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Dosimetric study of rapid arc and intensity-modulated radiotherapy with and without flattening filter

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ABSTRACT

Objective: This study aims to evaluate Intensity Modulated Radiotherapy (IMRT) and Rapid Arc based on Flattening Filter (FF) and Flattening Filter Free (FFF) beams.

Materials and Methods: Twelve patients with single brain metastases and a dose prescription of 25 Gy in 5 fractions are selected and for each patient, both IMRT and Rapid arc plans are created with and without FF. All plans are analysed and compared based on various dosimetric parameters for Planning Target Volume (PTV) and Organ at Risks (OARs) along with technical parameters.

Results: The results among PTV dosimetric parameters improved with Rapid Arc plans from IMRT in both FF and FFF modes like the D98% bettered as (23.59 ± 0.85) and (23.65 ± 1.16) respectively with P values 0.011 and 0.025. The D80% of FFF arc plan has P value 0.030 with dose value (24.89 ± 0.59) and HI95% of both FF and FFF showed significant values (0.09 ± 0.04) and (0.10 ± 0.05) with P values 0.009 and 0.058. Conformation Number and Dose Gradient Index values of FF arc plan improved as (0.8 ± 0.06) and (0.27 ± 0.05) with P values 0.014 and 0.0001. Among OARs, the D0.1cc and Dmax of the Brainstem improved as (11.18 ± 6.59), (13.54 ± 7.09) in the FF arc plan, and (11.44 ± 8.33), (12.66 ± 8.38) in FFF arc plans. The V5, V10 and mean dose values of Healthy Tissue enhanced as (5.38 ± 3.98), (1.89 ± 1.61), (0.89 ± 0.51) the in FF arc plan, and (5.15 ± 3.35), (1.81 ± 1.35), (0.87 ± 0.46) in FFF arc plan with P values 0.022 and 0.017 for V5 and V10 of FFF arc plan. With Technical Parameters, the MU came better as (1148.5 ± 162.1) and (1297.5 ± 307.1) in FF and FFF arc plans whereas with TT, the FF arc plan improved to (4.38 ± 1.09) with a P value of 0.011.

Conclusion: The study reveals the benefits of Rapid arc from IMRT in all sectors of PTV dosimetric parameters, OAR dose values, and technical parameters in both FF and FFF modes.

Key words: FF, FFF Rapid Arc, IMRT, DVH

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INTRODUCTION

One of the commonest signs of systemic cancer is Brain metastases and its diagnosis has increased due to developed imaging modalities like Magnetic Resonance Imaging (MRI) and improved systemic control of cancer [1]. To overcome the difficulty of conventional radiotherapy techniques in achieving OAR tolerance doses, modern delivery techniques like Intensity Modulated Radio-Therapy (IMRT) and Rapid Arc emerged. A basic principle of IMRT is the irradiation of the target from different angles with optimized radiation beams to deliver a high dose to the tumour and to reduce the dose to normal tissues as much as possible [2]. It is reported that by optimizing IMRT plans, it is possible for further dose escalation without increasing the toxicity of normal tissues [3]. It is also reported that even though IMRT enhances the Local Tumour Control Probability (LTCP) and decreases the radiation-induced Normal Tissue Control Probability (NTCP), it faces the problems of high output dose, increased treatment time, low dose exposure of a large volume of healthy tissues, high leakage, and transmission dose, scattered radiation as well as secondary cancer risk [4]. One of the main challenges of IMRT technology is that it is time-consuming, possesses complex procedures of quality assurance, has high peripheral doses, and has higher Monitor Units (MUs). It is also reported that IMRT requires accurate treatment volume margins as its conformity depends mainly on organ movement and subsequent requisite margins [5]. The idea of planning and delivery of volumetric modulated arc therapy-based technology called Rapid Arc is developed by Otto [6]. Rapid arc is the method of radiotherapy treatment by continuous rotation of radiation source through a complete 360° beam angle and it was developed by the optimization of ioned in some studies that no significant difference is found between a single arc and IMRT plan in their dosimetric parameters of both Planning Target Volume (PTV) and Organ at Risks (OARs) other than technical parameters [7, 8]. The main uniqueness of the present work is that we have compared both the techniques dosimetrically and technically with and without a Flattening Filter (FF) which makes it a complete study since FFF has its remarkable advantage of higher dose rate options which results in lesser treatment time of patients mainly in Stereotactic Radio Surgery (SRS) or Stereotactic Body Radiation Therapy (SBRT).

MATERIALS AND METHODS

A sum of twelve brain metastases patients is selected for the

study who were in the 45-75 age group, after achieving the institutional ethical committee approval. Patients were positioned in the supine position in a custom-made mask and Computed Tomographic (CT) images were taken using 1 mm slice thickness through the whole brain which was then exported to the Treatment Planning System (TPS - Eclipse TPS version 15.06) to later fuse with respective MRI for better segmentation and contouring of Tumour Volumes (TV) and OARs based on the treatment protocol (International Commission on Radiation Units and Measurements (ICRU) 50 and 62). The different tumour volumes contoured are Gross Tumour Volume (GTV) for which a symmetrical 3 mm margin was given to generate PTV by considering the geometric accuracy. The OARs delineated are Optic chiasm, Brainstem, Left and Right optic nerves, Left and Right eyes, and Left and Right Lens. An additional Healthy Tissue (HT) is defined as the patient's volume scanned by CT excluding the volume of PTV.

The dose prescribed for the tumour volume was 25 Gy in 5 fractions (5 Gray per fraction). For the same patient, both IMRT plan and Rapid arc plan are created each in both FF and FFF modes. The IMRT plans were created using 6 MV photon beams and 5 fixed beam gantry angles for a True beam linear accelerator provided with 120 leaves High Definition (HD) Multi-Leaf Collimator (MLC) using the Eclipse TPS and similarly, the Rapid arc plans used a double arc in a clockwise and anti-clockwise direction with angles based on tumour location. In both IMRT and Rapid arc, the FF plan dose rate set was 600 MU per min and for the FFF plan, it was 1200 MU per min. To minimize the tongue and groove contribution during Rapid Arc rotation, collimator rotation was set to 10° for one arc and 350° for the reverse arc. In all plans, all machine and optimization parameters were kept the same except the dose rate, to evade the bias and all plans were optimized to achieve the given planning objectives using the Photon optimizer (15.6.05) algorithm and the Anisotropic Analytical Algorithm (AAA) algorithm for dose calculation with 2.5 mm grid size. During optimization, priorities were tuned to obtain the optimum results for each case and the cumulative Dose Volume Histogram (DVH) was generated for evaluation. The plans under study were analysed based on DVH, target coverage, dose to OARs as well as technical parameters. The plan objectives for the PTV were that at least 95% of PTV should be covered by 95% of the dose prescribed and the dose maximum must not exceed 107%. The dose constraints followed for OARs are optic chiasm: Dmax<20 Gy; Brainstem: D0.1cc<20 Gy, Dmax<25 Gy; Left and Right Optic nerve: D0.2cc<23 Gy, Dmax <25 Gy; Left and Right Eye: Dmax <25 Gy; Left and Right Lens: Dmax<10Gy where Dmax-Maximum dose, D0.1cc- Dose to 0.1cc of volume, D0.2cc- Dose to 0.2cc of volume. Different dosimetric indices such as Conformity Index (CI), Homogeneity Index (HI), Conformation Number (CN), Coverage Index (COVI), and Dose Gradient index (DGI) were analysed for evaluating the plans [9]. It is also stated that an ideal plan will have full uniform dose coverage which is exactly confirmed to the target volume with a step-wise dose fall-off outside the target [10].

RTOG CI was used to evaluate the degree of conformity of dose distribution which is calculated as CI=PI/TV where PI is Prescribed Isodose volume and TV is the Tumour Volume. The RTOG 90-05 recommends that the CI value should be kept near 1 and it is optimal when the value comes between 1 and 2, if between 2 and 2.5 it is a minor variation and 2.5 is a major variation. The HI is described as HI=(D2%-D98%) per D50% where the values D2%, D98% and D50% are dose received by 2%, 98% and 50% volumes respectively. The HI value ranges from 0 to 1 where the lower HI value shows better homogeneity [11]. The CN was defined for each plan for the relative measurement of target coverage and sparing of OARs [12]. The CN is calculated by Van't Riet Model whose ideal value is 1 and is defined as CN95%=(TVpi/TV)×(TVpi/Vpi) where TVpi is the Target Volume within 95% of prescribed isodose volume, TV is the tumour volume and Vpi is the Volume of 95% of prescribed isodose volume. The COVI is calculated and noted down as COVI=TVpi/TV, whose ideal value is 1. The DGI whose ideal value is 1 is calculated using the formula PI/D50%, where PI is the prescribed isodose volume, and D50% is the volume of 50% of the prescribed isodose volume. The mean dose, D2%, D98%, and D50% values of PTV of all plans was also noted down for evaluation.

Among OARs, the maximum dose, the mean dose, and proper values of volume receiving Gy were noted. For the healthy tissue, V5, V30 and mean dose was taken, where V5 is the volume receiving 5 Gy and V30 is the volume receiving 30 Gy dose. For assessing the efficiency of IMRT and Rapid arc, delivering parameters such as MU and TT are noted and compared. To analyse the data, Paired t-test was used, where $p<0.05$ was considered statistically significant [13].

RESULTS

The beam on fields of IMRT plan of a patient is shown in Figure 1.

The beam on fields of Rapid Arc plan of a patient is shown in Figure 2.

From the results of PTV in Table 1, it is very evident that dosimetric parameters, except mean dose and D50%, showed significant values in rapid arc plans of both FF and FFF energies when compared to IMRT plans. The D98% values of both 6FF and 6FFF showed their significant values in arc plans as (23.59 ± 0.85) and (23.65 ± 1.16) with P values of 0.011 and 0.0925 respectively. For D80%, both the significant dose values are found with arc as (24.77 ± 0.46) and (24.89 ± 0.59) with P values 0.073

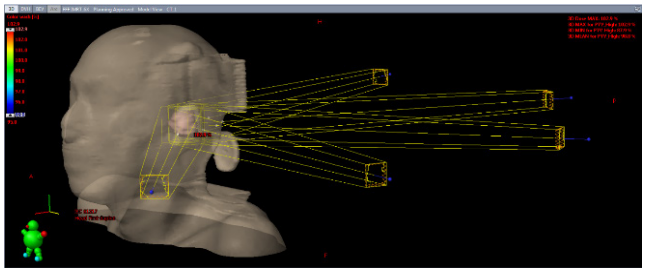

Fig. 1. Shows the beam on fields of IMRT plan of a patient.

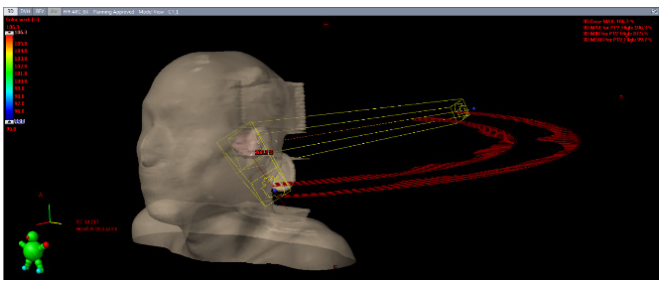

Fig. 2. Shows the beam on fields of Rapid Arc Plan of a patient

and 0.030, respectively for FF and FFF plans. For the dosimetric parameter HI95%, the significant dose values obtained for FF and FFF rapid arc plans compared to IMRT plans are (0.09 ± 0.04) and (0.10 ± 0.05), with the respective P values 0.009 and 0.058. Similarly, for CN95%, the FF and FFF rapid arc plans got their better values as (0.80 ± 0.06) and (0.79 ± 0.07) with P values of 0.014 and 0.296. For DGI value, it came significant with FF and FFF rapid arc plans as (0.27 ± 0.05) and (0.35 ± 0.22) with P values 0.0001 and 0.120 respectively.

From the results of PTV in Table 1, it is very evident that dosimetric parameters, except mean dose and D50%, showed significant values in rapid arc plans of both FF and FFF energies when compared to IMRT plans. The D98% values of both 6FF and 6FFF showed their significant values in arc plans as (23.59 ± 0.85) and (23.65 ± 1.16) with P values of 0.011 and 0.0925 respectively. For D80%, both the significant dose values are found with arc as (24.77 ± 0.46) and (24.89 ± 0.59) with P values 0.073 and 0.030, respectively for FF and FFF plans. For the dosimetric parameter HI95%, the significant dose values obtained for FF and FFF rapid arc plans compared to IMRT plans are (0.09 ± 0.04) and (0.10 ± 0.05), with the respective P values 0.009 and 0.058. Similarly, for CN95%, the FF and FFF rapid arc plans got their better values as (0.80 ± 0.06) and (0.79 ± 0.07) with P values of 0.014 and 0.296. For DGI value, it came significant with FF and FFF rapid arc plans as (0.27 ± 0.05) and (0.35 ± 0.22) with P values 0.0001 and 0.120 respectively.

From the results of OARs in Table 2, the significant results seen with Rapid arc plans for both FF and FFF energies, when compared to that of IMRT is mainly with the Brainstem and HT. The D0.1cc value of the Brainstem improved to (11.18 ± 6.59) and (11.44 ± 8.33) in FF and FFF Rapid arc plans, whereas the Dmax value enhanced to (13.54 ± 7.09) and (12.66 ± 8.38) in FF and FFF rapid arc plans respectively from their IMRT plan values. Among HT, the V5 improved to (5.38 ± 3.98) and (5.15 ± 3.35) in FF and FFF Rapid arc plans, with a significant P value of 0.022 in the FFF rapid arc plan from the IMRT plan values. Similarly, the V10 value of HT was reduced to (1.89 ± 1.61) and (1.81 ± 1.35) in their FF and FFF Rapid Arc plans with the P values 0.064 and 0.017, respectively. The mean dose of the same was also reduced to (0.89 ± 0.51) and (0.87 ± 0.46) in FF and FFF rapid arc plans from the IMRT plan values.

Tab. 1. PTV parameters of all plans along with the P values

PARAMETERS	FF			FFF		
	IMRT	Rapid Arc	P VALUE	IMRT	Rapid Arc	P VALUE
Mean Dose	25.01 ± 0.81	25.08 ± 0.55	0.629	25.17 ± 0.78	25.28 ± 0.92	0.647
D2%	25.99 ± 0.98	25.92 ± 0.62	0.65	26.13 ± 1.01	26.20 ± 0.67	0.538
D98%	22.76 ± 1.65	23.59 ± 0.85	0.011	22.87 ± 1.69	23.65 ± 1.16	0.025
D50%	25.06 ± 0.75	25.17 ± 0.56	0.392	25.20 ± 0.70	25.34 ± 0.59	0.206
D80%	24.45 ± 0.76	24.77 ± 0.46	0.073	24.63 ± 0.63	24.89 ± 0.59	0.03
CI95%	1.12 ± 0.26	1.10 ± 0.07	0.85	1.17 ± 0.25	1.12 ± 0.09	0.36
HI95%	0.13 ± 0.07	0.09 ± 0.04	0.009	0.13 ± 0.07	0.10 ± 0.05	0.058
CN95%	0.69 ± 0.15	0.80 ± 0.06	0.014	0.74 ± 0.18	0.79 ± 0.07	0.296
COVI	0.87 ± 0.15	0.94 ± 0.06	0.071	0.92 ± 0.11	0.94 ± 0.07	0.412
DGI	0.22 ± 0.07	0.27 ± 0.05	0	0.23 ± 0.07	0.35 ± 0.22	0.12

FF- Flattening Filter; FFF- Flattening Filter Free; IMRT- Intensity Modulated Radiotherapy; HI- Homogeneity Index; CN- Conformation Number; COVI-Coverage Index; DGI- Dose Gradient Index

Tab. 2. OARs parameters of all plans along with the P values

PARAMETERS		FF			FFF		
		IMRT	Rapid Arc	P VALUE	IMRT	Rapid Arc	P VALUE
OPTIC CHIASM	Max Dose	1.69 ± 1.86	2.96 ± 3.25	0.171	1.54 ± 1.79	2.35 ± 2.27	0.033
BRAINSTEM	0.1CC	11.86 ± 7.02	11.18 ± 6.59	0.153	11.57 ± 8.22	11.44 ± 8.33	0.766
	Max Dose	13.61 ± 7.82	13.54 ± 7.09	0.912	14.92 ± 8.50	12.66 ± 8.38	0.316
LT ON	0.2CC	0.70 ± 0.70	1.08 ± 1.12	0.066	0.67 ± 0.64	1.15 ± 1.33	0.072
	Max Dose	1.03 ± 0.90	1.52 ± 1.36	0.043	0.97 ± 0.81	1.56 ± 1.46	0.036
RT ON	0.2CC	0.71 ± 0.75	1.14 ± 1.22	0.021	0.68 ± 0.67	1.17 ± 1.29	1.016
	Max Dose	1.03 ± 0.93	1.14 ± 1.22	0.405	0.98 ± 0.86	1.17 ± 1.29	0.267
LEFT EYE	Max Dose	1.09 ± 0.79	1.21 ± 1.08	0.513	1.04 ± 0.77	1.23 ± 1.11	0.316
RIGHT EYE	Max Dose	1.21 ± 0.95	1.80 ± 1.19	0.011	1.14 ± 0.90	1.71 ± 1.20	0.03
LEFT LENS	Max Dose	0.48 ± 0.60	0.65 ± 0.59	0.209	0.40 ± 0.43	0.64 ± 0.61	0.033
RIGHT LENS	Max Dose	0.53 ± 0.48	0.69 ± 0.56	0.052	0.55 ± 0.55	0.69 ± 0.59	0.126
HEALTHY TISSUE	V5	5.84 ± 3.47	5.38 ± 3.98	0.067	5.65 ± 3.07	5.15 ± 3.35	0.022
	V10	2.29 ± 1.47	1.89 ± 1.61	0.064	2.28 ± 1.35	1.81 ± 1.35	0.017
	Mean Dose	0.93 ± 0.47	0.89 ± 0.51	0.258	0.92 ± 0.44	0.87 ± 0.46	0.102

FF- Flattening Filter; FFF- Flattening Filter Free; IMRT- Intensity Modulated Radiotherapy

Tab. 3. Technical parameters of all plans along with the P values

PARAMETERS	FF			FFF		
	IMRT	Rapid Arc	P VALUE	IMRT	Rapid Arc	P VALUE
MU	1282.8 ± 411.7	1148.5 ± 162.1	0.3285	1366.2 ± 398.4	1297.5 ± 307.1	0.601
TT	6.41 ± 2.06	4.38 ± 1.09	0.011	2.27 ± 0.66	3.06 ± 1.02	0.066

FF- Flattening Filter; FFF- Flattening Filter Free; IMRT- Intensity Modulated Radiotherapy; MU- Monitor Units; TT- Treatment Time

From table 3 of Technical Parameters, it is very evident that Rapid Arc plans showed better values in both FF and FFF energies. The MU values were reduced to (1148.5 ± 162.1) and (1297.5 ± 307.1) in FF and FFF Rapid Arc plans from their IMRT plan values, whereas the TT value was reduced to (4.38 ± 1.09) in FF arc plan with a significant P value of 0.011 in FF.

DISCUSSION

Our study result tables very evidently show the dosimetric benefits of rapid arc plans compared to IMRT plans in both FF and FFF modes. This is a conflicting statement to many reports, such as in the study of Zhai et al., where he proved the supremacy of IMRT over rapid arc technology with cervical cancer treatment [14]. It is stated that IMRT, with the aid of non-uniform beam intensity, can improve target coverage with less dose exposure to nearby organs at risk, mainly for huge and irregular tumour volumes [15]. This study is contrary to multiple studies which showed that IMRT delivers limited radiation to normal tissues and so only it is dosimetrically superior [16, 17]. Another study result says that IMRT had better PTV dose conformity and OAR sparing when compared to rapid arc, especially for single arc plans than double arcs [18].

Our positive results of Rapid arc with better value outcomes are, mainly seen with all the PTV dosimetric parameters except for mean dose and D50%. When fixed field IMRT has a restricted number of radiation beams which will result in missing some ideal beam angles, the Rapid arc technology makes use of all possible beam angles during optimization, which helps to generate optimal dose distribution and produces better plans [19]. It is priory reported in a study that the steeper dose gradient around the TV is attained by the use of multiple concentric arcs in the Rapid arc technique with tight dose objectives [20]. The uniqueness of our study results is contrary to other studies' results which claim that the HI and COVI values do not differ significantly in their values between IMRT and Rapid arc plans [21, 22].

Among the OAR parameters, it came significant mainly in D0.1cc, Dmax of Brainstem and V5, V10, mean dose of HT. Rapid arc will promote the clinical results in radiotherapy patients as it can reduce the shift of the patient's position as well as the influence of swallowing motion on OARs during the treatment delivery [23].

The study results also showed better output values with the technical parameters like MU and TT of the Rapid Arc plan when compared to that of IMRT. The Volumetric Modulated Arc Therapy (VMAT) technology flexibly modifies the dose rate as per the target dose and OAR positions in the vicinity so that the gantry can rotate with uniform velocity to reduce inertia and thereby the treatment can be accomplished in one or few arcs. Rapid arc therapy allowed simultaneous variation of dose rate, rotation speed of gantry, and multi-leaf collimator during the treatment delivery [24]. This study hereby reveals the radiobiological advantage of Rapid arc with its lesser treatment time as reported by Shibamoto et al. that for Rapid arc, the treatment time interval is very shorter, which may promote the biological effect as the sub-lethal repair occurs in 2 minutes to 3 minutes or longer time between two fractions of radiotherapy [25].

In both FF and FFF modes, the Rapid Arc gave lesser MU compared to IMRT, which is very advantageous as it is explained that the increased MUs in IMRT compared to Rapid Arc may increase the risk of low dose irradiation of HT with IMRT, which in turn enhance the risk of secondary malignancies [26, 27]. Some studies suggested the increase of Integral Dose in IMRT is due to a large number of beam lets and higher MUs used [28].

The lesser TT in Rapid Arc is beneficial as reported in a study that the extended delivery time it takes per fraction for IMRT may deteriorate the treatment accuracy due to the intra-fractional motion of the patient [29]. The IMRT technique needs more time for its delivery as it has to reprogram the linear accelerator between fixed gantry angles, rotate the gantry to each gantry angle position as well as deliver split fields with higher MUs. The feature of reduced TT in a rapid arc is advantageous in many aspects, such as comfort for patients lying with custom-made masks, reduction of the intra-fraction motion risks, minimizing the displacement of organs as well as helps to accommodate more patients for treatment under the same machine.

In our study, we have included a double arc for rapid arc plans as it is mentioned in studies that for intermediate complex targets lying adjacent to critical structures, two or three arcs will be needed instead of a single arc, and also that rapid arc with single arc and IMRT showed similar target dose distribution and OAR dose exposure compared to IMRT [30]. Similarly, stated by Bortfeld that a single arc rapid arc may intolerably compromise the quality of target dose distribution in complex cases [31].

When compared to studies that compared rapid arc and IMRT with positive outcomes on an arc, our study stays unique with its very positive results of Rapid arc on PTV parameters along with OAR and technical parameters, as most of them reported only improvement in OARs, reduced MUs, TT and no benefits on PTV parameters [32].

Even though the VMAT technology improves patient comfort during treatment delivery and treatment accuracy, the VMAT requires a longer time for plan creation that meets clinical requirements as the number of optimization variables such as the number of arcs, start angle of rotation, MLC speed and dose rate, collimator angle, size and position of secondary collimator angle, couch angle, optimization limit and weight settings, control of optimization process increases in VMAT and the optimization process becomes more complicated [33]. These are the efforts that can be compromised to generate a better treatment plan like Rapid Arc, which aids in precise and comfortable treatment delivery for patients. Moreover, Mehta et al reported upon their investigation that MLC movement and dose rate changes are controlled precisely in VMAT, which in turn improves the treatment accuracy significantly [34]. With Rapid arc, a very less treatment time helps in individual motion management with better patient comfort, and reduced body and organ motion which also redeems enough time for IGRT procedures.

CONCLUSION

One of the advantageous features of rapid arc over IMRT in both FF and FFF treatment modes is the exclusively improved PTV dosimetric parameters as well as its significant OAR dose values along with treatment efficiency of lesser MUs and TT. Thereby the study concludes Rapid Arc as the replacement of IMRT for its ability to achieve highly conformal radiation dose distribution, treatment delivery with reduced risks, and patient comfort along with its support to accommodate more patients for treatment under the same machine.

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