RESEARCH ARTICLE

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A comprehensive Study of the Out of Field Non Target Dose Associated with 6 and 10 MV Flattened and Flattening Filter Free X Ray Beam in a True Beam Linear Accelerator

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Abstract

Aim: To evaluate the out-of-field dose associated with flattened (FF) and flattening filter-free (FFF) 6 and 10 MV X-ray beams in a TrueBeam linear accelerator (Linac). **Materials and Methods:** Measurements were taken in a slab phantom using the metal oxide semiconductor field effect transistor (MOSFET) detector at varying depths (dmax, 5 cm, and 10 cm) for clinically relevant field sizes and up to 30 cm from the field edges for 6 and 10 MV FF and FFF beams in TrueBeam Linac. Dose calculation accuracy of the analytic anisotropic algorithm (AAA) and Acuros algorithm was investigated in the out-of-field region. Similarly, the out-of-field dose associated with volumetric modulated arc therapy (VMAT) head-and-neck plan delivered to a body phantom was evaluated. **Results:** The out-of-field dose for both FF and FFF photon beams (6 and 10 MV) decreased with increasing distance from the field boundary and size. Furthermore, regardless of FF in the field, higher-energy photon beams were associated with lower out-of-field dose. Both algorithms underestimated the dose in the out-of-field region, with AAA failing to calculate the out-of-field dose at 15 cm from the field edge and Acuros failing to calculate out-of-field radiation at 20 cm. At 5 cm from the field edge, an average of 50% underestimation was observed, and at 10 cm, an average of 60% underestimation was observed for both FF and FFF (6 and 10 MV) beams. The VMAT head-and-neck plan performed with the FFF beam resulted in a lower out-of-field dose than the FF beam for a comparable dose distribution. **Conclusion:** Compared with flattened beams, the FFF modes on TrueBeam Linac exhibited a clinically relevant reduction in the out-of-field dose. Further dosimetric studies are warranted to determine the significant benefit of FFF beams across different cancer sites.

Keywords: Nontarget dose- MOSFET- FFF beam

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Introduction

Over the past few decades, there have been significant advancements in radiation delivery techniques and technology. These improvements have substantially enhanced our ability to administer higher doses to tumors while minimizing the dose to surrounding organs at risk. However, despite advancements in treatment conformity, the issue of doses reaching normal tissues outside the treated volume persists. In radiotherapy (RT), radiation is administered to achieve therapeutic benefits within the clinical target volume. Due to uncertainties in positioning and delivery, a planned target volume (PTV) is delineated, encompassing healthy tissue that inevitably receives radiation [1]. Radiation outside the PTV, known as “out-of-field” or “nontarget” dosage, provides no therapeutic advantage and should be minimized. The TG-158 report recommends various techniques to reduce nontarget doses, including treatment volume reduction, modality switching, energy selection, wedge usage, and MLC and collimator orientation optimization. It is crucial to accurately evaluate the out-of-field doses associated with different treatment modalities, including comparing flattened and flattening filter-free (FFF) beams [2].

Currently, measurements, Treatment Planning System (TPS), and Monte Carlo (MC) simulations are employed to determine out-of-field dose distributions from external beam RT (EBRT). While modern treatment planning tools effectively characterize high-dose regions within the primary beam path, accuracy in dose determination beyond a few centimeters outside the treatment field border is generally unsatisfactory [3]. Alternative methods for assessing patient out-of-field dosage are necessary in such cases.

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Numerous studies have discussed out-of-field dose measurement methods from clinical linear accelerators. Nieto et al. compared TPS-calculated out-of-field doses to ion chamber and thermoluminescence measurements for the Elekta Axesse linear accelerator [4]. Covington et al. published a technical report on measuring peripheral doses for 6 and 10 MV FFF beams using an A12 ion chamber with the Varian TrueBeam Linac [5]. Kragl et al. studied the impact of FFF photon beams on nontarget doses for advanced treatment techniques with larger monitor units [6]. Several MC simulations have also been documented for flat beams on earlier machine models. Bendarx and Xu developed and validated the Varian linear accelerator model for in and out-of-field dose calculations [7]. Despite the abundance of out-of-field data for older Linacs in the literature, few studies have quantified TrueBeam out-of-field dose distributions. TrueBeam differs from previous Linac versions in its improved head shielding model and the addition of FFF beams. Therefore, existing out-of-field dose readings from older Varian machines, such as Clinac C-series units, may no longer be applicable [8].

FFF beams are expected to have lower out-of-field doses due to reduced scatter, leaf transmission, and head leakage [6]. TrueBeam (Varian Medical Systems Palo Alto, CA,USA) is a modern Linac featuring FFF capability and is widely used worldwide. The clinical use of FFF beams was initially driven by the need to minimize the long delivery time required for stereotactic radiosurgery treatment [9]. Additionally, extensive studies have investigated the application of FFF beams for various cancer sites. Sun et al. and Nicolini et al. found that FFF plans resulted in lower doses to organs at risk than FF plans for esophageal cancer treatment [10, 11]. Spurijt et al. reported comparable doses between FFF and FF plans for breast irradiation [12]. Consequently, FFF beams are increasingly replacing FF beams in advanced cancer radiation techniques, including those for cranial malignancies. Head-and-neck (H&N) cancers pose significant treatment challenges due to involvement of critical organs. Volumetric modulated arc therapy (VMAT) and intensity-modulated RT (IMRT) are commonly used procedures for H&N cancer treatment due to their dosimetric advantages and ability to spare nearby critical organs, leading to improved survival and quality of life. Analyzing the out-of-field dose associated with FFF VMAT delivery for H&N cancer treatment could provide additional benefits.

The objective of this study was to comprehensively analyze the out-of-field dose associated with 6 and 10 MV X-ray beams for Varian TrueBeam machines with and without flattening filters, considering field size and depth dependence. Additionally, the study investigated the out-of-field dose associated with VMAT delivery for H&N cancer treatment.

Materials and Methods

Slab Phantom measurement

Out-of-field dose measurements were conducted using Linac (Varian Medical Systems, Palo Alto, USA) for 6 and 10 MV FF and FFF beams. Following the recommendations of TG-158, measurements were performed utilizing the metal oxide semiconductor field effect transistor (MOSFET) dosimetry system (Best Medical Canada Ltd, Canada) (Figure 1) in a water-equivalent slab phantom (SP34 IBA Dosimetry GmbH, Germany). The slab phantoms were arranged for the dimensions of 30 × 60 × 20 cm³ (width × length × depth). For this study, measurements were taken at depths of maximum dose, 5 cm, and 10 cm. The Depths of maximum dose were as follows: 6 MV FF: 1.6 cm, 6 MV FFF: 1.4 cm; 10 MV FF: 2.3 cm, 10 MV FFF: 2.2 cm. All measurements were taken for a gantry angle of zero degrees and clinically relevant field sizes of 5×5 cm², 10×10 cm², and 15×15 cm². The source-to-axis distance was maintained at 100 cm throughout the measurements. Each measurement was performed with an irradiation of 100 Monitor Units at the isocenter. Out-of-field dose measurements were taken from the field edge up to 30 cm in 5-cm intervals (Figure 2) by longitudinally moving the couch, following the methodology described by Covington et al. in their technical report [5].

TPS calculation

In addition to phantom measurements, the accuracy of dose calculation by the Treatment Planning System (TPS) (Eclipse, V 15.6, Varian Medical Systems, Palo Alto, USA) in the out-of-field region was evaluated. A slab phantom of similar geometry to the measurement phantom was created in Eclipse TPS (Figure 3). A series of treatment plans were developed using a single anterior beam corresponding to each of the measured static field sizes. Reference points were added at the same depths (dmax, 5 cm, and 10 cm) and distances from the measured field sizes (up to 30 cm from the field edge). For a 100 MU irradiation at the isocenter, the out-of-field dose was calculated using both AAA and the Acuros algorithm and recorded.

Body phantom measurement

For this study, an in-house head and body phantom was simulated using the Somatom Definition CT simulator (Siemens Healthcare, GmbH, Germany). The head phantom, made of bee wax due to its electron density close to that of water, was utilized. Subsequently, the slab phantom with MOSFET holder plates was set up to mimic the body shape. A clinically relevant 6 MV X-ray (FFF and FF) H&N VMAT plan was created for this phantom in TPS (Figure 4) for a prescribed dose of 70 Gy. The plans were then transferred to the TrueBeam machine, wherein out-of-field dose measurements were conducted using a mobile MOSFET detector (Best Medical Canada Ltd, Canada). The plan was delivered five times to achieve a significant dose, and the average dose was considered. Measurements were taken from the field edge (50% isodose line) for distances up to 30 cm (Figure 5).

Results

Out-of-field dose measurement for FF and FFF beams using MOSFET

Figure 6 illustrates trends in the measured out-of-field

Figure 1. Photograph of the Out of Field Dose Measurement Using MOSFET Detectors in Slab Phantom

dose using MOSFET for the 6 MV FFF beam compared with the FF beam at depths of dmax, 5 cm, and 10 cm. The out-of-field dose measured in this region was normalized to the dose at the central axis and expressed as a percentage of doses at the central axis (CAX) on the ordinate. The out-of-field dose for both FF and FFF beams decreased exponentially from the field edge. For a field size of 5×5 cm², the out-of-field dose for the 6 FF beam was 0.99%, whereas that for the FFF beam decreased to 0.67% at the depth of dmax. Similarly, for other field sizes, the out-of-field dose decreased for the FFF beam compared with the FF beam of 6 MV. However, the out-of-field dose measured using MOSFET increased from 1.687% to 3.449% at a depth of 10 cm when the field

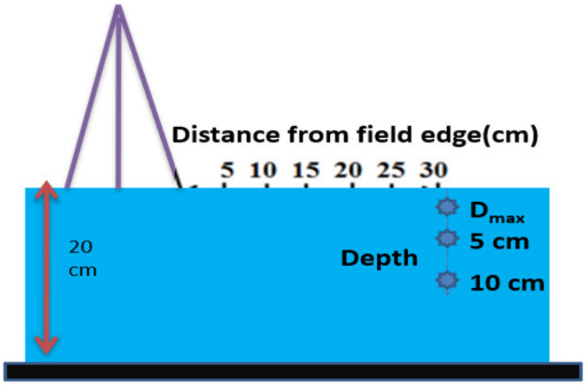

Figure 2. Schematic Diagram of Out of Field Dose Measurement

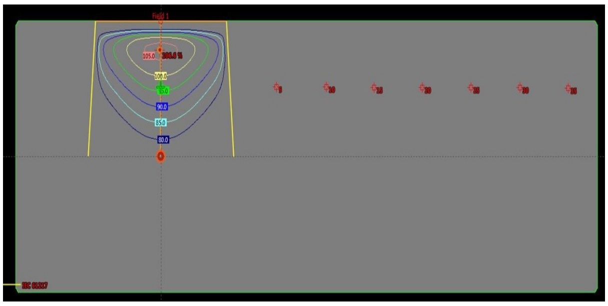

Figure 3. Slab Phantom Created in the Eclipse TPS

Table 1. Percent Ratio of the Measured Out of Field Dose to the CAX Dose at Varying Depth and Field Sizes at Distances Ranging from 5 to 30 cm from the Field Edge for a 6 MV FF and FFF Beam

			Out of field dose(% of dose at central axis)					
			Distance from the field edge (cm)					
Field size cm^2	Depth (cm)	Energy	5	10	15	20	25	30
5x5	1.5	6MV	0.999	0.549	0.383	0.150	0.100	0.067
5x5	5	6MV	1.200	0.600	0.436	0.164	0.109	0.091
5x5	10	6MV	1.687	0.752	0.479	0.205	0.114	0.114
5x5	1.5	6FFF	0.699	0.366	0.250	0.100	0.100	0.050
5x5	5	6FFF	0.919	0.450	0.263	0.113	0.056	0.056
5x5	10	6FFF	1.381	0.581	0.339	0.145	0.073	0.073
10x10	1.5	6MV	2.090	0.947	0.621	0.342	0.233	0.140
10x10	5	6MV	2.314	1.006	0.537	0.302	0.201	0.134
10x10	10	6MV	3.160	1.276	0.709	0.365	0.243	0.162
10x10	1.5	6FFF	1.320	0.652	0.398	0.239	0.175	0.111
10x10	5	6FFF	1.582	0.773	0.457	0.246	0.158	0.105
10x10	10	6FFF	2.608	1.043	0.587	0.304	0.152	0.109
15x15	1.5	6MV	2.894	1.379	0.727	0.485	0.333	0.197
15x15	5	6MV	3.425	1.558	0.779	0.536	0.341	0.227
15x15	10	6MV	4.442	1.904	0.923	0.577	0.385	0.231
15x15	1.5	6FFF	1.687	0.899	0.505	0.331	0.221	0.142
15x15	5	6FFF	2.281	1.072	0.579	0.357	0.238	0.153
15x15	10	6FFF	3.449	1.528	0.743	0.434	0.268	0.186

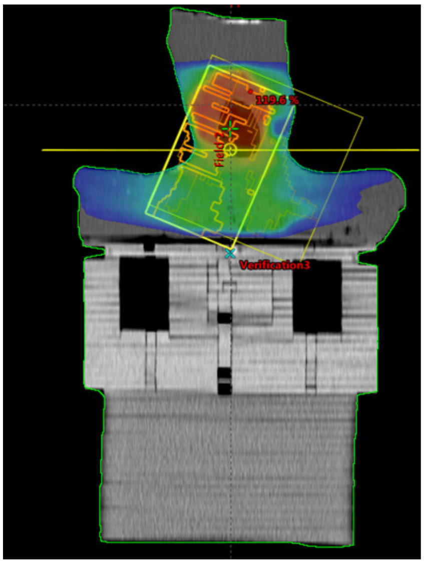

Figure 4. VMAT Plan for H&N Case Created in the TPS for Body Phantom

size was increased.

Table 1 presents out-of-field dose data of 6 MV (FF and FFF) beams for clinically relevant field sizes (5–15 cm) and distances of 5–30 cm. When the depth of the measurement was varied from dmax to 10 cm for a 10×10 cm² field size, the out-of-field dose increased from 2.090% to 3.160% for a 6 FF beam. Similarly, for the FFF beam, a consistent increasing trend for out-of-field dose with field size was observed. Figure 7 illustrates trends in the measured out-of-field dose for the 10 MV FFF beam versus the FF beam at depths of dmax, 5 cm, and 10 cm.

Figure 5. Out of Field Dose Measurement in the Body Phantom Using the MOSFET

For a field size of 10×10 cm², the out-of-field dose for a 10 FF beam was 1.295%, whereas that for the FFF beam was 0.635% at the depth of dmax. Similarly, for other field sizes, the FFF beam exhibited a lower out-of-field dose than a 10MV FF beam. At a depth of 10 cm, the out-of-field dose increased from 1.286% to 1.894% when the field size was increased from 5×5 cm² to 15×15 cm².

Table 2 displays out-of-field dose data of a 10 MV (FF and FFF) beam for clinically relevant field sizes (5–15 cm) and distances of 5–30 cm. The pattern remained consistent across all field sizes investigated for both FF and FFF beams. Furthermore, when comparing a 6 MV beam with a 10 MV beam, the out-of-field dose decreased with increasing energy. For example, at a field size of 5×5 cm² and depth of 10 cm, the out-of-field dose for a 6 MV

Table 2. Percent Ratio of the Measured Out of Field Dose to the CAX Dose at Varying Depth and Field Sizes at Distances Ranging from 5 to 30 cm from the Field Edge for a 10 MV FF and FFF Beam.

			Out of field dose (% of dose at central axis)					
			Distance from the field edge (cm)					
Field size cm²	Depth (cm)	Energy	5	10	15	20	25	30
5x5	2.3	10MV	1.295	0.598	0.448	0.149	0.100	0.066
5x5	5	10MV	1.235	0.617	0.463	0.206	0.154	0.048
5x5	10	10MV	1.286	0.617	0.412	0.154	0.103	0.051
5x5	2.3	10FFF	0.635	0.342	0.244	0.146	0.065	0.049
5x5	5	10FFF	0.672	0.362	0.258	0.103	0.069	0.052
5x5	10	10FFF	0.994	0.435	0.248	0.124	0.083	0.062
10x10	2.3	10MV	2.467	1.071	0.605	0.326	0.233	0.140
10x10	5	10MV	2.390	1.004	0.574	0.335	0.239	0.143
10x10	10	10MV	2.837	1.146	0.655	0.382	0.218	0.127
10x10	2.3	10FFF	1.135	0.567	0.378	0.236	0.142	0.047
10x10	5	10FFF	1.186	0.544	0.297	0.148	0.099	0.049
10x10	10	10FFF	1.742	0.755	0.407	0.232	0.116	0.077
15x15	2.3	10MV	3.374	1.484	0.720	0.495	0.315	0.225
15x15	5	10MV	3.153	1.437	0.742	0.510	0.371	0.232
15x15	10	10MV	3.916	1.619	0.783	0.522	0.313	0.209
15x15	2.3	10FFF	1.533	0.743	0.418	0.279	0.186	0.093
15x15	5	10FFF	1.554	0.777	0.389	0.291	0.194	0.146
15x15	10	10FFF	1.894	0.874	0.437	0.243	0.146	0.097

Table 3. The Ratio of Calculated to Measured Out of Field Dose for Both the AAA and Acuros Dose Calculation Models for 6MV Flattened and FFF Beam

			Ratio of out of field dose calculated and measured (Dcal/Dmes)					
Energy (MV)	Field size (cm^2)	Depth (cm)	Distance from the field edge (cm)					
			5 (cm)		10 (cm)		15 (cm)	
			AAA	Acuros	AAA	Acuros	AAA	Acuros
6FF		1.5	0.31	0.41	0.19	0.19	0	0
	5x5	5	0.57	0.47	0.19	0.19	0	0.26
		10	0.66	0.58	0.37	0.37	0	0
		1.5	0.56	0.57	0.41	0.42	0	0.32
	10x10	5	0.73	0.64	0.42	0.42	0	0.39
		10	0.83	0.84	0.59	0.6	0	0.36
		1.5	0.7	0.6	0.49	0.56	0	0.27
	15x15	5	0.75	0.69	0.46	0.53	0	0.39
		10	0.8	0.78	0.62	0.69	0	0.65
6FFF		1.5	0.31	0.31	0.3	0.3	0	0
	5x5	5	0.49	0.37	0.25	0.25	0	0
		10	0.59	0.49	0.47	0.41	0	0
		1.5	0.39	0.32	0.32	0.32	0	0.26
	10x10	5	0.61	0.54	0.41	0.42	0	0.24
		10	0.57	0.58	0.48	0.48	0	0.43
		1.5	0.42	0.42	0.34	0.34	0	0.2
	15x15	5	0.54	0.45	0.48	0.48	0	0.36
		10	0.58	0.58	0.46	0.54	0	0.48

FF beam was 0.752%, whereas for a 10 MV FF beam was 0.617%. Similarly, for a field size of 10×10 cm², the out-of-field dose at a depth of 10 cm for a 6 MV FF beam was 1.276%, whereas that for a 10 MV FF beam was 1.146% at a distance of 10 cm from the field edge. The same trend was observed for FFF beams.

Out-of-field dose calculation by TPS

Table 3 and 4 list the ratio (Dcal/Dmeas) of TPS-calculated dose to MOSFET detector measured dose from the field edge to 30 cm for the same irradiation dose of 6 and 10 MV FF and FFF beams. This ratio varied from 0.00 (100% underestimation) to 1.03 (3% overestimation of dose). As the distance between the point of interest and the field boundary increased, TPS accuracy deteriorated, as indicated by Dcalc/Dmeas values < 1. Even at distances close to the field, the out-of-field dose was underestimated by TPS. For example, at 5 cm from the field edge and a depth of 10 cm, the AAA algorithm underestimated the dose by 17% for a 10×10 cm² field size and 6 MV FF beam, whereas the Acuros algorithm underestimated it by 16%. On average, 50% underestimation was observed at 5 cm from the field edge and 60% underestimation was observed at 10 cm for both FF and FFF (6 and 10 MV) beams. Interestingly, the AAA algorithm failed to calculate the dose at 15 cm from the field edge, whereas Acuros started at 20 cm from the field edge.

Out-of-field dose measured while delivering VMAT

When the VMAT plan was delivered to the body phantom using the 6 MV FF and FFF beams (Figure 8), the out-of-field dose measured using the MOSFET detector decreased exponentially from the field edge. Plan delivery with the FFF beam resulted in a 7% reduction in the average nontarget dose between 1 cm and 5 cm from the field edge compared with that with the FF beam. At 10 cm, the FFF beam resulted in a 40% lower dose than the FF beam, and at 15 cm, the dose was reduced by 85%. Furthermore, the FFF beam resulted in a near-zero dose at 20 cm from the field edge, whereas the FF beam resulted in a dose of 0.45 cGy. The percentage difference between out-of-field nontarget doses increased with increasing distance from the field edge (Table 5). Additionally, the out-of-field dose calculated by the AAA was evaluated in TPS for the same measurement points. As the distance from the 5% isodose line increased, TPS underestimated the out-of-field dose by up to 75%.

Discussion

Despite previous comprehensive studies on the

Table 4. The Ratio of Calculated to Measured out of Field Dose for Both the AAA and Acuros Dose Calculation Models for 10MV Flattened and FFF Beam

Energy (MV)			Ratio of out of field dose calculated and measured (Dcal/Dmes)					
	Field size (cm^2)	Depth (cm)	Distance from the field edge (cm)					
			5 (cm)		10 (cm)		15 (cm)	
			AAA	Acuros	AAA	Acuros	AAA	Acuros
10FF	5x5	2.3	0.4	0.32	0.17	0.17	0	0
		5	0.34	0.34	0.17	0	0	0
		10	0.58	0.48	0.2	0.2	0	0
	10x10	2.3	0.52	0.52	0.37	0.37	0	0.36
		5	0.46	0.46	0.2	0.29	0	0.35
		10	0.56	0.6	0.4	0.4	0	0.35
	15x15	2.3	0.59	0.54	0.32	0.45	0	0.26
		5	0.49	0.49	0.33	0.34	0	0.26
		10	0.61	0.58	0.47	0.54	0.69	0.42
10FFF	5x5	2.3	0.46	0.47	0.29	0.29	0	0
		5	0.61	0.62	0.28	0.29	0	0
		10	0.74	0.76	0.57	0	0	0
	10x10	2.3	0.68	0.68	0.51	0.51	0	0.26
		5	0.75	0.85	0.55	0.55	0	0.34
		10	0.87	0.95	0.62	0.78	0	0.58
	15x15	2.3	0.68	0.62	0.51	0.51	0	0.46
		5	0.69	0.82	0.5	0.63	0	0.51
		10	1.02	1.03	0.78	0.92	0	0.79

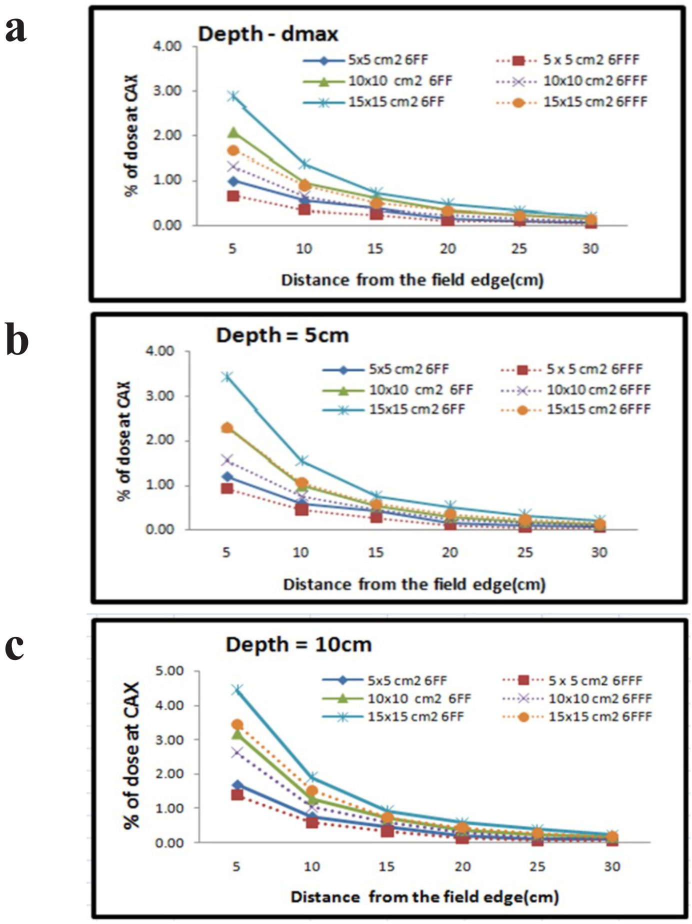

Figure 6. The Out of Field Dose Measurements are Shown at a Depth of (a) nominal dmax (1.5cm), (b) 5cm, and (c) 10cm and were acquired for field sizes ranging from 5x5 cm^2, 10x10 cm^2 and 15x15 cm^2, and distances of 5-30 cm from the field edge for the 6FF (solid line) and 6FFF (dashed line) beams.

Table 5. Calculation of Percentage of Difference between TPS Calculated and Measured Dose while Delivering VMAT H&N Treatment

Distance from the field edge (cm)	Out of field dose cGy/#				TPS vs Measurement	
	TPS		Measurment		Percentage of difference	
	FF	FFF	FF	FFF	FF	FFF
1	8.1	5	13.38	11.80	39.46	57.63
2	5.7	3.6	9.99	10.30	42.93	65.05
3	4.3	2.8	9.19	7.50	53.19	62.67
4	3.2	2.2	6.74	5.60	52.52	60.71
5	2.4	1.7	5.78	3.33	58.48	48.95
10	0.8	0.6	3.29	0.99	75.68	39.39
15	0	0	1.59	0.64	100.00	100.00
20	0	0	0.53	0	100.00	
25	0	0	0	0		
30	0	0	0	0		

dosimetric characteristics of FFF beams, quantifying the out-of-field dose for both 6 and 10 MV X-rays remains relevant, and its clinical impact warrants investigation. When limiting the dose to the fetus or organs with low dose tolerances (e.g., the gonads, the lens of the eye), the out-of-field nontarget dose may be clinically significant. It also becomes relevant when considering the risk of secondary malignancies or potential interference with implanted electronic devices such as pacemakers or defibrillators [13, 14, 15, 16]. The inherent differences in beam parameters between FFF and conventional FF beams necessitate in-depth characterizations of FFF beams as their clinical

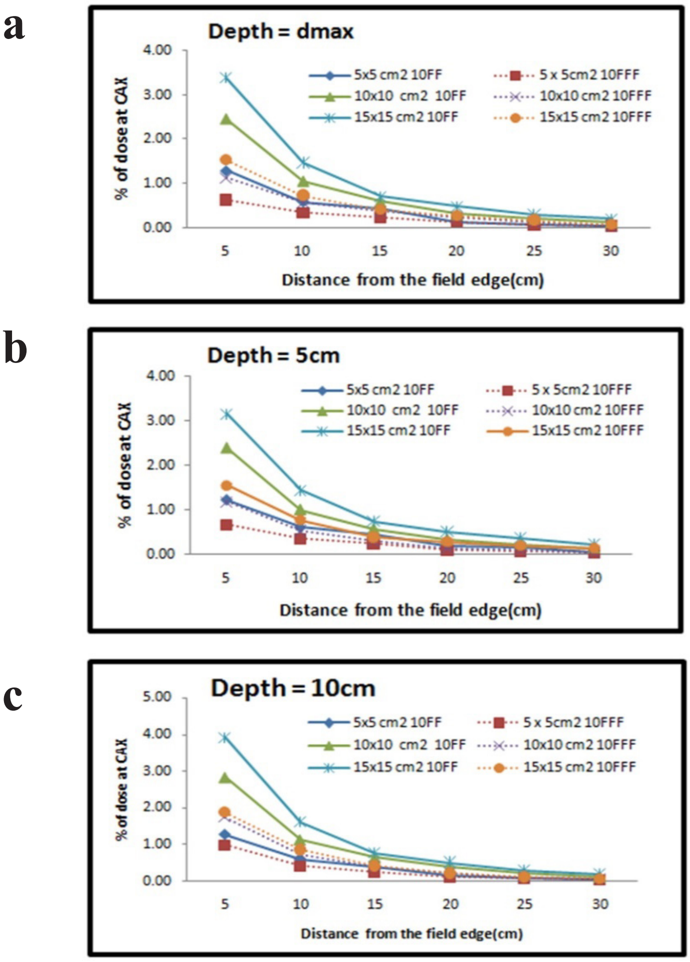

Figure 7. The Out of Field Dose Measurements are Shown at a Depth of (a) nominal dmax (2.3cm), (b) 5cm, and (c) 10cm and were acquired for field sizes ranging from 5x5 cm^2, 10x10 cm^2 and 15x15 cm^2, and distances of 5-30 cm from the field edge for the 10FF (solid line) and 10FFF (dashed line) beams

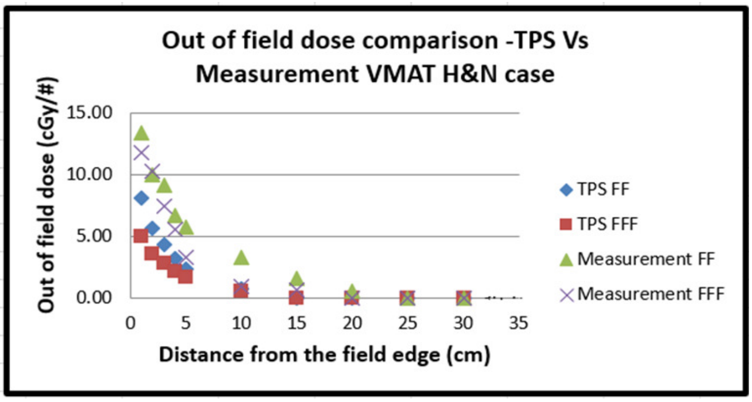

Figure 8. Measured and TPS Calculated Out of Field Dose Comparison for FF and FFF -6MV X-ray Beam for VMAT H&N Case

use in radiation therapy expands. It cannot be assumed that the out-of-field dose trends observed with FF beams are the same as those observed with FFF beams. Since out-of-field nontarget dose calculations with commercial TPS are known to be inaccurate, most out-of-field dose assessments involve phantom measurements or MC simulations [6, 17]. Our present study comprehensively evaluated the out-of-field dose associated with FFF beams of 6 and 10 MV through phantom measurement.

A study by Krishni Wijesooriya on the out-of-field dose mapping for 6 MV beams in both FF and FFF modes on a Varian TrueBeam machine provided valuable insights [8]. Although this study was conducted on TrueBeam, it only measured the out-of-field dose for 6 MV beams. The study revealed that the out-of-field dose presented with 6 MV FFF beams is as low as 64% compared with that presented with 6 MV FF beams. Additionally, the out-of-field dose decreased with field size, which aligns closely with our study results where the out of field dose presented with 6 MV FFF beams is as low as 62% compared with that presented with 6 MV FF beams.

Another technical report published by Covington et al. on the out-of-field dose of FFF beams explained that the out-of-field dose associated with 6 10 MV FFF beams decreases from the field edge with decreasing field size in the range of 20–30%. Our findings also confirmed that the out-of-field dose associated with a 6 MV beam can be up to 40% higher than that of a 10 MV beam due to increased scatter radiation.It further revealed that there is no clinically significant impact of collimator rotation when used in conjunction with MLC. Moreover, an average underestimation of -69% of out-of-field nontarget dose at extended distances by both AAA and Acuros algorithms was reported [5]. Our study's data closely agreed (<3% difference) with those of Covington et al. Calnot et al.'s recent study also confirmed that AAA and Acuros algorithm used in the Eclipse TPS significantly underestimate the out-of-field dose [18].

Through MC simulations of 6 MV and 6 MV FFF beams for the Varian 2100 Linac, Kry et al. confirmed that removing the flattening filter reduces the out-of-field dosage near the treatment field due to collimator scatter reduction [19]. Another study performed by Annamalai and Velayudham compared peripheral dose measurements using an ion chamber and MOSFET detector for 6 MV FF beams [20]. In this study, peripheral dose measurements were performed for field sizes ranging from 5×5 cm^2 to 20×20 cm2 at three different depths in the slab phantom. Dose was measured up to 30 cm from the field edge. Our study followed a similar set of measurements, and the results were comparable for 6 MV FF beams. However, we were unable to compare the FFF data as it was not performed in the Annamalai and Velayudham study. Therefore, MOSFET can be used to measure out-of-field dose in individual cancer patients, and its accuracy in estimating peripheral dose is sufficient for risk assessment. The advantages of MOSFETs include their small size, immediate reading, ease of usage, and linear response over vast dose ranges. Although they have angular and energy dependence, it is quite modest, with 3% energy dependence in the MV range and a 2–6% angular dependence, as quoted in TG-158. With a maximum accumulated dose, MOSFET dosimeters have a limited lifetime, but this is not a significant concern for out-of-field measurements since they often involve minimal doses [2].

Out-of-field dosage calculations are not commissioned or integrated into radiotherapy TPS [21]. Despite TPS displaying doses at locations outside of the treatment field, it should not be employed to predict out-of-field dosage. Significant differences have been reported between measured doses and doses calculated using photon-beam planning methods. Even for current convolution/superposition and AAA, large differences have been recorded between measured doses and those calculated from TPS [22, 23]. Photon-beam planning algorithms are known to underestimate the true out-of-field dose, although overestimations have also been observed. Studies have shown large and comparable inaccuracies in both simple conformal fields and IMRT fields [21]. Huang et al also quantified the accuracy of the Pinnacle TPS's out-of-field dose calculations for three IMRT treatment plans and found that TPS underestimated the out-of-field dose by an average of 50% at measurement locations, with the degree of dose underestimation increasing as the distance from the field edge increased [3]. It is noted that TPS underestimates not only collimator and other beam line scatter but also patient scatter. Similarly, our study found that TPS underestimates dosage by an average of

50% in the region of 5–10 cm from the field boundary. AAA is unable to calculate the dose at 15 cm from the field edge and underestimates it by 100%, while Acuros produces an underestimated dose figure. This discrepancy could be due to AAA employing a divergent dose matrix, wherein the width of the calculation matrix is determined by the jaw location. The default margin from the field is 12 cm; however, it can be adjusted to 7–12 cm to reduce the number of calculation points. Acuros employs the identical input fluence margins, but the dosage calculation is extended to the entire computation volume. Even though Acuros was able to compute beyond 10 cm from the field edge, the results were still understated. Therefore, it is not recommended to estimate out-of-field dose using TPS due to the underestimation of out-of-field dose and inability to calculate dose at long distances due to the limitations of the dose calculation matrix.

Although the usage of FFF radiation beams obtained by removing FF in standard linear accelerators is quickly expanding in RT, the clinical benefits are still under study [24]. FFF beams deliver greater intensity X-rays at the field center than conventional FF X-rays. A high dose rate FFF X-ray beam has the advantage of increased clinical benefit and shorter treatment duration. This is because in FFF mode, the FF's radiation attenuation effect is eliminated, resulting in reduced head leakage at a greater distance from the field edge. The use of linear accelerators in FFF mode has grown in popularity due to advanced treatment procedures such as stereotactic RT or IMRT. According to a dosimetric study conducted in TPS by Kumar et al., the FFF VMAT plan for H&N cancer delivered the lowest mean dose for OARs [25]. This is also confirmed by our study, wherein the out-of-field dose decreased for the same dose to PTV in FFF mode compared with that in FF mode when delivering an H&N VMAT plan in the body phantom.

Using the standard deviations of the measured out-of-field dose, we estimated the magnitude of dose error associated with MOSFET positioning uncertainty. This value typically ranges between 1.64% and 4.11%. For nearly all of our data points, the error associated with TPS dose calculation inaccuracies was much greater than the uncertainty associated with our MOSFET measurements. Therefore, despite the uncertainties associated with positioning errors, performing these measurements is worthwhile because the results would still be more accurate than simply using the TPS-calculated dose.

In conclusion, the out-of-field nontarget dose was measured using MOSFET for various field sizes ranging from 5×5 cm^2 to 15×15 cm^2 for 6 and 10 MV FF and FFF beams in a solid water phantom and a body phantom up to 30 cm from the field edge. This comprehensive dataset can be used to estimate the out-of-field dose in organs at risk at their respective points of measurement or in any electronically implanted devices. The out-of-field dose was found to decrease with increasing distance from the field edge and with decreasing field size. FFF beams were associated with lesser out-of-field dose than FF beams for both 6 and 10 MV beams, and higher-energy beams presented with lower out-of-field dose. The out-of-field dose calculated by AAA and Acuros algorithm was found to underestimate the out-of-field dose, and the percent error varied with field size for both FF and FFF beams in TPS. For a comparable dose distribution, the VMAT head-and-neck plan performed with the FFF beam resulted in a lower out-of-field dose than the FF beam. Further dosimetric studies are warranted to determine the significant benefit of FFF beams across different cancer sites.

Author Contribution Statement

Dr.Hemalatha.A,Mr.Gokulraj Anbu conceived the project. Dr.Athiyaman.M searched, collected, and screened all articles. Dr.Arun Chougule supervised the project.Dr.Neeti sharma and Dr.HS Kumar edited this manuscript. All authors read and approved the final manuscript

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Ethics statement

This does not involved any human or animal study.

Availability of data

All reviewed papers can be obtained from journals.

Conflicts of interest

The authors have no relevant conflicts of interest to disclose.

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