Oncology
and Radiotherapy ©
Vol.16 Iss.2:22-29 • Research Article

Analysis of dosimetric characteristics of energy 6 MV with and without flattening filter photon beam generated by the Varian True Beam linac using Kruskal Wallis H test

Achir Sara[1], Mohammed El Adnani Krabch[2], Mourad Trihi[1]
[1] Department of Physics, FSAC, Faculty of Sciences Aïn Chock, Casablanca, university Hassan II Casablanca, Morocco
[2] Oncology Clinic, Department of Medical Physics, Rabat, Morocco

SUMMARY

This study aims to assess the capacity of the beam-matching of the characteristics of the Flattened (FF) and Unflattened (FFF) photon beam of the 6 MV energy of the Varian TrueBeam linac located at the Achifaa Specialized Center in Casablanca (Morocco). The dosimetric parameters in this research such as Percentage Depth Dose (PDD), surface dose, beam profile, Output Factor (OF), Transmission Factor (TF) and Dosimetric Leaf Gap (DLG) are analyzed by a non-parametric Kruskal-wallis test to study their degree of independence and a coefficient of variation a descriptive statistical analysis to measure the difference between these measurements. We observed a similarity between the FFF and FF beam data for surface dose and the beam profile for large irradiation field sizes; the output factor for small to medium field sizes, it was noted that the maximum depth dose (dmax) and the DLG factor were less than 1 mm. But a slight disparity existed between the FFF beams compared to the FF beams for the surface dose which was higher for small fields, the dmax was 7% lower and closer to the surface, the average energy of the PDD was 5% lower; the TPR (20/10) phantom tissue ratio was 6% lower for the reference field size (10 × 10 cm2). The energy spectra of the photons were smoother generally, profiles are sharper for medium to large field sizes, the penumbra width was smaller and 7% lower, the output factor was 2% lower for the selected fields, 5% lower for medium to large field sizes, transmission factor was reduced by 17%. Finally, the parameters were reproducible between both types of beam energy × 6 MV (FFF-FF) since the p-value> 5% and V.R <20%; except the DLG of the MLC was 24% lower for the same X6 MV energy.

Key words: Kruskal-wallis test, flattening filter-free, dosimetric characteristics, true beam

Address for correspondence:

Achir Sara, Department of Physics, FSAC, Faculty of Sciences Aïn Chock, Casablanca, university Hassan II Faculty of Sciences Aïn Chock, Casablanca Morocco, email: achir.sara1@gmail.com

Word count: 5220 **Table:** 12 **Figures:** 05 **References:** 32

Received: - 25 January, 2022, Manuscript No. M- 52359
Editor assigned:- 27 January, 2022, PreQC No. P-52359
Reviewed:- 10 February, 2022, QC No. Q-52359
Revised:- 16 February, 2022, Manuscript No. R-52359
Published: - 27 February, 2022, Invoice No. J-52359

INTRODUCTION

A linear accelerator is a system that uses high-frequency electromagnetic waves (around 3000 MHz) to accelerate electrons to very high energies (around 25 MeV) through a linear tube. The beam that comes from this machine is typically used to treat surface lesions, strike metal targets (tungsten), or produce x-rays that can give treatment to deeper tumours [1]. The TrueBeam linear accelerator (TB-LINAC) equipped with a Millenium 120 leaf MLC (Varian Medical System, USA) was installed at the Achifaa specialist Center in Casablanca, Morocco.

The FF beam "flattening filter" was one of the basic components of the treatment head of the medical accelerator, located between the primary collimator and the ion chamber [2]. The principal function of the Flattening Filter (FF) in the X-ray beam path of the linear accelerator is to provide practically uniform fluence over a collimated field. This characteristic was the most commonly employed in traditional radiotherapy [3]. Studies by [4-7] mentioned that the flattened filter was one of the components that contribute to the dispersion of the number of particles. This is precisely the reason why many authors such as [8-13], have been interested in the removal of the flattened filter for its high performance compared to the flattened filter [2].

They concluded that this mode produces a softening of the spectrum, a reduction in scattered radiation from the head of the linear accelerator, a non-uniform beam profile (forward peaked dose profile), the maximum dose as close to the surface as possible, a higher surface dose, reduced MLC leakage and less variation in out-of-field dose [7,5].

In addition, there were many publications on the subject. Although FFF beams were installed in many centres, FF mode is stilled in use. In this study, energy 6 MV between FF and FFF photons of True Beam linear accelerator was investigated. The research is based on a descriptive and non-parametric statistical analysis for dosimetric characteristics.

MATERIAL AND METHODS

Nonparametric and descriptive statistical analysis

For nonparametric statistical analysis, the Kruskal-wallis test evaluates to test the null hypothesis that all independent samples K come from groups with equal means and the alternative hypothesis that at least one group is different. The hypotheses for the test are:

H_0: population medians are equal

H_1: population medians are not equal

(Significance p-value <0.05) and descriptive statistical analysis, the coefficient of variation assess the uniformity of the defined distribution (V.R<20%) [14-19].

Commissioning photon beams

The determination and comparison of parameters measured for commissioning Eclipse Treatment Planning System (TPS) involve Percentage Depth Dose (PDD), surface dose, beam profile, Output Factor (OF), Dosimetric Leaf Gaps (DLG) and Multileaf Collimator (MLC) transmission factor [20, 21]. All these parameters were measured by a 0.125 cc cylindrical chamber; model 31010 Semiflex (PTW German) was used for ionization field and reference. The chamber specifications include an effective length of 6.5 mm and an inner diameter of 5.5 mm. The output factor was measured with a PTW pinpoint chamber; model 31016 (PTW German), with the nominal sensitive volume, is 0.016 cc, an active length of 2.9 mm and an internal diameter of 2.9 mm [1].

Percentage Depth Dose (PDD): PDD refers to the percentage depth dose curve. The energy performance index of the beam is determined by the following formula of the depth of the measuring point for a constant SSD. This parameter depends on the energy and field size [2,13]. PDD was studied for FF and FFF beam at a depth of 10 cm with respect to the maximum absorbed dose position [13].

A maximum depth dose D_{max}, PDD at 10 cm quality index defined as the absorbed dose at any depth relative to the position of the maximum absorbed dose determined by the empirical formula TPR20/10=1.2661 D20/10 -0.0595 expressed as a percentage [13,22], PDD (20, 10) is ratio of the percentage depth dose at 20 cm and 10 cm depth. This factor gives a notion of stability of the photon beam [1]. A value of an additional energy parameter was obtained for comparison using a TPR (20, 10) a quotient of dose for 10 × 10 fields at the depths of 20 cm and 10 cm. This analysis of Percent Depth Dose (PDD) data was performed to evaluate the energy match between the FF and FFF beams that were compared for selective field sizes (6 × 6, 10 × 10, 20 × 20, 30 × 30 and 40 × 40) cm^2 [15].

Surface dose: The surface dose is the dose calculated at the entrance of the phantom [2]. The value of the surface dose of any calculated field size is obtained by dividing the dose for the first millimetre (1 mm) of the homogeneous water model by the dose D for the corresponding field [13].

In this work, for open field size (6 × 6, 10 × 10, 20 × 20, 30 × 30 and 40 × 40) cm^2, estimated surface doses was evaluated between the 6 MV FF and FFF configurations [2].

Profiles: Beam profiles for FF and FFF modes were compared, measured at selective field sizes (6 × 6, 10 × 10, 20 × 20, 30 × 30 and 40 × 40) cm^2 and evaluated at a depth of 10 cm and an SSD=100 cm [23]. The water phantom cannot measure the full profile for field sizes greater than 20 cm. In addition, the TPS treatment planning system accepts a half profile. In the present study, we cannot expose the data to these fields [1].

Output factor: In this study, the Output Factor (OF) was obtained based on the dose ratio of a given field size to a reference field size at the same depth in water. This factor includes the phantom and collimator scatter and was normalized to a (10 × 10) cm^2 reference field at a depth of 5 cm (95 cm SSD) [8]. The OF was measured for squared and rectangular field sizes ranging from (3 × 3) cm^2 to (40 × 40) cm^2 for 6 MV and 6 MV FFF photon beams. This factor takes it into consideration the variation of the total scatter factor. This data can determine variations in the configuration of the beam filter and other characteristics of the head structure of the linear accelerator [23].

Transmission factor: The multi-leaf collimator does not completely block a small part of the radiation, but transmits directly between the leaves [23]. For all MLCs closed behind the jaws, using the same size, the transmission can be estimated as the ratio of the measured dose in an open field, and the dose measured by all MLCs closed behind the jaws with the same size [1].

$$TF = \frac{R_{closed}}{R_{open}} \qquad (24)$$

Dosimetric Leaf Gap (DLG): The round leaf tip is a typical Varian MLC system. The physical difference between the light and the irradiation field formed by the MLC is defined as DLG [20]. Therefore, DLG should be measured as an important factor to quantify the contribution of this transmission to the calculation of the dose to the patient [24, 25].

RESULTS AND DISCUSSION

Percentage Depth Dose (PDD) and TPR $_{(20,10)}$

The PDD curves were measured from water surface (0 mm) to a depth of 300 mm for energy 6 MV without flattening filter and with a filter. For the (6 × 6) cm^2 and (40 × 40) cm^2 irradiation fields, the mean dose values at 10 cm depth for the FFF and FF beams showed a p value> 0.05, which proves that there is a statistically significant difference between these two beams. This is due to the hardening of the beam through the flat filter [14,26], the exponential region of the FFF profile has a steeper slope than the flattening filter, as shown in figure 1, except for the field (10 × 10) cm^2, (20 × 20) cm^2, (30 × 30) cm^2 the curves were similar and showed a p-value <0.05 (Table 1), but to quantify this effect, a comparison of the characteristics of the quality index between 6X FF and 6X FFF of the linear accelerator was defined in Table 2.

At PDD_{10} (%), the rate of change of the unflattened beam of this energy was 5% lower compared to the flattened beam, this is due to the decrease in the quantity of contaminating electrons and to the absence of a beam hardening effect [7], but the difference was not statistically significant. The result corresponds to that reported by [5, 12, 21] and seem convergent with the results of [9,18,22,27] with a slight difference (about 1%; 4%).

A significant parameter of the PDD of a beam is the depth of dose maximum; it's to note that the rate of change of d_{max} values of FFF beam was 7% lower and closer to the surface than FF beam for the selected field sizes, because of the low-energetic photons decrease [5], but this variation remains at a minimum. Indeed, it has been reported that the difference in the value of d_{max} between the filter and without a filter was less than 1 mm [28]. The result is slightly different from [3, 9] with a difference of (1%; 3%).

In Figure 1, the distance between both curves increases linearly with the irradiation field. The dose ratio between 20 cm and 10 cm depth (D20/D10) was used to quantify this effect. The FFF ratio was 7% lower than FF beam. Table 2, the difference between both curves is non-significant. This dose ratio shows a slight disparity with [2], (approximately 1%). The TPR20/10 beam quality index had no relation to the electron contamination in the incident beam [18]. This index is presented and compared for the voltage 6 MV FFF, FF in Table 3.

The absence of the flattening filter affects the quality index; hence the rate of change of the quality index TPR20/10 of the FFF was 6% lower than for the FF beam respectively for a reference field size (10 × 10) cm². The elasticity curve in depth of the MV FFF beam beyond d_{max} decreased slightly compared to that of the MV FF beam. In fact, the MV FFF beam favours a more pronounced dose reduction FF [8]. This downward movement is due to the reduction in scattering and electron contamination of the flattening filter which affects the dose in depth after the maximum depth dose (D_{max}).

This indicator of the True beam machine is compatible with the reports [5, 9, 21] and showed minimum variation (around 1%; 2%; 3%).

Indeed these quality indexes have demonstrated the reproducibility of the measurements of the PDD parameter of the energy X6 MV between FFF-FF.

Surface dose

The surface dose of 6MV FF and FFF configurations was determined for open field sizes (6 × 6, 10 × 10, 20 × 20, 30 × 30 and 40 × 40) cm². Table 4 indicates the surface dose between FF and FFF for these irradiation fields producing a

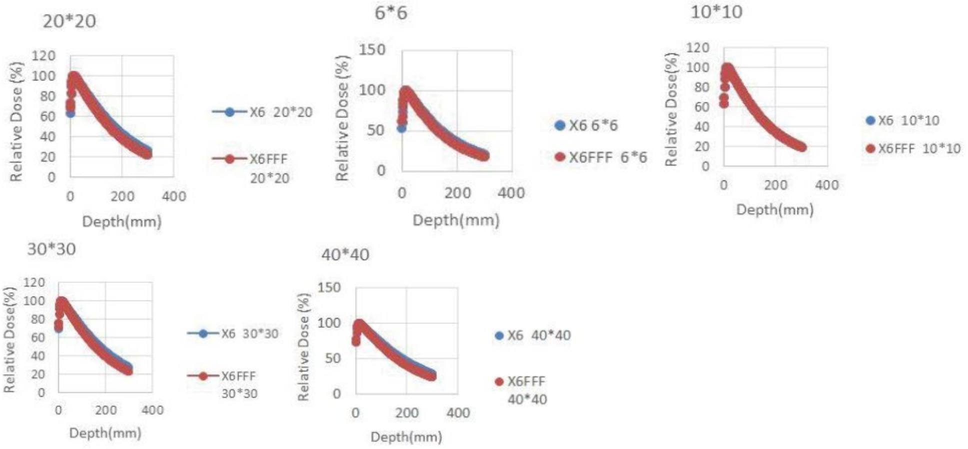

Fig. 1. Comparison of percentage depth dose curve for the energy 6 MV between FF versus FFF photon beams for (6 × 6, 10 × 10, 20 × 20, 30 × 30 and 40 × 40) cm² field sizes

Tab. 1. Observed results from kruskal-wallis test for the percentage depth dose of energy 6 mv

H0	Data	Statistical tests	F.S (cm²)	Sig.	P-value	Decision
H0: (FF)=(FFF)	PDD	kruskal-wallis	6 × 6	0,467	>0,05	Retain H_0
			10 × 10	0	>0,05	Retain H_0
			20 × 20	0		
			30 × 30	0		
			40 × 40	0,467	>0,05	Retain H_0

Tab. 2. Depth dose analyses parameters of FF and FFF photon beams performed at SSD=100 cm from the varian true beam accelerator

Energy	F.S (cm²)	PDD10 (%)	Dmax (mm)	PDD (20,10)
6 MV FF	10*10	66,1	13,5	0,57
6 MV FFF		63	12	0,54

Tab. 3. Difference of TPR (20/10) calculated beam quality index with FF and FFF beam energy

Index of quality	F.S (cm²)	Energy (MV)	
TPR20/10	10 × 10	6 MV FF	6 MV FFF
		0,663	0,624

p-value>0.05 overall, consequently this statistical test checks the reproducibility of the data. However, the coefficient of variation of surface dose values of FFF beams was 5% greater than FF for all field sizes. We observed that in general FFF beams generated more doses to the skin for small until medium fields; it was 9% less than FF and a similar or even less dose for large field sizes (Table 5).

The surface dose increased linearly with field size for FF and FFF photon beams, due to the removal of the flattening filter promoting the elimination of the primary electrons entering by the thin high Z targets used to generate bremsstrahlung photons [7,28-30]. The difference between them is clearly visible in Figure 2. The results presented in Table 5 were compared to the study [18, 21] with a difference of (2%; 3%).

Beam profile characteristics

As presented in Table 6, the FFF and FF beam profiles were compared using the Kruskal-wallis test. For large irradiation fields (30 × 30) cm^2 and (40 × 40) cm^2 the dose values at 10 cm depth showed a p-value> 0.05 but for the field (6 × 6) cm^2, (10 × 10) cm^2 and (20 × 20) cm^2 the curves were similar and showed a p-value <0.05. Overall this implies that there was no statistical difference between FFF and FF of the energy X6 (Table 6).

Figure 3 and Figure 4 show the dose profile and half-dose profiles of FF and FFF beams for selective field sizes (6 × 6, 10 × 10, 20 × 20, 30 × 30 and 40 × 40) cm^2 evaluated at a depth of 10 cm. From a field size, (6 × 6) cm^2 to (10 × 10) cm^2, the shape of the profile was very slightly affected for ×6 FFF. There was no significant difference; indeed the rates of change of FFF were 1% and 4% lower than FF (Figure 3 and Table 7). The average energy of photon spectra of FFF was 11% lower compared to FF, because the removal of FF elicits a rapid distribution of the low fluence [5,9,30].

In Figure 4, the FFF beam for large irradiation fields (30 × 30 cm^2 and 40 × 40 cm^2) appeared with a pronounced forward peak. Obviously this beam lacked flatness and that its maximum dose was on the central axis and gradually decreased towards the

Tab. 4. Observed results from kruskal-wallis test, for the surface dose of 6MV between FF and FFF photon beam

H_0	Data	Tests	F.S (cm^2)	Sig.	P-value	Decision
H0: (FF)=(FFF)	Surface_Dose	kruskal-wallis	6 × 6	0,406	>0,05	Retain H_0
			10 × 10			
			20 × 20			
			30 × 30			
			40 × 40			

Tab. 5. The variation rates of surface dose of the 6MV FF and FFF at SSD=100 CM

Energy	Statistical tests	Data	Field-size (cm^2)	6 MV FF	6MV FFF	Variation rates (%)
6 MV	Variation rates (%)	Surface_Dose	6 × 6	0,592	0,669	13%
			10 × 10	0,625	0,688	10%
			20 × 20	0,699	0,732	5%
			30 × 30	0,756	0,759	0%
			40 × 40	0,78	0,774	-1%
					Average of V.R (%)	5%

Tab. 6. Observed results from kruskal-wallis, for the mean of relative doses of 6MV between FF and FFF photon beam

H_0	Data	Test	Field-size (cm^2)	Sig.	P-value	Decision
H0: (FF)=(FFF)	Beam_profile	kruskal-wallis	6 × 6	0,02	< 0,05	Reject H_0
			10 × 10	0,01		
			20 × 20	0,01		
			30 × 30	0,154	> 0,05	Reject H_0
			40 × 40	0,362		
			Average	0,111	> 0,05	Reject H_0

Tab. 7. The variation rates of mean of relative doses of the 6MV FF and FFF at SSD=100 CM

Energy	statistical tests	Data	F.S (cm^2)	6 MV FF	6 MV FFF	Variation rates (%)
FF-FFF	Variation rates (%)	Beam-profile	6 × 6	25, 24	24, 88	-1%
			10 × 10	41, 73	40, 12	-4%
			20 × 20	50	44, 41	-11%
			30 × 30	28,41	23, 31	-18%
			40 × 40	73, 11	56, 46	-23%
					Average of V.R (%)	-11%

edge of field [12]. In order to quantify the peak amplitude of non-flat profiles, the relative dose at 80% for FFF beams can be used, profile measurements tend to decrease, a 5% reduction in dose for FFF compared to FF beams at the same depth and size of the field was observed (Table 8). This is due to the profiles normalized to 100% of the relative dose and the profile curves have different shapes [22]. Table 9 summarizes values of penumbras for selective field sizes for the photon beams studied.

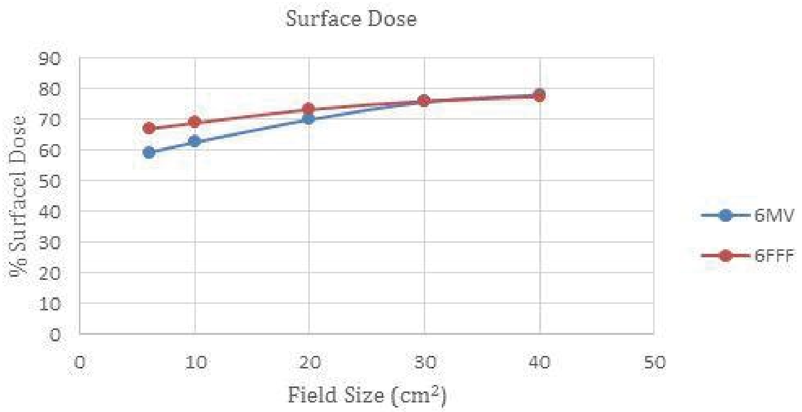

Fig. 2. Surface doses comparisons of energy 6MV between FF and FFF photon beam

Tab. 8. Values of relative doses for field sizes equal to 80% for FF and FFF photon beams for depth 100 MM

Relative dose 80 % of Energy=6 MV					
Depth (mm)	**Linear accelerator**	**F.S (cm^2)**	**FF**	**FFF**	**Variation rates (%)**
		6 × 6	97,3	96,3	-1%
		10 × 10	98,2	95,2	-3%
		20 × 20	100,5	95,5	-5%
		30 × 30	100,8	95	-6%
		40 × 40	101,8	93,2	-8%
				Average of V.R (%)	-5%

Tab. 9. Characteristics of beam profiles calculated with and without FF for energy 6 MV photon beams for the selected field sizes at a depth of 10 CM and a SSD of 100 CM

P80_20% (mm) of energy=6 MV FFF-FF					
Depth (mm)	**Linac**	**F.S (cm^2)**	**FF**	**FFF**	**Variation rates (%)**
100	True Beam	6 × 6	0,648	0,638	-2%
		10 × 10	1,631	1,544	-5%
		20 × 20	2,78	2,515	-10%
		30 × 30	2,807	2,542	-9%
		40 × 40	2,815	2,55	-9%
				Average of V.R (%)	-7%

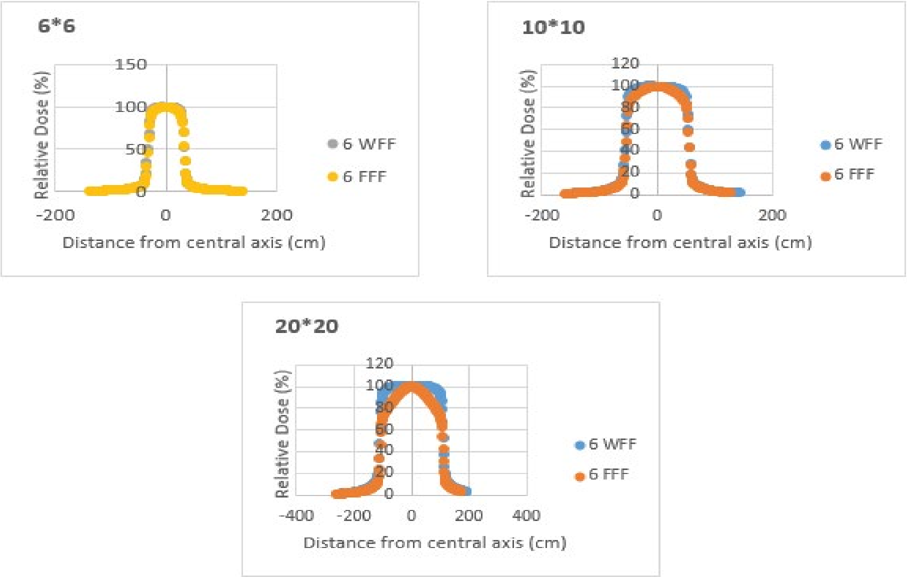

Fig. 3. Comparison of profile dose graph of FF and FFF 6 MV photon beams from (6 × 6) cm^2 to (20 × 20) cm^2

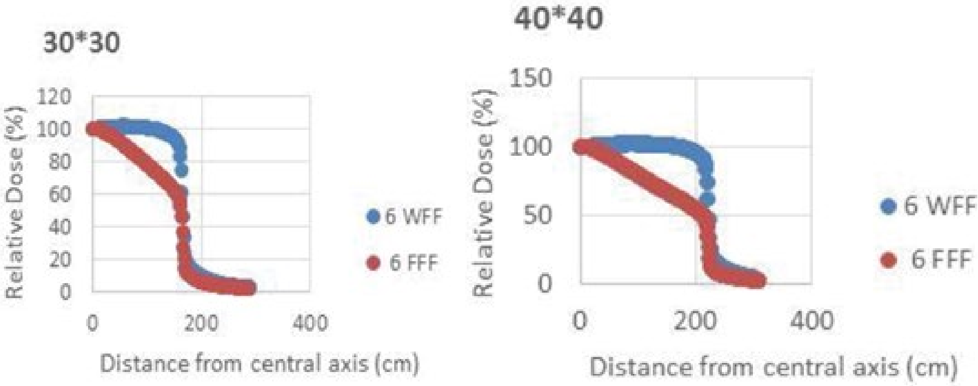

Fig. 4. Diagonal profile graph for the flattening filter (FF) and flattening filter-free (FFF) 6 MV photon beams (30 × 30) cm^2, 40 × 40 cm^2

Tab. 10. Observed results from kruskal-wallis test, for the output factor of 6mv FF and FFF photon beam

H_0	Data	Tests	F.S (cm^2)	Sig	P-value	Decision
H0: (FF)=(FFF)	FOC	kruskal-wallis	3 × 3 ≥ 40 × 40	0,443	>0,05	Retain H_0

Tab. 11. summarized of out-field-scatter-factor for FFF and FF beams

F.S(cm^2)	6 MV FF	6 MV FFF	Variation rates (%)
3 × 3	0,845	0,846	0%
4 × 4	0,87	0,868	0%
5 × 5	0,892	0,888	0%
7 × 7	0,926	0,916	-1%
10 × 10	0,962	0,946	-2%
12 × 12	0,98	0,958	-2%
15 × 15	1	0,974	-3%
20 × 20	1,027	0,993	-3%
25 × 25	1,046	1,004	-4%
30 × 30	1,061	1,014	-4%
35 × 35	1,071	1,017	-5%
40 × 40	1,078	1,023	-5%
			-2%

The width of the penumbra decreased with increasing field size, for FFF case was 7% lesser than FF case. These differences between FF and FFF in the penumbra width were due to its lower average energy, resulting in a shorter span of secondary electrons [5].

Relative photon output factor

Relative photon output factor measurements for FF (6 MV) and FFF (6 MVFFF) were performed for field sizes ranging from (3 × 3) cm^2 to (40 × 40) cm^2. This measured output factor varies from 0.845 to 1.078 for 6 MV, while from 0.846 to 1.023 for 6 MVFFF is presented. The increase of the output factor is in line with the increasing field size. These values are analysed statistically as can be seen in Table 10. This statistical analysis demonstrates that the distributions were homogeneous in nature since the p-value> 0.05.

As indicated in Figure 5 and Table 11, the out-of-field dose of the FFF beam decreases with increasing field size in relation to the FF beam, for a small field sizes, indeed there was no significant difference between the values of this parameter until that they converge to unity at a field size of (20 × 20) cm^2, but at (25 × 25) cm^2 to a larger field size, the output factor values of 6 MV FFF were 5% lower than 6 MV FF. This reduction is caused by less secondary radiation emanating from the jaw of the accelerator head, therefore less electronic contamination [31, 32].

However, the out-field-dose for the FFF beams was slightly low with a rate of change of 2% less than the FF beam for all irradiation field sizes. It was consistent with that reported by [2], the difference is not substantial with (approximately 1%-2%).

Transmission factor/dosimetric leaf gap

The transmission factor MLC and DLG are 17%, 24% inferior to the flattening filter of the same energy X6 MV (Table 12). The softening effect of the X-ray spectra and the reduction in the average beam energy 6 MV induce a decrease in the lateral dose and a change in the shape of the beam profile FFF that can lead to an optimization of the leakage radiation at the edge of the field could cause a reduction of MLC transmission [31].

In Table 12, transmission causes a decrease in the DLG value; these parameters are essential during the setting of the MLC treatment planning system [13]. The results of this work were

Tab. 12. MLC transmission factor and dosimetric leaf gap

Depth 100 mm	X6 FF MV	X6FFF MV
MLC-TF (%)	14,41	11,98
DLG (mm)	0,848	0,643

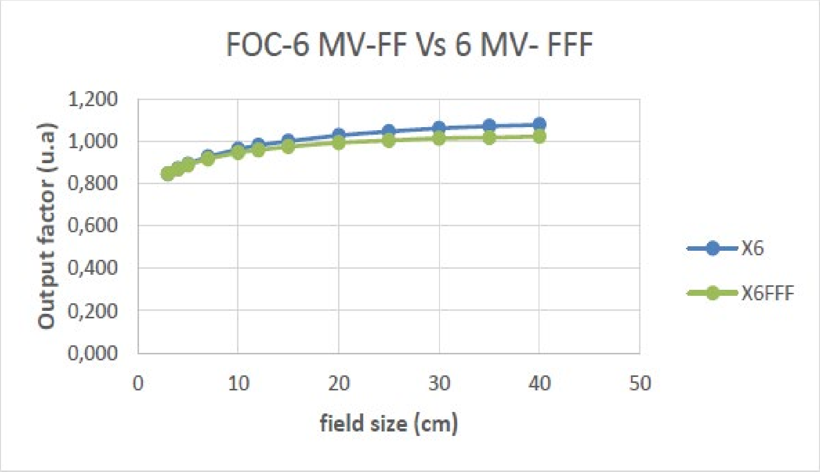

Fig.5. Output factors for energies 6MV, 6MV FFF

compatible with those of with a non-significant difference (approximately ranging from 1% up to 2%).

CONCLUSION

In this present work, dosimetric parameter analysis of which Kruskal-Wallis and the variation rates have been applied to evaluate the photon beams with and without the 6 MV energy flattening filter of a Varian True Beam TM medical linear accelerator.

The results showed that the surface dose, the beam profile for large field sizes and the out-of-field doses for small to medium field sizes are almost similar between FFF and FF as well as a maximum depth dose less than 1 mm for these two modes.

Despite this homogeneity, there was a slight difference in:

- Depth dose curves of FFF beam which have a greater depth compared to the FF beam
- D_{max} FFF closer to the surface
- Increase in surface dose for FFF for small field size.
- Non-uniform beam profile (direct peak dose profile) for medium to large field size
- Beam penumbra width for FFF less than FF.
- Output factor of FFF at large field size greater than FF

Especially since the coefficient of variation of these parameters of FFF beam is less than 20% and the p-value of the Kruskal Wallis test was greater than 5%. We can therefore deduce that these measurement data were homogeneous and reproducible between both types of X6 energy beams of the Varian True Beam TM except for the dosimetric leaf gap, its coefficient of variation was slightly greater than 20%.

Certainly in terms of quality of FFF beam, as the softening of the photon energy spectra, the shift of the maximum dose to the surface, the peak forward and the smaller penumbra width resulting in reduced dispersion coming from the head have been very beneficial for treatment.

Furthermore, for better comfort during treatment, surface dose optimization to avoid acute skin reactions, for a faster dose calculation and a more optimized radiotherapy treatment for cancer patients, we have found that is necessary to optimize the output factor for less radiation exposure to healthy tissue in order to eliminate any risk of secondary malignancies and many cancer complications. A reduction in leaf transmission affecting the DLG to prevents dose measurement errors in the PTV and OAR (organs at risk).

ACKNOWLEDGMENT

I would like to thank Pr. Trihi Mourad the thesis supervisor and professor of Faculty of Sciences Ain Chock Casablanca, University Hassan II of Casablanca. In addition, I would like to express my sincere thanks to Dr. Mohammed El Adnani Krabch, a medical physicist at 16 november oncology clinic in rabat for his support of this work.

1. Mohammed El Adnani Krabch et al. Measurements of Photon Beam Flattening Filter Using an Anisotropic Analytical Algorithm and Electron Beam Employing Electron Monte Carlo. Iran J Med Phys. 2019;16:200-209.
2. Mohammed M. Evaluation of the dosimetric characteristics of 6 MV flattened and unflattened photon beam. J King Saud Univ Sci. 2017;29:371-379.
3. Wagdy A, Khaled M, Ashry H, et al. A comparative study between flattening filter-free beams and flattening filter beams in radiotherapy treatment. Oncol Transl Med. 2017;3:260-266.
4. Georg D, Knoos T, McClean B, et al. Current status and future perspective of flattening filter free photon beams. Med Phys. 2011;38:1280-1293.
5. Hrbacek J, Lang S, Klock S. Commissioning of photon beams of a flattening filter-free linear accelerator and the accuracy of beam modeling using an anisotropic analytical algorithm. Int J Radiat Oncol Biol Phys. 2011;80:1228-1237.
6. Pichandi A , Ganesh KM, Jerin A, et al . Analysis of physical parameters and determination of inflection point for Flattening Free beams in medical linear accelerator. Reports of practical oncology and radiotherapy: J Gt Cancer Cent Pozn Pol Soc Radiat Oncol .2014;19:322-331.
7. Vassiliev O ,Titt U ,Ponisch F, et al. Dosimetric properties of photon beams from a flattening filter free clinical accelerator, 2006;51:1907-1917.
8. Ponisch F, Titt U, Vassiliev O, et al. Properties of unflattened photon beams shaped by a multileaf collimator. Med Phys. 2006; 33:1738-1746.
9. Cashmore J. The characterization of unflattened photon beams from a 6 MV linear accelerator. Phys Med Biol. 2008;53:1933-1946.
10. Wang Y, Khan M, Ting J, et al. Surface dose investigation of the flattening filter-free photon beams. Int J Radiat Oncol Biol Phys. 2012;83:281-285.
11. Ong CL, Dahele M, Slotman BJ, et al. 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;86:743-774.
12. Bennett LC, Vassiliev ON. Examination of Out-of-Field Dose and Penumbral Width of Flattening Filter Free Beams in Medical Linear Accelerators. Proc N Am Part Accel. 2016;54:396-398.
13. Suvendu KS, Kshitish CM, Sanjib KM, et al. A Study On Depth Dose Of Flattened And Flattening Filter Free Photon Beam Of Millennium True Beam Linear Accelerator Used For Cancer Treatment. Int J Sci Res. 2019;8:2277-8179.
14. Georg D, Kragl G, Wetterstedt S, et al. Photon beam quality variations of a flattening filter free linear accelerator. Med Phys. 2010;37:49-53.
15. Titt U, Vassiliev ON, Poenisch F, et al. A flattening filter free photon treatment concept evaluation with Monte Carlo. Med phys. 2006;33:1595-1602
16. Shende R, Gupta G, Patel G, et al. Commissioning of TrueBeamTM Medical Linear Accelerator: Quantitative and Qualitative Dosimetric Analysis and Comparison of Flattening Filter (FF) and Flattening Filter Free (FFF) Beam. Int J Med Phys Clin Eng Radiat Oncol. 2016;51-69.
17. Chaikh A, Giraud JY, Perrin E, et al. The choice of statistical methods for comparisons of dosimetric data in radiotherapy. Radiat Oncol. 2014;9:205.
18. ANSES/PR3/07/01 version A: 2015 ANSES. Guide de validation des méthodes d’analyses. Anses- Pôle Recherche et Référence.
19. Sherwani RAK, Shakeel H, Awan WB. Analysis of COVID-19 data using neutrosophic Kruskal Wallis H test. BMC Med Res Methodol. 2021;21:215.
20. Stephanie Glen.”Welcome to statistics How to!” From Statistics How To.com: Elementary Statistics for the rest of us!.
21. Saidi K, El Baydaoui R, El Gouach H, et al. Commissioning Measurements of Flattening Filter and Flattening Filter and Flattening Filter Free Photon Beams Using a TrueBeam Stx Linear Accelerator. Iran J Med Phys. 2021;18:49-62.
22. Baic B, Kozowska B, Kwiatkowski R, et al. Clinical advantages of using unflattened 6-MV and 10-MV photon beams generated by the medical accelerator Elekta Versa HD based on their dosimetric parameters in comparison to conventional beams. Nukleonika. 2019;64:77-86.
23. Beyer GP. Commissioning measurements for photon beam data on three TrueBeam linear accelerators, and comparison with Trilogy and Clinac 2100 linear accelerators. J Appl Clin Med Phys. 2013;14:273-288.
24. Varadharajan E, Ramasubramanian V. Commissioning and Acceptance Testing of the existing linear accelerator upgraded to volumetric modulated arc therapy. Rep Pract Oncol Radiother. 2013;18:286-297.
25. Ulmer W, Pyyry J, Kaissl W. A 3D photon superposition/convolution algorithm and its foundation on results of Monte Carlo calculations. Phys Med Biol. 2005;50:1767
26. Dalaryd M, Knöös T, Ceberg C. Combining tissue-phantom ratios to provide a beam-quality specifier for flattening filter free photon beams. Med Phys. 2014;41:111716.
27. Chang Z, Wu Q, Adamson J, et al. Commissioning and dosimetric characteristics of TrueBeam system: composite data of three TrueBeam machines. Med Phys. 2012;39:6981-7018.
28. Kragl G, Wetterstedt S, Knäusl B, et al. Dosimetric characteristics of 6 and 10 MV unflattened photon beams. Radiother Oncol. 2009;93:141-146.
29. Arslan A, Sengul B. Comparison of radiotherapy techniques with flattening filter and flattening filter-free in lung radiotherapy according to the treatment volume size. Sci Rep. 2020;10:1-8.
30. Tanaka Y, Akino Y, Mizuno H, et al. Impact of detector selections on inter-institutional variability of flattening filter-free beam data for TrueBeam™ linear accelerators. J Appl Clin Med Phys. 2020;21:36-42.
31. Mesbahi A. Dosimetric characteristics of unflattened 6 MV photon beams of a clinical linear accelerator: a Monte Carlo study. Appl Radiat Isot. 2007;65:1029-1036.
32. Daci L, Malkaj P. True beam commissioning experience at Nordland Hospital Trust, Norway. Am Inst Phys. 2016;1722:150001.