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RESEARCH ARTICLE

Study to Analyze the Dosimetric Characteristics of High Dose Rate Flattening Filter-Free Beam from different Linear Accelerators

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Abstract

Background: Numerous radiation-generating devices produce flattening filter-free (FFF) beams for treating cancer patients clinically, while all those machines produce FFF beams, they differ in their treatment head, collimation system, Multi leaf collimator (MLC) configurations, MLC speed, gantry speed, and dose rate. Objective of this study was to compare dosimetric characteristics of FFF beams used in different linear accelerators (Linacs) from multiple radiotherapy centres. **Methods:** Dosimetric data for 6MV FFF and 10MV FFF beams from Elekta Versa HD™ (EVH1 & EVH2), Varian TrueBeam™ (VT1 & VT2), and 6MV FFF from Varian Halcyon™ (VH1 & VH2) were analyzed. This study compared different dosimetric parameters included depth of maximum dose (Dmax), beam quality index, percentage depth dose (PDD), beam profiles, penumbra, off-axis ratio, percentage surface dose (PSD), head leakage, and multi-leaf collimator (MLC) leakage. **Results:** The VH showed significantly lower MLC transmission (0.007–0.03%) compared to VT (1.21–1.23%) and EVH (0.23–0.34%). PSD for a 30×30 cm² field was lower in EVH (37.1–38.4%) than VT (49.3–51.1%) but higher for a 28×28 cm² field in VH (66.2–69.1%). Head leakage showed no major differences, with values in the patient plane of 0.004–0.014% (EVH), 0.005-0.03% (VT), and 0.012–0.10% (VH); and other than patient plane of 0.02–0.10% (EVH), 0.007% (VT), and 0.012–0.209% (VH). Penumbra was slightly lesser in VH (8.9 mm) than VT (9.5 mm) and EVH (9.8 mm). VH exhibited excellent MLC shielding and a narrower penumbra, ensuring better conformity and minimal leakage. EVH had lower PSD, offering improved skin sparing. VT showed higher MLC transmission, indicating slightly higher out-of-field dose. Head leakage was lesser for all machines, confirming effective shielding design. **Conclusion:** Overall analysis shows clear performance variations among the evaluated linac platforms. EVH exhibited a higher energy spectrum, while VH and VT demonstrated slightly lower values. VH showed the lowest MLC leakage. Comprehensive dosimetric comparisons are essential when commissioning FFF linacs. Machine specific parameter must be assessed and optimized for clinical needs. Such evaluations are key for advanced radiotherapy quality. Centres should consider these technical details in commissioning and deployment.

Keywords: Flattening Filter- Flattening Filter Free- Linear accelerator- Dosimeter

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Introduction

In a standard linear accelerator (Linac), the flattening filter (FF) is strategically placed between the primary collimator and the monitor chamber. Its primary function is to ensure a uniform dose distribution of the photon beam at a specified depth, thereby producing flat dose profiles with consistent variation across the beam. Crafted from materials with high atomic numbers, the FF typically takes on a conical shape to effectively flatten the initially

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forward-peaked bremsstrahlung photon beam [1-4]. The inclusion of the FF notably diminishes the photon beam dose rate and serves as a significant source of head scattered radiation. In its role, the FF acts as both an attenuator and a scatterer, while also contributing to beam hardening [1, 2].

The Flattening Filter Free (FFF) beam from a medical Linac produces bremsstrahlung radiation with a bell-shaped profile, highest in intensity at the center. FFF beams exhibit unique characteristics compared to flattened beams, including differences in photon energy spectrum, a sharper penumbra, reduced head scatter, decreased out-of-field dose, increased ion recombination, higher surface dose, and reduced vault-shielding requirements [1-5]. Numerous radiation-generating devices produce FFF beams for treating cancer patients clinically, including Elekta VersaHD (EVH), Elekta Unity, Varian TrueBeam (VT), Varian Halcyon (VH), Siemens Artiste, ViewRay MRIdian, Accuray CyberKnife, and Tomotherapy [1]. While all these machines produce FFF beams, they differ in their treatment head, collimation system, Multi leaf collimator (MLC) configurations, MLC speed, gantry speed, and dose rate. This study aims to analyze the beam parameters of three types of linear accelerators, with two machines of each type obtained from different institutions: VT, VH and EVH.

VT systems use a tungsten target, with the same electron beam used to produce both flattened and FFF beams. In the carousel containing the FF, 0.8 mm thick brass plate filters electrons and low-energy photons, replacing the FF used in FFF beams. Unlike VT, EVH does not use the same electron beam to generate both the FFF and corresponding flattened beam. Each beam is characterized by its unique set of parameters, including settings for radio frequency and gun settings defining the electron beam energy, as well as dosimetry calibration settings. In the Linac head, the bremsstrahlung beam is filtered using a stainless steel disc of 2mm instead of the typical FF [2].

The current study involved analyzing and comparing measured data from two VT and two EVH Linacs units for 6MV FFF and 10MV FFF, as well as two VH unit for 6MV FFF. The measured datasets include beam quality index (TPR 20/10), PDD, depth of maximum dose (Dmax), percentage surface dose (PSD), MLC leakage, head leakage, beam profile parameters of degree of unflattness, beam symmetry, off-axis ratio (OAR), penumbra, and field size.

Materials and Methods

Equipment

Varian Truebeam

VT Linac offers the dose rates reaching up to 1400 monitor units per minute (MU/min) for 6MV FFF and 2400 MU/min for 10MV FFF, respectively. The VT features a Tertiary Collimation System with the High Definition 120 MLC. This MLC comprises two banks, each containing 60 tungsten leaves. The central 8 cm consists of 32 leaves, each 0.25 cm wide at isocenter, while the outer 14 cm consists of 28 leaves, each 0.50 cm wide. The maximum MLC-defined field length perpendicular to leaf motion is 22.0 cm at isocenter, with a leaf thickness of 6.9 cm [2, 6, 7].

Elekta VersaHD

EVH Linac provides the dose rates can reach up to 1400 MU/min for 6MV FFF beams and 2400 MU/min for 10MV FFF beams, with a maximum field size of 40 × 40 cm^2. The MLCs replace the jaws in the perpendicular direction, with no additional backup jaws or diaphragms. The Agility collimator features 80 pairs of interdigitating MLCs, each with a projected leaf width of 5 mm at the isocenter. With a primary collimator speed of 9 cm/s [2, 8].

Varian Halcyon

The VH Machine is characterized by its enclosed, ring-mounted gantry and utilization of a 6MV FFF beam and the dose rate of 800MU/min. notably, it boasts a significantly faster gantry rotation capability compared to conventional C-arm linacs, with a maximum speed of 360° in 15 seconds. The VH is specifically engineered for the delivery of dynamic MLC plans in clinical mode, featuring a dual-layered, stacked MLC capable of projecting to a maximum field size of 28x28cm^2 at isocenter. Comprising 58 upper and 56 lower MLCs, each leaf is 1 cm wide, totalling 114 leaves. To minimize inter-leaf leakage, the top layer is laterally displaced by 0.5 cm relative to the lower layer. These leaves are capable of moving at a maximum speed of 5.0 cm/s. Unlike traditional systems, the Halcyon does not incorporate moving collimating jaws, as its dual-stack MLC design ensures adequate shielding [9, 10].

PDD and Beam profile

Beam data acquisition for VT1 and VT2 (VT1& VT2), EVH1 and EVH2 (EVH1 & EVH2) and VH1 and VH2 (VH1&VH2) adhered to Atomic Energy Regulatory Board (AERB) recommendations. Measurements were conducted for VT1, VT2, EVH1 and EVH2 Linacs using a PTW beam scan water tank with a PTW Semiflex 3D chamber (0.07 cc active volume) for both the field and reference. The acquisition sampling time was set to 0.3 s with a step size of 1 mm. Before measurement, a radiation beam center check ensured proper positioning of the chamber along the central axis (CAX) of radiation in the horizontal plane. PTW's software was employed, adjusting for the shift in the chamber's effective point of measurement. PDD measurements was conducted along the CAX with a source to surface distance (SSD) of 100 cm for field sizes of 10x10cm^2, normalized to 100% using values at the Dmax [8]. In-plane and cross-plane profile scans were performed with an SSD of 90 cm and depth of 10 cm for a field size of 20x20 cm^2. All acquired PDDs and profiles underwent processing using PTW's MEPHYSTO mc^2 navigation software. Data collection for the VH1 and VH2 6MV-FFF beam was carried out in a water tank (3D Scanner, Sun Nuclear Corporation) using a 0.0125 cc point chamber (SNC 125), with adjustments made for the effective point of measurement. The data analysed with Sun check software.

Beam Quality index (TPR20/10)

Beam quality index measurements were conducted at depths of 20cm and 10cm with source-to-axis distance (SAD) setup according to the International Atomic Energy Agency (IAEA) Technical Report Series (TRS398) Protocol [11]. For VT1, VT2, EVH1 and EVH2 Linacs, the measurements were performed using the TPR20/10 Phantom with a PTW Farmer chamber of 0.6 cc volume. For the VH1 and VH2 the measurements were carried out using a 3D Scanner with SNC 125 chamber.

Percentage Surface dose

For EVH1, EVH2, VT1 and VT2 the PSD measurements were carried out using a solid water phantom with a Markus Parallel plate ionization chamber. The measurements were performed at an SSD 90cm for field sizes of 30x30cm^2 by delivering 100 MU. The measurement depth ranged from 0 to 5 mm with an increment of 1.0 mm, including Dmax. The measurement values were normalized at Dmax. Correction factors, as described in the Mellenberg article [12], were applied to the Markus chamber response to correct for side wall scatter. Temperature and pressure corrections were applied using the formula: (T+273.15) / 293.15] x (1013.25/P) [11]. The chamber-to-source distance remained unchanged, resulting in a tissue maximum ratio (TMR) measurement that needed to be converted to PDD to determine the relative surface dose [13]. The relative surface dose at a depth of 0.5 mm was determined by interpolating between the measurements at 0 mm and 1.0 mm depths. For VH1 and VH2 the percentage surface dose values at 0.5 mm have taken from PDD measurements with a 0.0125 cc point chamber (SNC 125) using a 3D Scanner SNC.

Leakage Measurements

MLC leakage measurements were conducted using a cylindrical ionization chamber with a brass build-up. The measurements included 24 points with the MLC leaves fully closed. The chamber was positioned in a plane perpendicular to the beam axis, encompassing the machine isocenter, at distances around within a range of 1 meter from the isocenter in all directions. Leakage measurements at the patient plane were conducted with a 2-meter radius perpendicular to the beam axis of the isocenter plane. Measurements were also taken in areas other than the patient plane, at a 1-meter distance from the path of the electron beam, using a pressurized ionization survey meter [14].

Results

All the data were collected from six different machines of EVH1, EVH2, VT1, VT2, VH1, and VH2 representing three types of linear accelerators. Two machines of each type were included in the study, and these were sourced from different institutions to ensure independent and representative measurements.

Central axis measurements

PDD, Dmax, TPR20/10 and PSD

The PDD at a depth of 10 cm with a field size of 10x10 cm^2 for EVH1, EVH2, VT1, and VT2 for 6MV FFF was observed as 67.4%, 68.2%, 63.3%, and 63.14% and for 10MV FFF was 72.4%, 72.7%, 70.9%, and 70.9%. For VH1, VH2 the PDD for 6MV FFF was 63.01% and 63.10%, respectively. Dmax for EVH1, EVH2, VT1 and VT2 for 6MV FFF was 1.69 cm, 1.60 cm, 1.31cm, and 1.37cm, and for 10MV FFF was 2.40cm, 2.43cm, 2.10cm, and 2.20cm. For VH1, VH2, the Dmax for 6MV FFF was 1.34cm and 1.30cm, respectively. The beam quality index values for EVH1, EVH2, VT1, and VT2 for 6MV FFF were 0.676, 0.677, 0.635, and 0.630 and for 10MV FFF were 0.718, 0.720, 0.707, and 0.707. For VH1, VH2, the beam quality index for 6MV FFF was 0.637 and 0.629, respectively. The PSD of 30x30cm^2 for EVH1, EVH2, VT1, and VT2 for 6MV FFF were 37.1%, 38.4%, 49.3%, and 51.1% and for 10MV FFF were 32.0%, 33.0%, 37.2%, and 39.2%. For VH1, VH2, the PSD for 6MV FFF with field size of 28x28cm^2 was 69.1% and 66.2%, respectively as shown in Table 1.

Off Axis Measurements

The beam profiles were measured in-plane and cross-plane for a 20x20cm^2 field size at a depth of 10cm in the SAD setup for 6MV FFF and 10MV FFF beams of VT1, VT2, EVH1, and EVH2, as well as for VH1 and VH2 of the 6 MV FFF beam. In the profiles, we analyzed the degree of un-flatness, symmetry, off-axis ratio, Field size, and penumbra.

Table 1. Central Axis Measurements Parameters of TPR 20/10, Dmax, PDD and PSD for 6MV FFF and 10MV FFF beam for EVH1, EVH2, VT1, VT2 and 6MV FFF beam for VH1 and VH2

Machine	TPR2010		Dmax (cm)		PDD (%)		PSD (%)	
	6 FFF	10 FFF	6 FFF	10 FFF	6 FFF	10 FFF	6 FFF	10 FFF
EVH1	0.676	0.718	1.69	2.39	67.41	72.37	37.1	32
EVH2	0.677	0.72	1.56	2.43	68.18	72.7	38.4	33
VT1	0.635	0.707	1.31	2.2	63.28	70.89	49.3	37.2
VT2	0.63	0.707	1.37	2.1	63.14	70.9	51.1	39.2
VH1	0.637	*	1.34	*	63.01	*	69.1	*
VH2	0.629	*	1.3	*	63.01	*	66.2	*

Table 2. Degree of Unflateness of 6 MV FFF and 10MV FFF beam for EVH1, EVH2, VT1, VT2 and 6MV FFF beam for VH1 and VH2

	Degree of Unflateness											
	6 FFF						10 FFF					
Machine	Lateral Width-Inplane (cm)			Lateral Width-Cross plane (cm)			Lateral Width-Inplane (cm)			Lateral Width -Cross plane(cm)		
	90%	75%	60%	90%	75%	60%	90%	75%	60%	90%	75%	60%
EVH1	8.86	16.22	19.43	8.68	15.99	19.62	6.62	12.56	18.27	6.26	12.2	18.08
EVH2	8.7	15.9	19.6	8.5	15.7	19.4	6.5	12.5	18.3	6.3	12.3	18.2
VT1	9.82	17.25	19.5	9.8	17.28	19.49	6.4	12.56	19.42	6.3	12.52	19.5
VT2	9.9	17.2	19.2	9.4	16.9	17.7	6.5	12.64	18.2	6.45	12.66	18.4
VH1	10.43	17.76	19.45	10.44	17.79	19.48	*	*	*	*	*	*
VH2	10.4	17.74	19.46	10.43	17.76	19.49	*	*	*	*	*	*

Table 3. Symmetry of 6MV FFF and 10MV FFF beam for EVH1, EVH2, VT1, VT2 and 6MV FFF beam for VH1 and VH2

Machine	Symmetry			
	6 FFF		10 FFF	
	Inplane (%)	Cross plane (%)	Inplane (%)	Cross plane (%)
EVH1	100.7	100.4	100.8	100.8
EVH2	100.6	100.9	100.6	101.5
VT1	100.5	100.9	100.6	100.7
VT2	100.5	101.1	101.1	100.4
VH1	100.6	100.7	*	*
VH2	100.1	100.6	*	*

Degree of un-flatness and Symmetry

We assessed the degree of un-flatness by measuring the lateral distance from the central axis at 90%, 75%, and 60% dose points on both sides of the beam profile. For EVH1 and EVH2, the 90%, 75% and 60% dose levels for the 6MV FFF beam were slightly lower compared to VT1, VT2, VH1, and VH2. For 10MV FFF, there were almost no significant changes for EVH1, EVH2, VT1, and VT2 as depicted in Table 2. There were no significant differences in symmetry among all six machines as shown in Table 3.

Off Axis Ratios

OAR at ±3 cm from the central axis at a depth of 10cm for a 10cm x 10cm field size showed no significant changes for the 6MV FFF and 10MV FFF beams of EVH1, EVH2, VT1 and VT2. Similarly, there were no significant changes for VH1 and VH2 for the 6MV FFF beam as illustrated in Table 4.

Field Size

The field size can be defined by the collimator opening and verified using beam profiles, specifically by measuring the lateral separation between inflection points along the major axes. The inflection point can be approximated as the midpoint on either side of the high gradient region of the beam profile. The start and end of the high gradient region of the beam profile are used to determine the height of the high gradient region. The inflection point is positioned at half the height of the high gradient region from either side of the beam profile. There was no significant change observed in the lateral separation between inflection points among all six machines as depicted in Table 5.

Penumbra

To determine the penumbra, measured the lateral separation between points on either side of the beam profile located at 1.6 and 0.4 times the dose value of the inflection point. The penumbra measurements with SAD setup using field size of 20x20cm^2 at 10cm depth were observed, For EVH1, EVH2: a maximum of 9.8mm and 8.0mm with the 6MV FFF beam, and 9.3mm and 8.0mm with the 10MV FFF beam. For VT1, VT2: 8.5mm and 9.5mm with the 6MV FFF beam, and 8.45mm and 9.5mm with the 10MV FFF beam. For VH1, VH2: 8.2mm and 8.9mm with the 6MV FFF beam as shown in Table 5.

Leakages Measurements

Radiation leakage through beam limiting devises for EVH1, EVH2, VT1, and VT2 for 6MV FFF was observed as 0.55%, 0.42%, 0.36% and 0.32% and for 10MV FFF was 0.77%, 0.32%, 0.36%, and 0.34 % respectively. Leakage through MLC for EVH1, EVH2, VT1, and VT2 for 6MV FFF was 0.34%, 0.23%, 1.21% and 1.23% and for 10MV FFF was 0.29%, 0.26%, 1.26%, and 1.31 % respectively. For VH1 and VH2, 6MV FFF MLC leakage was 0.007% and 0.03%, respectively.

Head leakage in patient plane for EVH1, EVH2, VT1, and VT2 for 6MV FFF was 0.014%, 0.004%, 0.005% and 0.03% and for 10MV FFF was 0.008%, 0.007%, 0.005%, and 0.007 % respectively. For VH1 and VH2, 6MV FFF was 0.012% and 0.01%, respectively. For other than patient plane for EVH1, EVH2, VT1, and VT2 for 6MV FFF was 0.02%, 0.1%, 0.007% and 0.007% and for 10MV FFF was 0.01%, 0.09%, 0.003%, and 0.004% respectively. For VH1 and VH2, 6MV FFF was 0.209% and 0.012%, respectively as shown in Table 6.

Discussion

Central axis measurements

PDD, Dmax, Beam Quality index

The effect of removing a FF on PDD results in the softening of the photon energy spectrum and changes to the depth dose curve [14, 15]. The presence of a FF in the beam path causes a beam hardening effect, shifting the dose maximum to greater depths for FF beams [3]. Depth dose curves of FFF beams exhibit a more rapid dose fall-off in the exponential region compared to beams produced with a FF [16, 17]. Electron contamination from the FF is a significant factor influencing the variation of Dmax with increasing field size. Therefore, removing the FF eliminates one of the primary sources of electron contamination [18-20]. The depth dose curve can change depending on the beam-shaping device, even when identical field sizes are used for both the MLC and jaws [4]. In our study shows that lower beam quality was observed in Varian machines compared to Elekta as illustrated in Figure 1. Indicates that the photon beam contains relatively more low-energy components, which can lead to a higher surface dose, slightly broader penumbra, and minor variations in dosimetric behaviour particularly relevant for superficial treatments and small-field dosimetry. According to Song H et al. [21], for certain models such as the Varian 2100C and earlier Philips/Elekta systems, Elekta 6MV photon beams were approximately 0.4MV harder than those from Varian, reflecting a marginally higher average photon energy. Nevertheless, for advanced modalities like Intensity Modulated Radiation Therapy (IMRT) or Volumetric Modulated Arc Therapy (VMAT), these energy differences generally have minimal clinical impact due to the averaging effect of multiple fields and beam angles [22]. Therefore, the selection between linac platforms should account for these subtle dosimetric distinctions in conjunction with other factors such

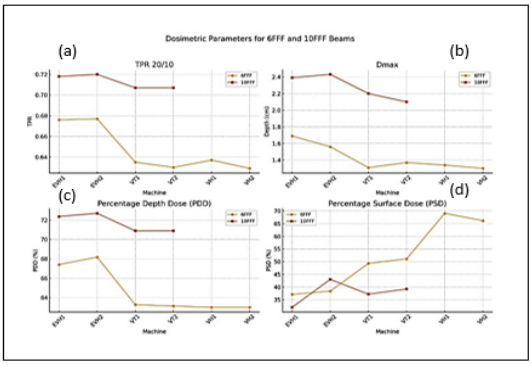

Figure 1. Comparison of Dosimetric Parameters of TPR 20/10 (a), Dmax (b), PDD (c), and PSD (d) for 6FFF and 10FFF Beams of EVH1, EVH2, VT1, VT2 and 6FFF Beam of VH1, VH2.

as MLC design, workflow efficiency, and software integration. In clinical practice, both Varian and Elekta linacs can be commissioned to achieve well-matched beam qualities suitable for most treatment applications. However, inherent design variations often result in Varian beams being slightly softer, which may influence surface dose and penumbra characteristics. These variations are generally small and can be effectively managed through appropriate commissioning procedures and quality assurance protocols.

Percentage surface dose

PSD is typically higher for lower beam energies, and in FFF beams, the softened x-ray spectra affect both depth and lateral dose distribution, leading to increased surface dose and a slight shift in the Dmax towards the surface [1]. Removing the FF increases surface dose slightly, but the reduced head scatter results in less variation in dose near the surface with field sizes compared to flattened beams [16]. Although the softer beam can increase surface dose, this effect is diminished by the elimination of scattered radiation and electron contamination from the FF. FFF beams generally exhibit smaller surface dose variations with field size compared to flattened beams, with higher surface doses for smaller field sizes and similar or lower doses for large field sizes, as reported for both Varian and Elekta linacs [16, 17, 23]. Our study shows that the PSD is higher in Varian linacs compared to Elekta linacs,

Table 4. Off Axis Ratio for 6 MV FFF and 10MV FFF Beam for EVH1, EVH2, VT1, VT2 and 6MV FFF Beam for VH1 and VH2

	off axis Ratio							
	6FFF				10FFF			
Machine	Inplane (%)		Cross Plane (%)		Inplane (%)		Cross Plane (%)	
	Plus 3cm	minus3cm	Plus 3cm	minus 3cm	Plus 3cm	minus 3cm	Plus 3cm	minus 3cm
EVH1	93.7	92.9	92.4	93.6	89.4	91.3	89.2	88.9
EVH2	92.6	93	93.6	92.8	88.8	89.7	90.7	90.7
VT1	94.8	94.8	94.7	95	91.1	91	90.8	91.2
VT2	94.8	94.6	95	94.8	90.6	91.1	91.1	91.1
VH1	94	94.2	94.4	94.2	*	*	*	*
VH2	94.5	94.2	94.5	94.4	*	*	*	*

Table 5. Field Size and Penumbra for 20x20cm^2 of 6 MV FFF and 10MV FFF beam for EVH1, EVH2, VT1, VT2 and 6MV FFF beam for VH1 and VH2

Machine	Separation between IPL&IPR				Penumbra							
	6FFF		10FFF		6FFF				10FFF			
	Inplane (cm)	Cross plane (cm)	Inplane (cm)	Cross plane (cm)	In plane (mm)		Cross plane (mm)		In plane (mm)		Cross plane (mm)	
					Lt	RT	Lt	RT	Lt	RT	Lt	RT
EVH1	20	20	20.1	20	8.3	8.3	9.7	9.8	8.45	8.34	9.32	9.2
EVH2	20	20	20	20	7	7	8	8	7	7	8	8
VT1	19.9	20	19.9	20	8.5	8.5	8	8	8.4	8.45	7.94	7.92
VT2	19.8	19.9	19.8	20	9.5	9.5	7.4	7.4	9.47	9.5	8.65	8.66
VH1	19.9	19.6	*	*	7.9	8.2	8.1	8	*	*	*	*
VH2	20	20	*	*	8.7	8.7	8.9	8.7	*	*	*	*

Table 6. Radiation leakage for BLD, MLC and Linac head of 6 MV FFF and 10MV FFF beam for EVH1, EVH2, VT1, VT2 and 6MV FFF beam for VH1 and VH2

	Radiation Leakages (%)							
Machine	Through BLD		Through MLC		Patient plane		Other than Patient plane	
	6FFF	10FFF	6FFF	10FFF	6FFF	10FFF	6FFF	10FFF
EVH1	0.55	0.77	0.34	0.29	0.014	0.008	0.02	0.01
EVH2	0.42	0.32	0.23	0.26	0.004	0.007	0.1	0.09
VT1	0.36	0.36	1.21	1.26	0.005	0.005	0.007	0.003
VT2	0.327	0.34	1.23	1.31	0.03	0.005	0.007	0.004
VH1	*	*	0.007	*	0.012	*	0.209	*
VH2	*	*	0.03	*	0.01	*	0.012	*

with the VH exhibiting the highest values as depicted in Figure 1. This may be due to significant differences in the treatment head and collimator designs between Varian and Elekta linacs [21]. In Varian Linacs, the MLC is positioned closer to the patient's surface, and several studies have reported that this configuration can lead to higher surface and buildup doses compared to Elekta Linacs [24]. The increase in dose at the surface is likely attributed to a greater contribution from head scatter. Additionally, in Varian linacs, the jaws are located upstream of the MLC, whereas in Elekta machines they are positioned downstream [22]. The PSD for the 30×30 cm² field size could not be measured for the VH, as the Halcyon system has a maximum field size limitation of 28×28 cm².VH employs a distinct design featuring a dual-layer, fully rotating MLC and no secondary jaws, simplifying the treatment head but potentially reducing beam hardening. This design may increase the relative proportion of low-energy photons at shallow depths [9, 21]. Moreover, surface dose rises with field size due to increased scatter contribution a phenomenon further amplified in FFF beams and by the absence of secondary jaws, which normally minimize high-energy scatter from field edges. In contrast, conventional C-arm linacs such as the VT use secondary jaws and EVH use backup diaphragm that contribute to beam hardening, thereby lowering the surface dose.

Grady F et al. [25] reported that VH using 6MV FFF beams deliver a significantly higher surface dose approximately 8–15% greater than conventional flattened linacs for treatments involving the breast, chest wall, and other superficial regions. This increase arises from reduced beam hardening and a higher proportion of low-energy photon contamination inherent to FFF beams. While the elevated surface dose can help prevent underdosage in superficial targets, it also increases the risk of acute and late skin toxicity, particularly in breast, post-mastectomy, and skin treatments. In post-mastectomy cases, bolus material may no longer be necessary for adequate superficial coverage, as VH surface dose is comparable to that achieved with bolus on conventional linacs. However, when bolus is applied, there is a heightened risk of skin overdose, potentially exacerbating acute reactions and impairing long-term cosmetic outcomes. Furthermore, the treatment planning system (TPS) tends to underestimate surface dose on VH, necessitating careful review during plan evaluation. Therefore, routine bolus protocols such as the use of a 1 cm bolus on alternate days should be reconsidered for VH treatments.

Off Axis Measurements

Beam Profile

The absence of a FF results in lateral dose profiles that differ significantly from the typical flat profiles of conventional linacs with a FF. The peak in the profile, typically associated with FFF beams, is more prominent with medium to large field sizes and depends on the photon beam energy [16, 17, 23]. The peak becomes more pronounced with higher energy, which can be attributed to the smaller scattering angles associated with higher energies. The profiles of FF beams exhibit notable

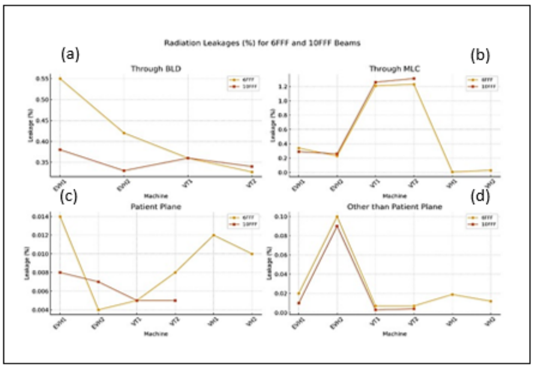

Figure 2. Radiation Leakages Through BLD (a), MLC (b), Patient Plane (c), and Non-patient Plane (d) for 6FFF and 10FFF Beams of EVH1, EVH2, VT1, VT2 and 6FFF Beam of VH1, VH2.

shape variations with depth. These include horns at the depth of Dmax, a flat profile at depths where the FF is effective, and distinct undershoot shoulders at greater depths [26]. In contrast, the shape of the profile with depth is more consistent for FFF beams than for flattened beams [14, 23, 27]. The shapes of the plateau region are independent of the collimating device, as this part of the beam is not directly affected by the collimators. However, the penumbra differs depending on the beam-shaping device [4]. The determination of penumbra for unflattened beams requires a modified approach, as the conventional 80%-20% dose values are not directly applicable. Pönisch et al. [4]. Introduced a method to renormalize flattened beam profiles for calculating penumbrae in unflattened beams. This method suggests rescaling based on the ratio of dose values at the inflection points within the penumbral region [4, 23].

According to AERB guidelines, the inflection point method combined with the 1.6- and 0.4-times Reference dose value (RDV) approach is specifically recommended for determining the penumbra of FFF beams, rather than the conventional 80%–20% method. Unlike flattened beams, FFF beam profiles lack a uniform, plateau-like central region, making the traditional 80%–20% definition unsuitable and often ambiguous. For flattened beams, the central plateau provides well-defined 80% and 20% dose levels relative to the central axis dose. However, FFF beams exhibit a peaked central dose without a flat region, making these percentage-based levels non-representative of the true penumbral slope. Consequently, the 1.6 and 0.4 time of RDV method is preferred for FFF beams, as it provides a consistent, unambiguous, and reproducible assessment of penumbra width independent of the central dose peak.

Leakage Measurements

A well-designed MLC is characterized by several key features, including low leaf transmission, minimal tongue and groove effect, a small penumbra, precise leaf positioning, and high speed [28, 29].In EVH, the MLC is characterized by a single-focus design with curved leaf tips and a narrow tongue and groove, featuring an interleaf gap of 90µm. Additionally, the interleaf gap is defocused from the source to prevent direct beam irradiation through the gap [30, 31].On the other hand, VT machines use an HDMLC with leaf tips that have a curved shape. VH features a dual-layer MLC system. This design significantly reduces leakage between MLC leaves [15]. This study revealed that for VH the MLC leakage is significantly lower compared to VT and EVH as shown in Figure 2. The VH, with its ultra-low leakage design, offers notable advantages for IMRT and VMAT compared to conventional C-arm linacs. VH features a unique double-stacked, interleaved MLC system that precisely shapes treatment fields while significantly reducing interleaf radiation leakage, even in highly modulated beam configurations [9]. Unlike most linacs, VH eliminates the use of secondary collimator jaws a common source of leakage during IMRT and VMAT delivery further minimizing out-of-field dose. Independent evaluations have demonstrated that VH MLC leakage is exceptionally low, making it particularly suitable for complex, high-modulation treatments where leakage-induced dose could otherwise be clinically relevant. The combination of low leakage, rapid leaf motion, and faster gantry speed enables Halcyon to deliver sophisticated treatment plans efficiently while maintaining better normal tissue sparing [25].

Gu A et al. [32] reported that VH treatment plans produce lower low-dose exposure specifically reduced V5 and V10 volumes to organs at risk such as the heart, lungs, contralateral breast, and spinal cord, particularly in breast and thoracic treatments. For breast VMAT plans, VH achieved notable reductions in heart mean dose (−112 cGy, 24.8% lower) and heart V5 (−9.4%) compared to VT. Similarly, Shao K et al. [33] observed that VH reduced leakage results in a lower integral dose, representing less unnecessary radiation outside the target volume. Its more confined low-dose distribution especially for V5 Gy for lungs, contralateral breast, and liver minimizes the risk of late radiation-induced effects, such as secondary malignancies and pneumonitis, while maintaining comparable target coverage and dose conformity to that of conventional linacs.

In the study, the consistency of dosimetric characteristics among FFF beam-matched linacs across six machines was investigated, focusing on FFF beams. Parameters such as beam quality index, PDD, Dmax, PSD, MLC leakage, head leakage, and beam profile parameters of degree of unflattening, beam symmetry, off-axis ratio, penumbra, and field size were analyzed according to AERB and vendor specifications. Our analysis demonstrates clear performance variations among the evaluated linac platforms. EVH exhibited superior energy spectrum quality. Both VH and VT showed subtle reductions in spectral performance. Notably, VH provided lower MLC leakage and higher PSD compared to VT and EVH. This may be advantageous for certain clinical configurations. These findings underscore the importance of comprehensive dosimetric comparisons when commissioning different linac platforms using FFF beams. Machine specific parameters such as energy spectrum, MLC leakage, and associated dosimetric behaviours must be thoroughly assessed. Optimization should be based on clinical requirements. Such evaluations are essential to ensure the highest treatment quality standards, especially for advanced FFF-based radiotherapy techniques. We strongly recommend that centres consider these technical nuances in their commissioning processes and clinical deployment strategies.

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Statement of Transparency and Principals

- Author declares no conflict of interest
- Study was approved by Research Ethic Committee of author affiliated Institute.
- Study's data is available upon a reasonable request.
- All authors have contributed to implementation of this research.

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