RESEARCH ARTICLE

Editorial Process: Submission:09/26/2025 Acceptance:03/27/2026 Published:04/07/2026

Dosimetric and Delivery Assessment of Stereotactic Body Radiotherapy Using Flattened and Unflattened Beams for the Single-Isocenter Treatment of Multiple Liver Targets

Jayadevan P. M.[1,2]*, Sudesh[1], Shine N. S.[1], Nithin K.[2], Dhanya[2]

Abstract

Background: Stereotactic Body Radiotherapy (SBRT) is increasingly applied in the management of liver cancers. Flattening filter-free (FFF) beams, which offer higher dose rates, enable faster delivery and improved patient comfort. This retrospective study compares the dosimetric and delivery characteristics of SBRT using FFF and conventional flattened beams for the treatment of multiple liver targets. **Methods:** Twenty-six patients with 2–11 hepatic targets were treated using a single-isocenter volumetric modulated arc therapy (VMAT) technique. Treatment plans were created for 6X, 6FFF, and 10FFF photon beams, with prescription doses ranging from 27.5 Gy to 50 Gy in 5 fractions. Plan evaluation metrics included Planning Target Volume (PTV) coverage (V95%, V98%, V100%), mean liver dose (MLD), normal liver volume receiving <15 Gy, and maximum doses to Organs at Risk (OARs). Delivery parameters were assessed by gamma passing rate, monitor units (MU), and beam-on time (BOT). Repeated-measures ANOVA, with post-hoc least significant difference (LSD) testing, was used for statistical analysis. **Results:** Comparable Planning Target Volume (PTV) coverage was achieved with all beam modalities. No statistically significant differences were noted in mean liver dose (MLD), normal liver volume receiving <15 Gy, or other Organ at Risk (OAR) doses, except for lower spinal cord doses with FFF beams ($p = 0.003$). The 2%/2 mm gamma passing rate for 6FFF was 1% lower than for 6X and 10FFF. Monitor unit (MU) values were higher for 6FFF (4.3%) and 10FFF (1.5%) compared with 6X ($p = 0.01$). Beam-on time (BOT) was significantly shorter with 6FFF (3.8 ± 0.28 min) and 10FFF (3.8 ± 0.30 min) relative to 6X (5.1 ± 0.22 min) ($p = 0.001$). **Conclusion:** Flattening filter-free (FFF) beams reduce beam-on time (BOT), providing an advantage for breath-hold techniques. However, despite the higher dose rate of 10FFF, no additional reduction in overall treatment time was observed.

Keywords: Stereotactic body radiotherapy- Liver metastasis- Single isocenter- Flattening Filter Free

Asian Pac J Cancer Prev, **27 (4)**, 1451-1458

Introduction

Stereotactic Body Radiotherapy (SBRT) is widely accepted as a feasible treatment option for both cranial and extracranial lesions, including those in the lung, liver, and spine. For primary as well as metastatic liver targets, highly focused Volumetric Modulated Arc Therapy (VMAT) enables the precise delivery of high radiation doses in fewer fractions (typically 3–5). This approach provides superior target conformity and sharp dose gradients, thereby improving tumour control while minimising radiation exposure to surrounding healthy tissues [1–6]. Traditionally, treatment plans adopted separate isocenters for each target, with each isocenter positioned at the geometric centre of the corresponding target. In contrast, the implementation of a single-isocenter technique for multiple targets has been shown to substantially reduce treatment time and monitor units (MU), which refers to the machine output required to deliver the planned dose, thereby improving patient comfort by reducing the need for repeated repositioning and setup. This technique was initially introduced for cranial lesions and has since been increasingly adopted for extracranial lesions as well [7–12].

Multiple targets of varying dimensions can be conveniently treated using VMAT with 6 MV flattened photon beams (6X), while dosimetrically equivalent plans can also be achieved using flattening filter free (FFF) photon beams of different energies, such as 6 MV FFF (6FFF) and 10 MV FFF (10FFF). FFF beams, compared to conventional flattened (FF) beams of the same nominal energy, exhibit higher dose rates, reduced head scatter and leakage, lower mean energy, and are expected to reduce out-of-field dose. Their use is particularly beneficial for minimising treatment time, which is especially important in hypo fractionated treatments such as stereotactic

[1]*Department of Physical Sciences, Banasthali Vidyapith, Rajasthan, India.* [2]*Department of Radiation Oncology, Rajagiri Hospital, Aluva, Kerala, India. *For Correspondence: jayadevanpm@gmail.com*

radiotherapy (SRT) and SBRT [13].

Vieillevigne et al. investigated the dosimetric effect of Planning Target Volume (PTV) size on Dynamic Conformal Arc (DCA) and VMAT techniques using both FF and FFF beams for SBRT in a phantom with single targets, and concluded that there was no significant dosimetric difference between FF and FFF energies for VMAT [14]. Laoui et al. [15] evaluated that the 6FFF beam exhibits a sharper dose fall-off compared to the 10FFF beam, which directly correlates with reduced irradiation of normal brain tissue volume. The dosimetric impact of different FF and FFF energies in multiple lung lesions was evaluated by Pokhrel et al., who found that 6FFF provided better conformity and lung sparing, along with reduced beam-on time [10]. The study by Aokie et al. suggests that VMAT-SBRT using the FFF technique significantly reduces treatment time by more than half for lung SBRT, while maintaining high local control rates and low toxicity [16]. Wang et al. found that flattening filter-free (6FFF) mode is feasible for treating multiple brain lesions, with dosimetric outcomes similar to 6X. While 6FFF plans used 10-20% more monitor units, they significantly reduced beam-on time by 50% [17]. Dang et al. reviewed the efficacy of FFF beams for multiple treatment sites and recommended for planning and treatment due to comparable plan quality, faster beam-on time, minimise intra-fraction motion, and shorter overall treatment time [18].

A dosimetric comparison of VMAT plans using FF and FFF beams for hepatic metastases was reported by Giacomo Reggiori et al. The study, conducted on both virtual lesions and few actual patient datasets, demonstrated that FFF beams reduced beam-on time by approximately fourfold compared to FF beams, while maintaining comparable PTV coverage and normal tissue sparing [19]. Mancosu et al. evaluated patients, predominantly with primary and metastatic liver lesions, treated with 6FFF beams, and reported clinically acceptable PTV coverage, OAR doses, and reduced beam-on time (BOT), where BOT represents the actual radiation delivery time [20]. To our knowledge, this study to provide a direct comprehensive comparison of three different photon energies 6X, 6FFF, and 10FFF in single-isocenter VMAT for patients with multiple liver lesions which is less commonly reported than single energy or two energy comparisons. Unlike previous reports that focused solely on 6FFF or on comparisons between FF and FFF beams, our analysis integrates both dosimetric and delivery efficiency endpoints within the same cohort.

Materials and Methods

Patient selection and CT simulation

A cohort of 26 patients with multifocal hepatocellular carcinoma and liver metastases was selected for this retrospective treatment planning study. All patients, each with 2 to 11 targets, were treated between January 2020 and December 2024. Of these, 13 patients had 2 targets, 10 patients had 3 targets, and 3 patients had equal or more than 5 targets (Table 1). All patients were immobilised using masks, with their arms positioned above the head. Twelve patients underwent the Deep Inspiration Breath Hold (DIBH) technique using Respiratory Gating for Scanners (Varian Medical Systems Inc RGSC, version 1.1), while another twelve treated under abdominal compression with a vacuum cushion and an abdominal pressure belt to minimise internal organ motion. Due to clinical constraints, two patients were managed under free-breathing conditions. A contrast-enhanced multiphase CT scan was performed from the carina to the top of the pelvis, using a 1.25 mm slice thickness.

Treatment planning

Three treatment plans were generated for each patient's CT dataset, independent of the motion-management technique, using three photon energies (6X, 6FFF, and 10FFF) in the Eclipse treatment planning system (Varian Medical Systems Inc. Version 15.1 Palo Alto, CA, USA). 10 MV photon beams were not considered in this study due to their conventional dose rate, higher Multi Leaf Collimators (MLC) transmission and the potential for neutron production. VMAT plans were generated for the TrueBeam linear accelerator from the same manufacturer, utilising High-Definition MLC (HD MLC) and a 6D couch. The maximum dose rates used were 600 MU/min for 6X, 1400 MU/min for 6FFF, and 2400 MU/min for 10FFF. Multiple targets were treated using a single-isocenter approach. The prescription dose for liver SBRT ranged from 27.5 Gy to 50 Gy in 5 fractions, determined based on the available normal liver volume [21]. A dose escalation of up to 120% of the prescription was intentionally delivered within the Gross Tumour Volume (GTV), analogous to the lower isodose line prescription used in conventional static-field SBRT, to target radioresistant hypoxic cells. In some cases, different prescription doses were assigned to individual targets due to their proximity to luminal gastrointestinal structures. The planning objective was to achieve 95% coverage of the PTV with 100% of the prescription dose.

Each treatment plan utilised four half-arcs (clockwise and counterclockwise) covering gantry angles from 181° to 30°. For centrally located lesions, an additional non-coplanar beam was incorporated when deemed necessary. Multiple full arcs were applied for lesions extended medially and laterally. The number of arcs were determined based on the need to achieve optimal collimator rotation and to reduce the MLC modulation and restrict MU per arc, reducing the risk of unintended radiation exposure to the normal tissues [22]. Isocenters were initially positioned at the geometric centroid of the lesions as defined by the treatment planning system, and efforts were made to ensure that all targets were encompassed within the HD MLC field whenever their spatial proximity allowed. Same optimisation parameters were given for all energies with the Photon optimizer (Version 15.6.06), prioritising maximum target coverage and sparing of organs at risk. Manual normal tissue objectives (NTO) were applied in each case, with a fall-off factor from 100% to 10% over a 5 mm distance. A maximum MU objective with a priority of 50 was set to restrict the MU to twice the prescription dose (cGy) per fraction. Intermediate calculations were performed with low aperture control to reduce MLC modulation, and jaw tracking was enabled to minimise MLC transmission. Final dose calculation was executed using the AcurosXB external beam algorithm (Version 15.6.06) with inhomogeneity correction and a grid size of 1.5 mm.

Plan evaluation

Treatment plan comparisons for each energy were performed using quantitative plan evaluation based on cumulative dose-volume histograms (DVH) recommended by Radiation Therapy Oncology Group (RTOG) 1112 [21]. Combined target coverage for each patient was assessed by evaluating the percentage of the target volume receiving 100%, 98%, and 95% of the prescription dose (Figure 1). Normal tissue assessment included the normal liver volume receiving less than 15 Gy and the mean liver dose (MLD) calculated for Liver – GTV. The maximum dose to 0.5 cc of the bowel, oesophagus, stomach, duodenum, and spinal cord was also assessed dosimetrically as per recommendations [21].

The delivery aspects for each energy were evaluated using patient-specific quality assurance (PSQA) with an Electronic Portal Imaging Device (EPID) by Varian Medical Systems. Local gamma evaluation was performed with a stringent 2%/2 mm tolerance limit, applying a 95% passing criterion and a 10% background threshold [23]. For each energy, the total MU, BOT, and modulation factor (MF) were also assessed. BOT was measured in a more practical clinical setting, from the start of the first arc to the end of the last arc, excluding the time required for table rotation for non-coplanar beams. The MF was calculated as the total number of MU divided by the total prescribed dose (cGy) per fraction.

For statistical analysis, repeated measures Analysis of Variance (ANOVA) was carried out for comparing 6X, 6FFF and 10FFF followed by post hoc analysis by using Least significant difference test for pair wise comparison. Correlation between average distance from the isocenter to the centroid of each target and liver volume < 15Gy was done using Karl Pearson's correlation coefficient.

Results

The PTV coverage was evaluated as the percentage of volume receiving 100%, 98%, and 95% of the prescription dose. No statistically significant differences were observed among the three energies for V100%. However, 6X yielded a statistically significant improvement in PTV coverage at V95% and V98% (p = 0.03), consistently showing slightly higher coverage than 6FFF and 10FFF (95% PTV coverage: 95.8 ± 1.4 for 6X, 95.3 ± 1.5 for 6FFF, and 95.2 ± 1.5 for 10FFF), as summarised in Table 2. Similarly, all energies provided clinically acceptable MLD (12.98 ± 0.62, 12.92 ± 0.62, 12.95 ± 0.61 Gy for 6X, 6FFF and 10FFF respectively), and the normal liver volume receiving < 15 Gy was within acceptable limits as shown in the Figure 2a. Evaluation of maximum doses to OARs showed that the 6FFF energy delivered lower doses to the bowel, duodenum, oesophagus, stomach, and spinal cord compared to 6X and 10FFF, although the differences were not statistically significant. Spinal cord doses were consistently lower for FFF beams compared to 6X (p=0.003).

Table 3 shows the correlation between mean distance from isocenter to the centroid of target and the spared

Table 1. Patient Characteristics for the Retrospective Treatment Planning Study.

Parameter	Mean ± SD (range)
Prescription dose (Gy)	38.6 ± 5.3 (27.5 - 50)
Number of targets per patient	3 ± 1.8 (2 – 11)
PTV volume (cc)	295 ± 242 (45 – 838)
Total liver volume (cc)	1340 ± 354 (677 – 2236)
Mean distance from the isocenter to the centroid of each target (cm)	5.26 ± 1.6 (2.25 – 8.83)

SD, Standard Deviation

Table 2. Summary of Planning Target Volume (PTV) Coverage, Maximum Dose (to 0.5cc) to Organs at Risk, and Delivery Accuracy Parameters for Flattened (6X) and Unflattened (6FFF, 10FFF) Beam Energies

Variable	Mean ± SE			F-value	P-value
	6X	6FFF	10 FFF		
PTV Coverage (%)					
$V_{98\%}$	$91.8^{a} \pm 1.8$	$90.9^{ab} \pm 1.7$	$90.7^{b} \pm 1.8$	3.774*	0.03
$V_{95\%}$	$95.8^{a} \pm 1.4$	$95.3^{ab} \pm 1.5$	$95.3^{b} \pm 1.5$	3.764*	0.03
$V_{100\%}$	86.1 ± 2.4	85.1 ± 2.4	84.6 ± 2.5	3.367*	0.066
Maximum dose to 0.5cc (Gy)					
Bowel	16.1 ± 2.2	15.8 ± 2.3	15.9 ± 2.2	0.348ns	0.609
Spinal Cord	$11.5^{a} \pm 1.1$	$10.3^{b} \pm 1.1$	$10.\ 8^{b} \pm 1.2$	8.462**	0.003
Duodenum	16.2 ± 2.2	15.9 ± 2.3	16.1 ± 2.3	0.265^{ns}	0.635
Oesophagus	16.0 ± 1.5	15.8 ± 1.5	16.4 ± 1.4	0.304^{ns}	0.68
Stomach	21.1 ± 1.7	20.9 ± 1.8	21.2 ± 1.7	0.629^{ns}	0.502
MU	$2006.4^{b} \pm 38$	$2092.8^{a} \pm 44$	$2036^{ab} \pm 28$	5.056**	0.01
Beam ON time (min)	$5.1^{a} \pm 0.22$	$3.8^{b} \pm 0.28$	$3.8^{b} \pm 0.3$	39.58**	0.001
Gamma (2%/2mm)	$99.6^{a} \pm 0.08$	$98.5^{b} \pm 0.3$	$99.6^{a} \pm 0.06$	14.67**	0.001

SE, Standard Error; **, Significant at 0.01 level; *, Significant at 0.05 level; ns, non-significant; Means having different letter as superscript differ significantly

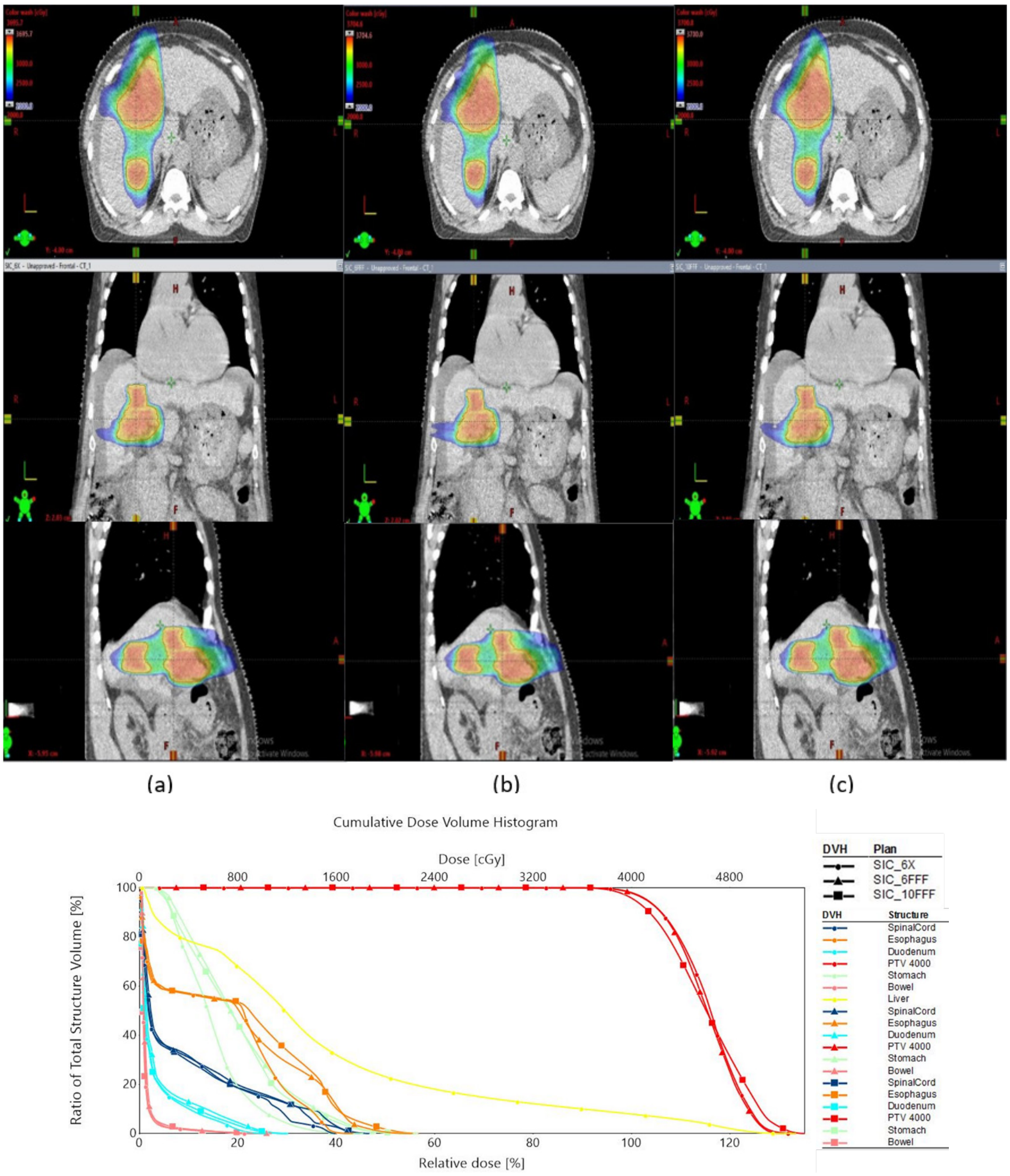

(a) (b) (c)

Figure 1. Dose Distribution for a Representative Patient from the Sample Data. The patient had three targets with a prescribed dose of 33 Gy in 5 fractions. (a–c) Dose distributions using 6X, 6FFF, and 10FFF photon beams in transverse, frontal, and sagittal views, respectively. (d) Dose–volume histogram (DVH) for the PTV and organs at risk.

Table 3. Correlation between the Mean Distance from the Isocenter to the Centroid of Each Target (cm) and the Normal Liver Volume Receiving Less than 15 Gy (Karl Pearson correlation coefficient)

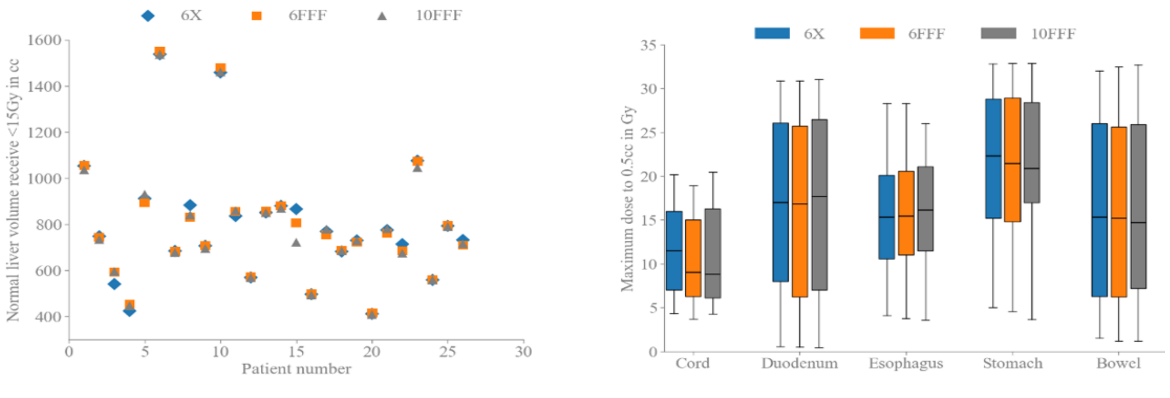
Photon energy	Correlation	p-value
6X	0.308	0.126
6FFF	0.337	0.092
10FFF	0.335	0.094

normal liver volume receiving dose < 15Gy was done by using Karl Pearson's correlation coefficient. While there's a weak positive correlation for all beam types using a single isocentre, none of these correlations are strong or statistically significant, suggesting that there's no reliable linear relationship between the normal liver volume and the average distance from target to isocentre.

The MU was highest for 6FFF (2092.8 ± 44), followed by 10FFF (2036 ± 28) and 6X (2006.4 ± 38), with a p value of 0.01. The forward peak beam profile of FFF was also reflected in the MF values: 6X = 2.65 ± 0.41, 6FFF = 2.77 ± 0.44, and 10FFF = 2.71 ± 0.41. The BOT was comparable for 6FFF and 10FFF (3.8 ± 0.28 and 3.8 ± 0.3, respectively), but shorter than that of 6X (5.1 ± 0.22). In PSQA, treatment plans for all energies met the gamma analysis passing criteria; although, 6FFF consistently showed lower passing rates compared to 6X and 10FFF, as illustrated in the Figure 3.

Discussion

Patients with more than two liver targets were selected for this retrospective planning study to evaluate the impact of using three different energies, due to differences in their dose profiles and dose rates. Based on our previous study, the single-isocenter technique was chosen for



(a) (b)

Figure 2. (a) Scatter plot comparing the difference in normal liver volume receiving less than 15 Gy between patients planned with flattened and unflattened photon beams. (b) Range of maximum dose in Gy to Organs at Risk (to 0.5cc) for different energies

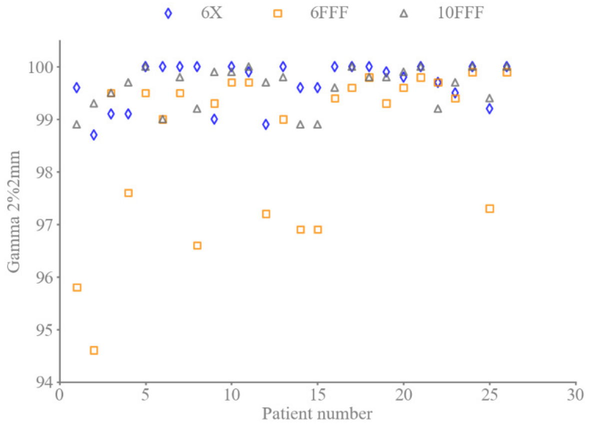
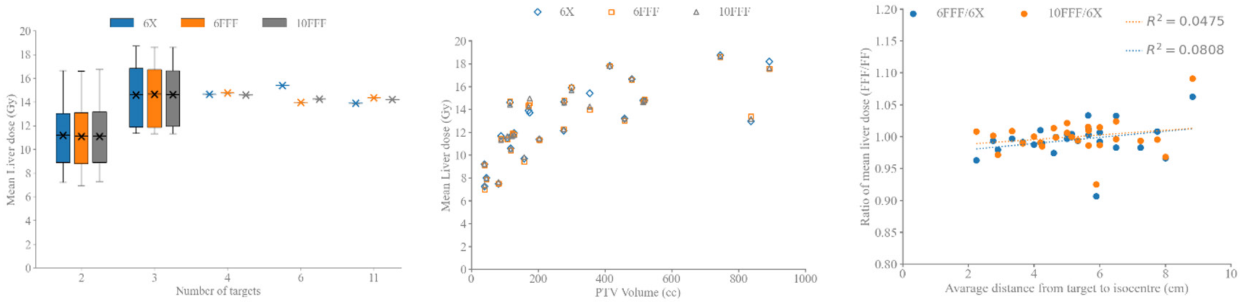


Figure 3. Local Gamma Analysis with a 2%/2 mm Passing Criteria was Performed for All patients Using Flattened and Flattening Filter Free Energies. The 6FFF beams consistently showed lower passing rates.

multiple targets, as it achieved comparable PTV coverage, acceptable OAR doses, and shorter treatment durations [9]. Multiple arcs were used in our study to mitigate the interplay effect, particularly at a dose rate of 2400 MU/min. This effect was previously evaluated under phantom conditions simulating lung motion by Ong et al., who reported that employing more than two arcs and more than two fractions reduced the interplay effect to a level unlikely to be clinically significant [24]. While PTV coverage and OAR doses were comparable across the different beam types; however, the spinal cord dose was observed to be consistently lower with FFF beams. In most cases, the spinal cord was outside the primary radiation field, and the reduced dose may be attributed to the lower mean energy, decreased MLC leaf leakage, and reduced head leakage associated with FFF beams [25]. It is important to note that Shine et al. reported that the dose fall-off outside the treatment field with FFF beams can be underestimated by the treatment planning system, suggesting that further investigation is needed to verify the low spinal cord dose results [26]. This highlights the need for measured out of field dose verification to confirm the accuracy of TPS calculated values.

As shown in Figure 4, the increase in liver dose with respect to the number of targets rises up to three targets, after which there is no further increase. This indicates that target volume should also be considered, and there is a linear trend of increasing liver dose with respect to the PTV volume. One case deviated from this trend, showing a lower MLD despite a larger PTV. This was due to the



(a) (b) (c)

Figure 4. Relation between (a) mean liver dose and number of targets. (b) mean liver dose and PTV volume. (c) Ratio of mean liver doses (FF/FFF) and average distance from target to isocentre.

lesion being in segment II of the left lobe, where its peripheral location limited irradiation of the remaining uninvolved liver. This highlights that lesion location, in addition to PTV size, influences liver dose. Van Timmeren et al. evaluated for multiple lung metastasis and stated that the difference in lung dose vary with inter target distance with a weak correlation but has the influence of different PTV volume and the available lung volume [27]. But in our study, there is no strong correlation between the average distance from the target to the isocenter and the ratio of MLD when using FFF beams compared to 6X. The MLD remains largely comparable across the average distance from the isocenter to the centroid of each target, with slightly higher variation in 10FFF/6X. This suggests that FFF modes do not significantly affect liver dose based on target-to-isocenter distance in this dataset.

The gamma passing rate for 6FFF was consistent with the trend reported by Mancosu et al. [20], but remained slightly lower than that of 6X and 10FFF. The difference in MU between the energies was limited by the implementation of the same MU objectives; however, MU being 4.3% higher for 6FFF and 1.5% higher for 10FFF compared to 6X, as shown in the Table 2. The lower gamma passing rate observed for 6FFF is likely attributable to its higher MU, consistent with the negative correlation between MU and gamma pass rate reported by Wu et al. [28]. BOT was 1.3 times longer for 6X compared to FFF beams due to differences in dose rate, which is relatively small compared to the findings of Suresh et al., who reported about a fourfold increase for the VMAT technique by considering only beam-on time without accounting for the practical time gaps between successive beams [29]. In our study, the inclusion of four half arcs and the associated gantry preparation time reduced the benefit of higher dose rates. As a result, 10FFF did not show a significant advantage over 6FFF because its maximum potential dose rate was limited by beam modulation and gantry speed constraints. This represents a study specific limitation, as clinics using fewer arcs may observe a greater impact from the higher dose rate capability of 10FFF. In clinical practice, setup time for non-coplanar beams and verification is similar for all energies. Thus, the absolute difference of 1.3 minutes in BOT can still be considered a practical advantage of FFF beams, especially for patients undergoing DIBH, where higher dose rates improve patient comfort.

The study did not account for intrafraction motion of liver targets during treatment, which is an essential consideration for determining the necessity of faster treatment delivery. Even so, the reduction in BOT achieved with FFF beams would be expected to lessen the impact of such motion across different motion management strategies, highlighting the practical benefit of shorter treatments. Sharma et al. investigated liver motion and demonstrated the additional margins required around targets under different motion management techniques [30]. Nevertheless, it remains to be established whether multiple liver targets, particularly when located in different lobes, exhibit synchronous motion or move independently. This aspect requires further investigation, as it has direct implications for defining appropriate target margins. This study did not evaluate potential neutron production from 10FFF beams, which is expected to be minimal at 10 MV and represents an aspect not addressed in this work. Although conformity index (CI), gradient index (GI), and homogeneity index (HI) are standard dosimetric parameters in treatment planning, were not reported as they were clinically less informative for this cohort. Overlapping or adjacent OARs relative to the PTV limited the interpretability of CI, the intentionally heterogeneous dose distributions typical of SBRT reduced the usefulness of HI, and GI were less applicable since the planning approach prioritised normal liver sparing with permissible dose spillage in non-liver directions.

In conclusion, FFF beams can be effectively used for treating multiple liver targets in SBRT, providing comparable PTV coverage, MLD, and OAR doses to those achieved with flattened beams. The FFF dose profile did not show a statistically significant correlation between MLD and either the distance of targets from the isocenter or PTV volume. The reduction in treatment time with FFF beams enhances patient comfort, especially when using DIBH motion management, and also helps reduce intrafraction movement. However, the advantage of higher dose rates with 10FFF was not realised in practice due to limitations in gantry speed and the increased number of arcs required for treatment delivery.

Author Contribution Statement

Jayadevan P.M.: Contributions to the conception or design of the work, collected data, analysed and interpreted the data and wrote manuscript. Dr. Sudesh: Revising the manuscript critically for important intellectual content and approved the final version to be submitted for publication. Dr. Shine N.S.: Substantial contributions to the conception or design of the work, interpretation and revising the manuscript. Nithin K: Contributed to the acquisition of data and analysis. Dhanya: Contributed to the acquisition of data

Acknowledgements

Data availability All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

There are no conflict of interest to disclose for this paper

References

1. Benedict SH, Yenice KM, Followill D, Galvin JM, Hinson W, Kavanagh B, et al. Stereotactic body radiation therapy: The report of aapm task group 101. Med Phys. 2010;37(8):4078-101. https://doi.org/10.1118/1.3438081.
2. Michel R, Françoise I, Laure P, Anouchka M, Guillaume P, Sylvain K. Dose to organ at risk and dose prescription in liver sbrt. Rep Pract Oncol Radiother. 2017;22(2):96-102. https://doi.org/10.1016/j.rpor.2017.03.001.
3. Comito T, Clerici E, Tozzi A, D'Agostino G. Liver metastases and sbrt: A new paradigm? Rep Pract Oncol

Radiother. 2015;20(6):464-71. https://doi.org/10.1016/j.rpor.2014.10.002.

4. Schefter TE, Kavanagh BD. Radiation therapy for liver metastases. Semin Radiat Oncol. 2011;21(4):264-70. https://doi.org/10.1016/j.semradonc.2011.05.006.
5. Rusthoven CG, Lauro CF, Kavanagh BD, Schefter TE. Stereotactic body radiation therapy (sbrt) for liver metastases: A clinical review. Semin Colon Rectal Surg. 2014;25(1):48-52. https://doi.org/10.1053/j.scrs.2013.09.009.
6. Scorsetti M, Alongi F, Castiglioni S, Clivio A, Fogliata A, Lobefalo F, et al. Feasibility and early clinical assessment of flattening filter free (fff) based stereotactic body radiotherapy (sbrt) treatments. Radiat Oncol. 2011;6:113. https://doi.org/10.1186/1748-717x-6-113.
7. Clark GM, Popple RA, Prendergast BM, Spencer SA, Thomas EM, Stewart JG, et al. Plan quality and treatment planning technique for single isocenter cranial radiosurgery with volumetric modulated arc therapy. Pract Radiat Oncol. 2012;2(4):306-13. https://doi.org/10.1016/j.prro.2011.12.003.
8. Sanford L, Molloy J, Kumar S, Randall M, Mcgarry R, Pokhrel D. Evaluation of plan quality and treatment efficiency for single-isocenter/two-lesion lung stereotactic body radiation therapy. J appl clin med phys. 2019;20:118–27. Https://doi.Org/10.1002/acm2.12500.
9. Jayadevan PM, Sudesh, Shine NA, Nithin K, Dhanya. Comparative dosimetric analysis of single versus multiple isocenter stereotactic body radiotherapy for liver metastasis. Biomed phys eng express. 2025;11:015044. Https://doi.Org/10.1088/2057-1976/ada001.
10. Pokhrel D, Sanford L, Larkin S, Dhanireddy B, Bernard ME, Randall M, et al. On the use of single-isocenter vmat plans for sbrt treatment of synchronous multiple lung lesions: Plan quality, treatment efficiency, and early clinical outcomes. J Appl Clin Med Phys. 2020;21(8):160-7. https://doi.org/https://doi.org/10.1002/acm2.12938.
11. Tang C, Gong C, Liu B, Guo H, Dai Z, Yuan J, et al. Feasibility and dosimetric evaluation of single- and multi-isocentre stereotactic body radiation therapy for multiple liver metastases. Front Oncol. 2023;13:1144784. https://doi.org/10.3389/fonc.2023.1144784.
12. Barik BK, Kumari J, Sahoo DK, Majumdar SKD, Barik SK, Das DK, et al. Mono iso-centric vmat planning for sbrt of multiple liver metastasis- a case report. J Med Imaging Radiat Sci. 2023;54(3):556-61. https://doi.org/10.1016/j.jmir.2023.06.005.
13. Georg D, Knöös T, McClean B. Current status and future perspective of flattening filter free photon beams. Med Phys. 2011;38(3):1280-93. https://doi.org/10.1118/1.3554643.
14. Vieillevigne L, Bessieres S, Ouali M, Lanaspeze C. Dosimetric comparison of flattened and unflattened beams for stereotactic body radiation therapy: Impact of the size of the ptv on dynamic conformal arc and volumetric modulated arc therapy. Phys Med. 2016;32(11):1405-14. https://doi.org/10.1016/j.ejmp.2016.10.007.
15. Laoui S, Roa DE, Kuo J, Baldytchev M, Gonzales J, Dietrich S, et al. Flattening filter free beam energy selection and its impact in multitarget intracranial stereotactic radiosurgery treatments. Med Dosim. 2020;45(4):363-7. https://doi.org/10.1016/j.meddos.2020.05.001.
16. Aoki S, Yamashita H, Haga A, Nawa K, Imae T, Takahashi W, et al. Flattening filter-free technique in volumetric modulated arc therapy for lung stereotactic body radiotherapy: A clinical comparison with the flattening filter technique. Oncol Lett. 2018;15(3):3928-36. https://doi.org/10.3892/ol.2018.7809.
17. Wang JZ, Rice R, Mundt AJ, Sandhu A, Murphy KT. Feasibility and advantages of using flattening filter-free mode for radiosurgery of multiple brain lesions. Pract Radiat Oncol. 2012;2(4):e165-e71. https://doi.org/10.1016/j.prro.2012.03.006.
18. Dang TM, Peters MJ, Hickey B, Semciw A. Efficacy of flattening-filter-free beam in stereotactic body radiation therapy planning and treatment: A systematic review with meta-analysis. J Med Imaging Radiat Oncol. 2017;61(3):379-87. https://doi.org/10.1111/1754-9485.12583.
19. Reggiori G, Mancosu P, Castiglioni S, Alongi F, Pellegrini C, Lobefalo F, et al. Can volumetric modulated arc therapy with flattening filter free beams play a role in stereotactic body radiotherapy for liver lesions? A volume-based analysis. Med Phys. 2012;39(2):1112-8. https://doi.org/10.1118/1.3679858.
20. Mancosu P, Castiglioni S, Reggiori G, Catalano M, Alongi F, Pellegrini C, et al. Stereotactic body radiation therapy for liver tumours using flattening filter free beam: Dosimetric and technical considerations. Radiat Oncol. 2012;7:16. https://doi.org/10.1186/1748-717x-7-16.
21. Dawson LA, Hospital PM, Zhu A, Oncology Co-Chair M, Knox J, Hospital M, et al. Radiation therapy oncology group rtog 1112 randomized phase iii study of sorafenib versus stereotactic body radiation therapy followed by sorafenib in hepatocellular carcinoma study team (4/24/13) principal investigator/radiation oncology. 1112.
22. Hubley E, Pierce G. The influence of plan modulation on the interplay effect in vmat liver sbrt treatments. Phys Med. 2017;40:115-21. https://doi.org/10.1016/j.ejmp.2017.07.025.
23. Miften M, Olch A, Mihailidis D, Moran J, Pawlicki T, Molineu A, et al. Tolerance limits and methodologies for imrt measurement-based verification qa: Recommendations of aapm task group no. 218. Med Phys. 2018;45(4):e53-e83. https://doi.org/10.1002/mp.12810.
24. Ong CL, Dahele M, Slotman BJ, Verbakel WF. Dosimetric impact of the interplay effect during stereotactic lung radiation therapy delivery using flattening filter-free beams and volumetric modulated arc therapy. Int J Radiat Oncol Biol Phys. 2013;86(4):743-8. https://doi.org/10.1016/j.ijrobp.2013.03.038.
25. Kragl G, Baier F, Lutz S, Albrich D, Dalaryd M, Kroupa B, et al. Flattening filter free beams in sbrt and imrt: Dosimetric assessment of peripheral doses. Z Med Phys. 2011;21(2):91-101. https://doi.org/10.1016/j.zemedi.2010.07.003.
26. Shine NS, Paramu R, Gopinath M, Jaon Bos RC, Jayadevan PM. Out-of-field dose calculation by a commercial treatment planning system and comparison by monte carlo simulation for varian truebeam(®). J Med Phys. 2019;44(3):156-75. https://doi.org/10.4103/jmp.JMP_82_18.
27. van Timmeren JE, Ehrbar S, Chamberlain M, Mayinger M, Hoogeman MS, Andratschke N, et al. Single-isocenter versus multiple-isocenters for multiple lung metastases: Evaluation of lung dose. Radiother Oncol. 2022;166:189-94. https://doi.org/10.1016/j.radonc.2021.11.030.
28. Wu S, Chen J, Li Z, Qiu Q, Wang X, Li C, et al. Analysis of dose verification results for 924 intensity-modulated radiation therapy plans. Precis Radiat Oncol. 2018;2(4):125-30. https://doi.org/10.1002/pro6.58.
29. Suresh t, madeswaran s. The dosimetric comparison of different sbrt techniques for treatment of liver cancer using flattened and flattening filter free beam. Iran J Med Phys. 2022;19:371–82. https://doi.org/10.22038/ijmp.2022.63812.2090.
30. Sharma M, Nano TF, Akkati M, Milano MT, Morin O, Feng M. A systematic review and meta-analysis of liver tumor position variability during sbrt using various motion management and igrt strategies. Radiother Oncol. 2022;166:195-202. https://doi.org/10.1016/j.

radonc.2021.11.022.

This work is licensed under a Creative Commons Attribution-Non Commercial 4.0 International License.