HA plans with 6MV-FFF that listed in the section of dosimetric comparison. Afterward, point dose and film results were compared between HA plans with 6MV and 6MV-FFF beam. Percentage difference of point dose measurement and gamma results were analysed using paired t-test. All tests were two tailed with defined significance level of 0.05.

Off-centre Winston Lutz test

To evaluate the precision of treatment delivery for targets away from isocentre, off-centre Winston Lutz test [28] was performed during the commissioning of HyperArc. First, CT images of a Winston Lutz phantom (WL^3 phantom, Varian Medical Systems) were acquired and imported into the TPS. Multiple Winston Lutz test plans were created with the isocentre placed at various distances away from the centre of the phantom. In each plan, eight fields were created and their configurations are shown in Table 2. All fields are collimated by MLCs to create a 2 x 2 cm^2 field in which the field centre was aligned to the central ball bearing of the phantom. Phantom off-axis up to 9 cm were evaluated in lateral, longitudinal, and vertical direction. After setting up the WL^3 phantom with the laser isocentre, couch shift was applied to set the phantom off-axis, followed by CBCT match. During the Winston Lutz test, MV images were acquired by the electronic portal imaging device (EPID) panel. The image set was then analysed by DoseLab Pro (Version 7, Varian Medical Systems). DoseLab Pro determined the maximum total delta from the acquired images of the Winston Lutz test. The maximum total delta is the maximum amount of variation observed between the radiation field centre and the expected linac isocentre (i.e. ball bearing centre) during the rotation of gantry, collimator, and couch; therefore, it is a maximum discrepancy found in each set of Winston Lutz test.

Results

Verification of TPS calculated target quality metrics

Manual and TPS calculated RTOG CI, Paddick CI, GI, and ICRU83 HI of seven HA test plans were tabulated in Table 3. Comparing manual and TPS calculation, the differences in Paddick CI ($p = 0.22$) and ICRU83 HI ($p = 0.96$) are not statistically significant. On the contrary, our analysis indicates TPS calculation yields significantly better GI than manual calculation ($p = 0.005$), while manual calculated Paddick CI values are, on average, smaller than TPS calculation ($p = 0.002$).

Dosimetric comparison of HyperArc plans

Table 4 shows the comparison of plan quality between VMAT and HA techniques in brain SRT. Our results indicate no significant difference in $V_{100\%}$ of PTV ($p = 0.42$) and D_{max} ($p = 0.38$) between VMAT and HA plans. However, our analysis shows that better Paddick CI ($p = 0.00006$), GI ($p = 0.001$), as well as V_{18Gy} to normal brain ($p = 0.0003$) can be found in most HA plans than VMAT plans. Case 4 is the only exception with VMAT plans achieved better in both conformity index and gradient index than the corresponding HA plan. Nevertheless, V_{18Gy} to normal brain of the HA plan is still smaller than the VMAT plan in this case.

Table 5 compares the plan qualities between HA plans using 6MV and 6MV-FFF beam. Results indicate no difference can be found in the dosimetric parameters $V_{100\%}$ to PTV ($p = 0.74$), D_{max} ($p = 0.71$), Paddick CI ($p = 0.72$), and V_{18Gy} to normal brain ($p = 0.16$) between the two energies. Our results show that all 6MV-FFF plans have significantly smaller GI values ($p = 0.0003$), which indicates 6MV-FFF beam can create better dose fall-off outside the PTV. Additionally, numbers of monitor unit per Gray are compared in this study, and the results indicate, on average, 6MV-FFF plans required higher MU/Gy than 6MV plans with case 3 is the only exception.

Table 6 shows the values of Paddick CI, GI, and the low dose volume in HA plans using static jaw technique (SJT) or jaw tracking technique (JTT). To investigate how JTT impacts the amount of low dose received by patients, the volume of 10%, 20%, and 30% prescription dose in each plans were determined. Our results indicate there is no significant difference in Paddick CI ($p = 0.13$) and GI ($p = 0.50$) between plans using SJT and JTT. On the contrary, jaw tracking technique reduces the amount of low dose received by the patient. On average, the low dose volume is

reduced by 7%, 12%, and 14% for $V_{30\%}$ (p = 0.0009), $V_{20\%}$ (p = 0.002), and $V_{10\%}$ (p = 0.007) respectively when JTT is applied in HA planning.

Dosimetric validation of HyperArc plans

Point dose and film verification plans of VMAT and HA plans listed in Table 4 were delivered and the results are tabulated on Table 7. Table 7 includes percentage differences of point dose measurement and passing rates of gamma analysis to film using 3%, 1mm and 5%, 1mm criteria. In addition, mean and standard deviation (SD) of point dose and film results were calculated and shown in the table. In our point dose measurement, percentage differences between measurement are calculation were determined to be 1.3 ± 1.2% and 1.6 ± 1.1% for VMAT and HA plans respectively and our statistical analysis shows no significant difference between the results (p = 0.46). In absolute gamma analysis of film with 3%/1mm criteria, the average passing rates were determined to be 91.3 ± 7.2% and 88.6 ± 8.0% for VMAT and HA plans (p = 0.46). With 5%/1mm criteria, the average passing rates in absolute gamma analysis were determined to be 97.4 ± 2.3% and 94.9 ± 5.4% for VMAT and HA plans respectively (p = 0.09). In relative gamma analysis using 3%/1mm criteria, average passing rates were determined to be 95.9 ± 5.5% and 98.0 ± 1.8% for VMAT and HA plans (p = 0.18), and 99.1 ± 1.4% and 99.6 ± 0.4% for VMAT and HA plans using 5%/1mm criteria in relative analysis (p = 0.15). As a result, our statistical analysis shows no significant difference in film results between VMAT plans and HA plans.

Table 8 shows both point dose and film measured results of HA plans using 6MV and 6MV-FFF beam. No significant difference was found in all our film analysis between the two energies. In absolute gamma analysis, average passing rates are 91.4 ± 6.2 % and 91.9 ± 8.2 % for VMAT and HA with 3%/1mm criteria (p = 0.75), 96.9 ± 2.3 % and 97.3 ± 3.2 % for VMAT and HA with 5%/1mm criteria (p = 0.50). In relative gamma analysis of film, average passing rates are 98.6 ± 1.6 % and 98.4 ± 2.2 % for VMAT and HA using 3%/1mm criteria (p = 0.81), 99.7 ± 0.5 % and 99.6 ± 0.6 % for VMAT and HA with 5%/1mm criteria (p = 0.83). On the contrary, point dose results indicate 6MV-FFF plans have better agreement with the calculation than 6MV plans (p = 0.049), with the percentage differences equal to 1.7 ± 1.2 % and 0.9 ± 1.7 % for 6MV and 6MV-FFF plans respectively.

Off-centre Winston Lutz test

Maximum total delta obtained from off-centre Winston Lutz test are tabulated in Table 9. Each value of maximum total delta is an average of five measurements and the uncertainty is the standard deviation. Our results show that the delta value increases when the target distance is further away from machine isocentre in both lateral and longitudinal direction. However, maximum total delta only changed slightly (between 0.5 and 0.7 mm) when off-centre Winston Lutz test was performed in the vertical direction.

Discussion

Our retrospective planning study shows that HyperArc plans have improved conformity index and gradient index compared to our previously treated VMAT plans. Our investigation on target quality metrics shows that there is discrepancy up to 0.09 in Paddick CI whether it is determined manually or calculated by Eclipse. The improved conformity index of HA plans could be the result of difference in manual and TPS calculation rather than improvement in dose conformity. Since the same beam model and optimization objectives were used in both VMAT and HA plans, the steeper dose gradient of HA plans is the result of SRS NTO. SRS NTO improves dose fall-off outside the targets without applying additional tuning structures in HA plans [13]. If proper parameters are set

manually in normal tissue objective, a similar sharp dose gradient around PTV can be achieved in VMAT planning. However, SRS NTO put higher weighting on potential dose overlapping area between targets in order to reduce the amount of dose bridging if there are more than one target in the plan [29]. This additional feature of SRS NTO cannot be achieved alone using automatic NTO or manual NTO; therefore, SRS NTO is a better normal tissue objective for treatment plans with multiple targets. Additionally, the improved gradient index of HA plans leads to the reduction of radiation received by normal brain tissue; hence, it reduces the change of developing radionecrosis in brain.

Collimator angle optimization in HA planning reduced the "island blocking problem" [30] and it is recommended to be used in all HA plans. In our experience, the collimator angle optimizer worked extremely well in HA planning for treating 2 to 3 targets simultaneously. However, it is expected to become difficult to optimize collimator rotation with increasing number of targets. As a result, splitting treatment to multiple plans could be an option if the collimator angle optimizer fails to find a fixed collimator angle to properly shield area between targets.

When comparing the dosimetric impact of HA plans using 6MV flattened beam and flattening filter free beam, our results indicate both 6MV and 6MV-FFF beams can achieve similar coverage and dose conformity to the PTVs. However, using 6MV-FFF beam leads to better dose fall-off than 6MV beam, and it could be the result of a steeper penumbra of the reduced beam hardening of 6MV-FFF beam. Additionally, our results show that using 6MV-FFF beam to treat off-centre target requires higher MU to deliver the same amount of dose to the target. The reason is because of the lower intensity in off-axis shown on the beam profiles. Therefore, similar MU/Gy is expected to find in single target plans between the two energies when the isocentre is located in the PTV. Case 7 is an exception with about 30% higher in MU/Gy when using 6MV-FFF beam because it is an off-centre treatment. With a separation about 13 cm between the centre of PTV and the isocentre, case 7 required much high MU/Gy than the other plans with multiple targets. Nevertheless, a realistic separation for intracranial target should be within 7 cm, so MU/Gy of 6MV-FFF should be about 10 - 15% higher than 6MV plans that shown in our multiple-target plans. Since the amount of MU increased should not increase the amount of leakage radiation significantly, it is recommended to use 6MV-FFF energy in HA plans. Not only the treatment delivery is faster when using 6MV-FFF beam, our study found that 6MV-FFF plans is better dosimetrically. However, there would be no time benefit of using 10MV-FFF beam in our brain SRT program, which has a higher maximum dose rate than 6MV-FFF beam (2400 vs 1400 MU/min). With prescription dose per fraction between 6 and 9 Gy, instantaneous dose rate of our 6MV-FFF plan rarely reached 1400 MU/min. Even planning with 10MV-FFF beam, the instantaneous dose rate in a plan is expected to remain below 1400 MU/min, so treatment time could not be improved.

Since jaw tracking is designed to reduce the amount of MLC leakage and not affecting the MLC aperture in any control point, jaw tracking should only affect the amount of low dose (< 50% of the prescribed dose) received by the patient. Our planning study indicates that dosimetric parameters, such as conformity index and gradient index, show no significant difference between plans using static jaw technique and jaw tracking technique; therefore, the same planning objective should be able to achieve using JTT. However, JTT reduces the amount of low dose received by the patient in both single- and multiple-target treatments. As a result, it is recommended to use jaw tracking in all HA planning to reduce the low dose to normal tissue and could allow more flexibility on future brain metastasis treatment.

HyperArc does not require configuring a specific beam model during HA commissioning, so this reduces time required to commission HA. A technical note by Popple and Snyder provides a good introduction to beam configuration regarding dose calculation on small target [19]. Since beam configuration in Eclipse ignores profiles and depth dose curves for open field less than 2 x 2 cm^2, comparing TPS calculation to measurement of depth dose curves and beam profiles for field size < 2 x 2 cm^2 is recommended. Even though the investigation of small field dosimetry is not within the scope of this article, the authors recommend physicist should investigate the accuracy of your beam model in calculating dose of small target if this has not been done prior to HyperArc commissioning. In our experience, a 6MV beam model had already been used in our brain SRT treatment since 2017. Accuracy of this

beam model in dose calculation had been studied during the commissioning of our brain SRT program, and the subsequent patient specific QA results gave us enough experience and confidence on the accuracy of dose calculation for VMAT based SRT plans. When commissioned the new machine and HyperArc, same beam data and beam configuration were used to create the beam model of our new machine. Therefore, same result in dosimetric verification is expected to the new beam model.

In our dosimetric verification study, the results show that the difference between VMAT and HA plans is not statistically significant. This result is not surprising because they used the same beam models in dose calculation. Hence, the same level of agreement between measurement and calculation is expected. The only difference is the use of SRS NTO in planning optimization in HA plans. So, this result also indicates that SRS NTO in plan optimization does not significantly increase the complexity of beam modulation even though it improves the dose fall-off in the plans. On the contrary, the average point dose result of 6MV-FFF plans shows better agreement than plans using 6MV beam. Although the p-value is only slightly smaller than the significance level of 0.05, the difference is still statistically significant. This small difference could be the result of availability of output factor down to 1 x 1 cm^2 in 6MV-FFF beam model compared to only 3 x 3 cm^2 in 6MV beam model.

Although mono-isocentric technique is efficient in irradiating multiple brain metastases in a single treatment, small setup uncertainty can propagate and lead to bigger positional errors to targets away from the isocentre. Hence, different PTV margins may be required to ensure dose coverage to off-centre targets. At WRCC, Winston Lutz test has been performed routinely since the introduction of brain SRT program, and a tolerance of 1 mm was defined. In our off-centre Winston Lutz test, evaluation was performed up to 9 cm away from the isocentre. Our result indicates an increase in maximum total delta associated with the increase in separation between target and isocentre. When the target is 9 cm off-centre, our results show that maximum delta could exceed 1 mm, which exceeds the tolerance in our Winston Lutz test. In more realistic scenario, maximum separation between target and isocentre is approximately 7 cm for treatment of multiple brain metastases using mono-isocentric technique. In this case, the maximum total delta was within 1 mm tolerance. As a result, we decided not to adjust the PTV margin for mono-isocentric technique. Nevertheless, each department should evaluate their machine capability and determine adequacy of the PTV margin.

Conclusion

Since the introduction of HyperArc at WRCC, forty patients have been treated with HA technique in the first 17 months. Besides brain metastases in cerebellum and cerebrum, we also treated brain metastases in brainstem. Recently, patients with acoustic neuromas were treated at WRCC using HA technique. HyperArc simplifies the planning of stereotactic treatment for brain. Also, it improves the dosimetry and patient safety, as well as the efficiency in treatment delivery compared to the standard VMAT technique. In our experience, HA greatly improves efficiency in treatment planning, thus improving the turnaround time in our pre-treatment process. The simplification of creating high quality SRS plans and quicker turnaround time help in expanding our brain SRT program, so it becomes available to more patients. Even though commissioning HyperArc is simple, it is the responsibility of the physicist to investigate the dosimetric accuracy and treatment precision of their own systems and determine the limitations such as how small and how far a target can be treated accurately and safely.

Declarations

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors

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