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Commissioning Measurements of Flattening Filter and Flattening Filter Free Photon Beams Using a TrueBeam Stx® Linear Accelerator

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ABSTRACT

Introduction: TrueBeam STx® latest generation linear accelerators (linacs) were installed at Sheikh Khalifa International University Hospital Casablanca, Morocco, this study aimed to present and analyse the dosimetric characteristics obtained during the commissioning.

Material and Methods: Dosimetric parameters, including percentage depth dose, profiles, output factor, multileaf collimator (MLC) transmission, and dosimetric leaf gaps (DLG) factors were systematically measured for commissioning. Moreover, six photons beams (i.e., X6MV, $X6_{FFF}$MV, X10MV, $X10_{FFF}$MV, X15MV, and X18MV) were examined in this study, and a comparison was made between flattening filter (FF) and flattening filter free (FFF) beams.

Results: According to the results, the FF and FFF beams symmetry and flatness were in the tolerance intervals. The unflattness values were estimated at 1.1% and 1.2% for $X6_{FFF}$MV and $X10_{FFF}$MV, respectively. Furthermore, tissue phantom $\text{ratio}_{(20/10)}$(TPR) values of the FF beams were X6MV, 0.664; X10MV, 0.738; X15MV, 0.761; and X18MV, 0.778, and the TPR $_{(20/10)}$ values of the FFF beams included 0.632 and 0.703 for 6_{FFF}MV and 10_{FFF}MV, respectively. The results also revealed that the output factor values increased with field size, the surface dose decreased with increasing energy, and the FFF obtained lower mean energy. The MLC transmissions factors were 0.0121, 0.0103, 0.0136, 0.0122, 0.0133, and 0.0121 for X6, $X6_{FFF}$, X10, $X10_{FFF}$, X15, and X18, respectively; additionally, the DLG factors were obtained at 0.32, 0.26, 0.41, 0.37, 0.42, and 0.38 mm for X6, $X6_{FFF}$, X10, $X10_{FFF}$, X15, and X18, respectively.

Conclusion: Photon beams reference dosimetric characteristics were successfully matched with the international recommendations and vendor technical specifications.

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Introduction

Sheikh Khalifa International University Hospital, Casablanca, Morocco, experienced the installation and start-up of the TrueBeam STx® S/N H192507 (Varian Medical System, USA) full-option machine. This machine consists of 6, 10, 15 and 18MV photon beams equipped with flattening filters, as well as 6 and 10MV photon beams without flattening filters. TrueBeam system is an accelerator developed by Varian Medical System, many key elements of which differ significantly from those found in previous model (e.g., Clinac®). One of its main features is the possibility of having two types of photon beams, namely standard flattening filter beams (FF) and flattening filter-free beams (FFF). This type of photon beam flattening filter-free (FFF) has been studied extensively during these recent years [1-12]. The design of the TrueBeam head is moderately altered from its predecessors [13,14]. The carousel system has been transformed to increase the use of several photon energies (i.e., FF and FFF modes) as well as the electron beams.

The dose rates can go up to 1400 MU/min for 6_{FFF}MV and 2400 MU/min for 10_{FFF}MV beams [1]. TrueBeam dosimetric characteristics were measured for commissioning Eclipse Treatment Planning System (TPS) in terms of percentage, depth-dose curves (PDDs), beam profile, dosimetric leaf gaps (DLG), output factors (OF), and multileaf collimator (MLC) transmission factor. There are several studies evaluating the properties of FFF beams based on dosimetric measurements or Monte Carlo simulations [3, 12]. The reports of AAPM TG142 [15], TG-106 [16], TG-51 [17] and IAEA TRS-398 protocols [18] provided us with guidelines to perform our commissioning tasks.

This study aimed to present the dosimetric data for the configuration of the TPS together with comparative and retrospective results of different parameters in order to understand the different types of TrueBeam energies and the differences between FF and FFF technologies.

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Materials and Methods

Commissioning Beam Data

Data were collected for the commissioning of the Eclipse TPS (version 13.5) according to vendor-specific recommendations. Varian Medical System and Eclipse TPS employ analytical anisotropic algorithm (AAA) based on measured (PDD), beam Profile, OF, DLG, and MLC transmission factor.

TrueBeam STx® Linear Accelerator

The TrueBeam STx® is a digital linear accelerator designed to deliver both FF and FFF beams. The maximum field size of the unit was 40×40cm^2 defined by jaws, and the HD120MLC was installed under the primary collimators as an integrated component of the treatment unit [2].

Multileaf Collimator

The Truebeam STx® linear accelerator has an HDMLC-type micro tungsten MLC that contains 120 leaves. Each carriage (A and B) has 60 leaves, and the leaf pairs (n=32) have a projection width of 2.5 mm at the isocenter surrounded by 28 leaf pairs which have a projection width of 5 mm at the isocenter. The HDMLC covers a total length leaves of 22 cm at the isocentric plane [19].

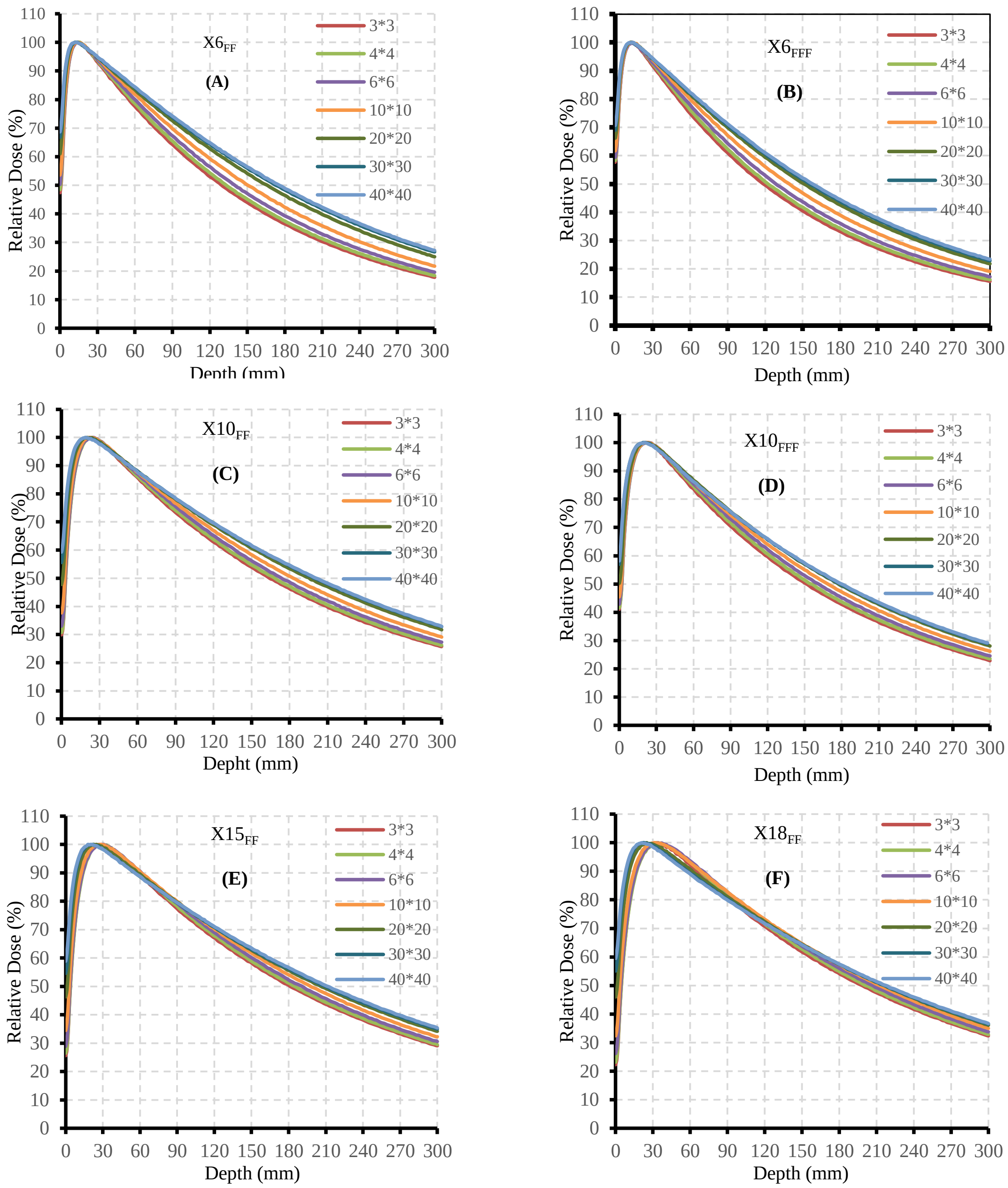

Figure 1. The 6MV, 6$_{FFF}$MV, 10MV, 10$_{FFF}$MV, 15MV and 18MV percent depth dose with various field settings from 3×3 to 40×40cm^2. (A), (B), (C), (D), (E), and (F).

Commissioning Beam Data of the Treatment Planning System

All the commissioning measurements for this TrueBeam machine were carried out using 3-dimensional scanning system MP3-M water phantom (PTW, Freiburg, Germany) water phantom is connected to a control unit, which contains the remote control to position the ionization chambers. The detector position is defined before each measurement in MEPHYSTO (Medical Physics Tool) mc^2 software (PTW-Freiburg, Germany). The detector provides data at certain points during the movement from one point to another inside the water phantom tank.

A support is attached to the water tank to put the reference chamber, which is placed in the air at the corner of the radiation field. Its data are used as a correction coefficient for the data taken from the field detector placed in the center. The detectors are connected to the electrometer (TANDEM), and the data were analyzed in MEPHYSTO mc^2 software (Version 3.2) [20]. All data and collection tests were carried out following international recommendations such as TRS 398 [18], AAPM TG-142[15] and TG-106 [16]. A procedure, including MLC DLG was used according to Varian specified guidelines [14]. Moreover, the detector utilized for the dosimetric measurements is a Semiflex 0.125 cm^3 cylindrical chamber; model 31010 (PTW-Freiburg, Germany). The beam data measurement was carried out in accordance with the recommendation of the AAA for the photon beam to activate Eclipse TPS (version 13.5). Beam data commissioning was performed for standard photon energies (i.e., X6MV, X10MV, X15MV, and X18MV) FF beams and FFF beams (i.e., $X6_{FFF}$MV and $X10_{FFF}$MV) [4].

In total two Semiflex (31010) 0.125cm^3 ionization chambers were used as detectors (PTW-Freiburg, Germany) [3]. The nominal voltage of both detectors was +400V. One of them was utilized as "field" detector and the other was employed as a "reference" detector as specified above. Eclipse Algorithms Reference Guide [21] provided us with guidelines to perform measurement results. the position of the accelerator gantry and collimator were fixed at 0 degrees[20].

Percentage Depth Dose and Profiles

The percentage depth dose (PDD) and depth dose profiles were measured at 100 cm source to surface distance (SSD) (Figure 1- 7). In addition, the PDDs curves were acquired for 7 different field sizes ranging from 3×3cm^2 to 40×40cm^2. The PDD is defined as the dose at certain point Dx of the central axis over the maximum dose Dzmax on the central axis multiplied by 100:

$$PDD(z) = \frac{D(x)}{D(zmax)} \times 100\ \% \quad (1)$$

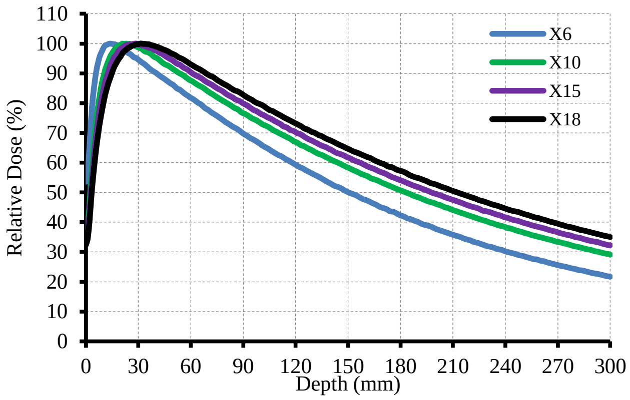

Figure 2. The 6MV, 10MV, 15MV and 18MV percent depth dose with a reference field size of 10×10cm^2.

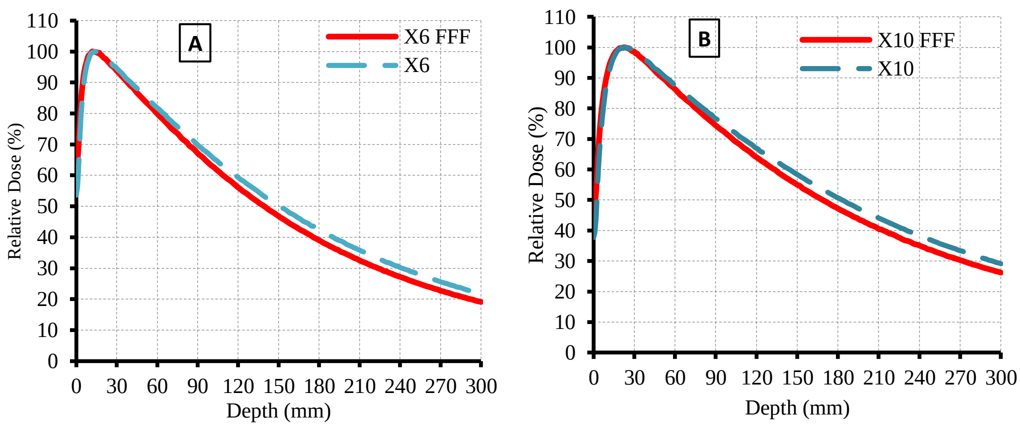

Figure 3. (A) Comparison of percentage depth dose curve for 6_{FF}MV beam vs 6_{FFF}MV beam with a reference field size of 10×10cm^2; (B) Comparison of percentage depth dose curve for 10_{FF}MV beam vs 10_{FFF}MV beam with a reference field size of 10×10cm^2

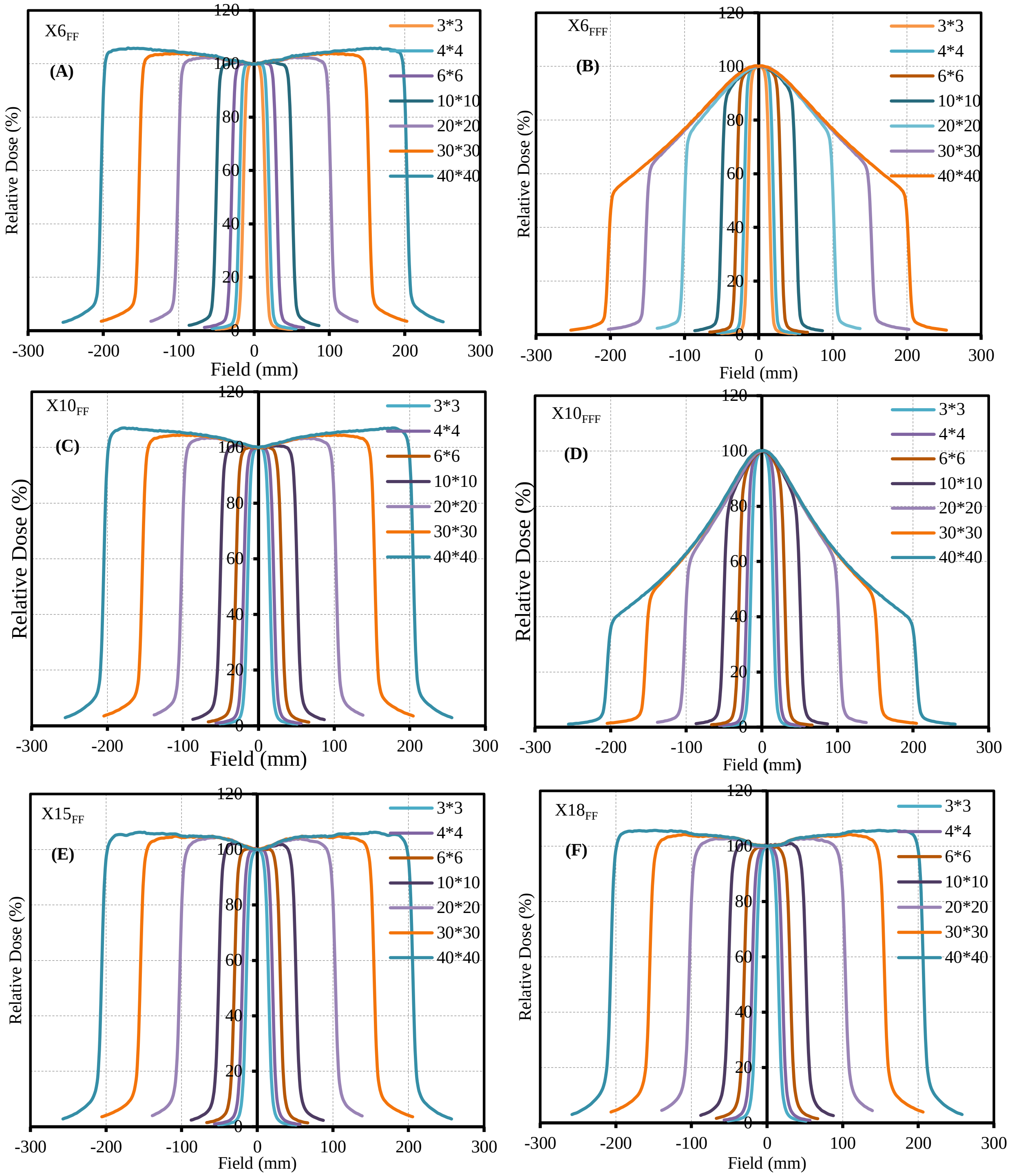

Figure 4.The 6MV, 6_{FFF}MV, 10MV, 10_{FFF}MV, 15MV and 18MV profiles with various field settings from 3×3 to 40×40cm^2. (A), (B), (C), (D), (E), and (F).

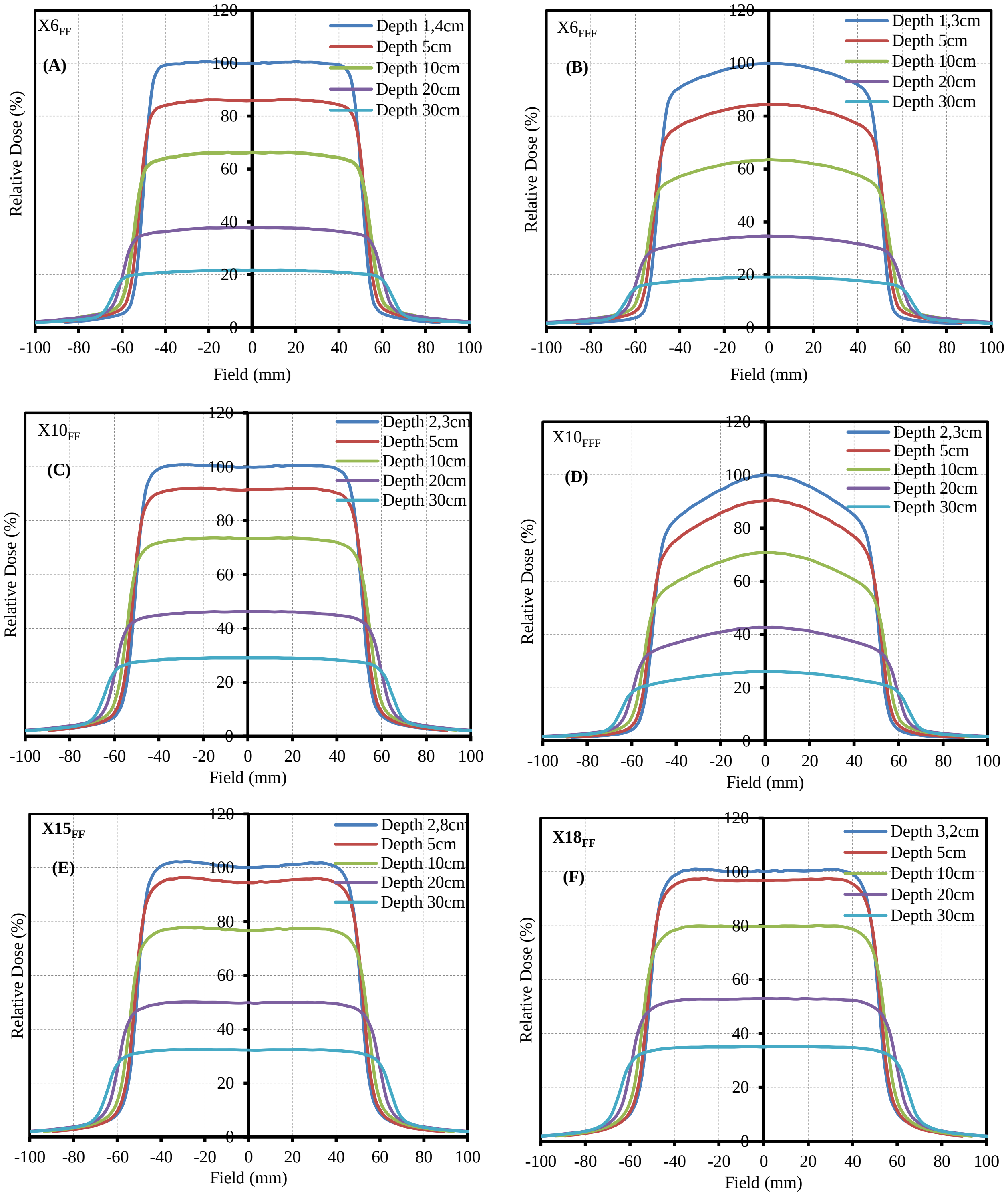

Figure 5. The 6MV, 6_{FFF}MV, 10MV, 10_{FFF}MV, 15MV and 18MV profiles with various depths (Z_{max}, Z_{5cm}, Z_{10cm}, Z_{20cm}, Z_{30cm}) for a reference field size of 10×10 cm^2. (A), (B), (C), (D), (E),and (F).

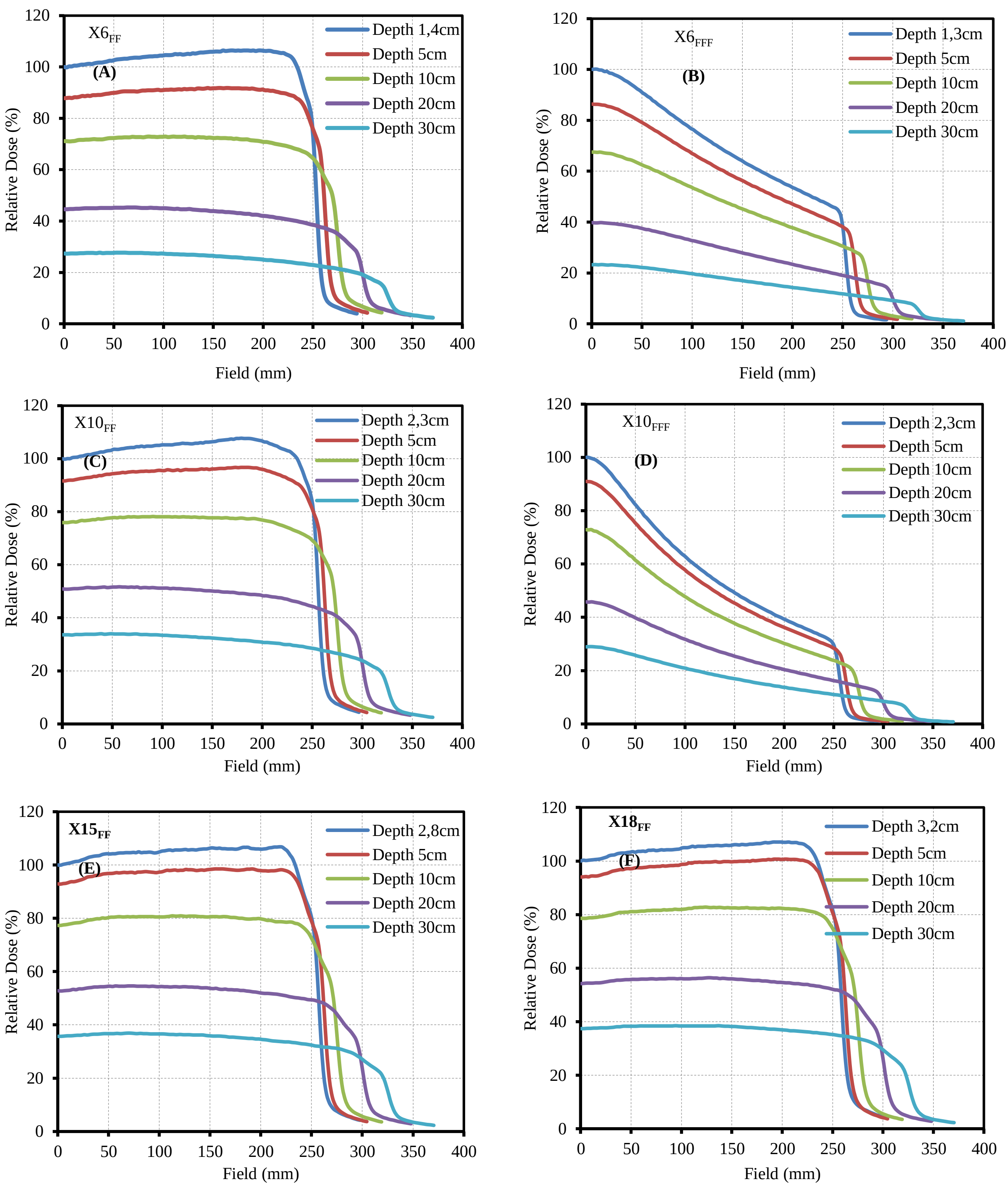

Figure 6.The 6 MV, 6_{FFF}MV, 10MV, 10_{FFF}MV, 15MV and 18MV hemi diagonal profiles with various depths (Z_{max}, Z_{5cm}, Z_{10cm} , Z_{20cm}, and Z_{30cm}) in a field size of 40×40 cm^2. (A), (B), (C), (D), (E), and (F).

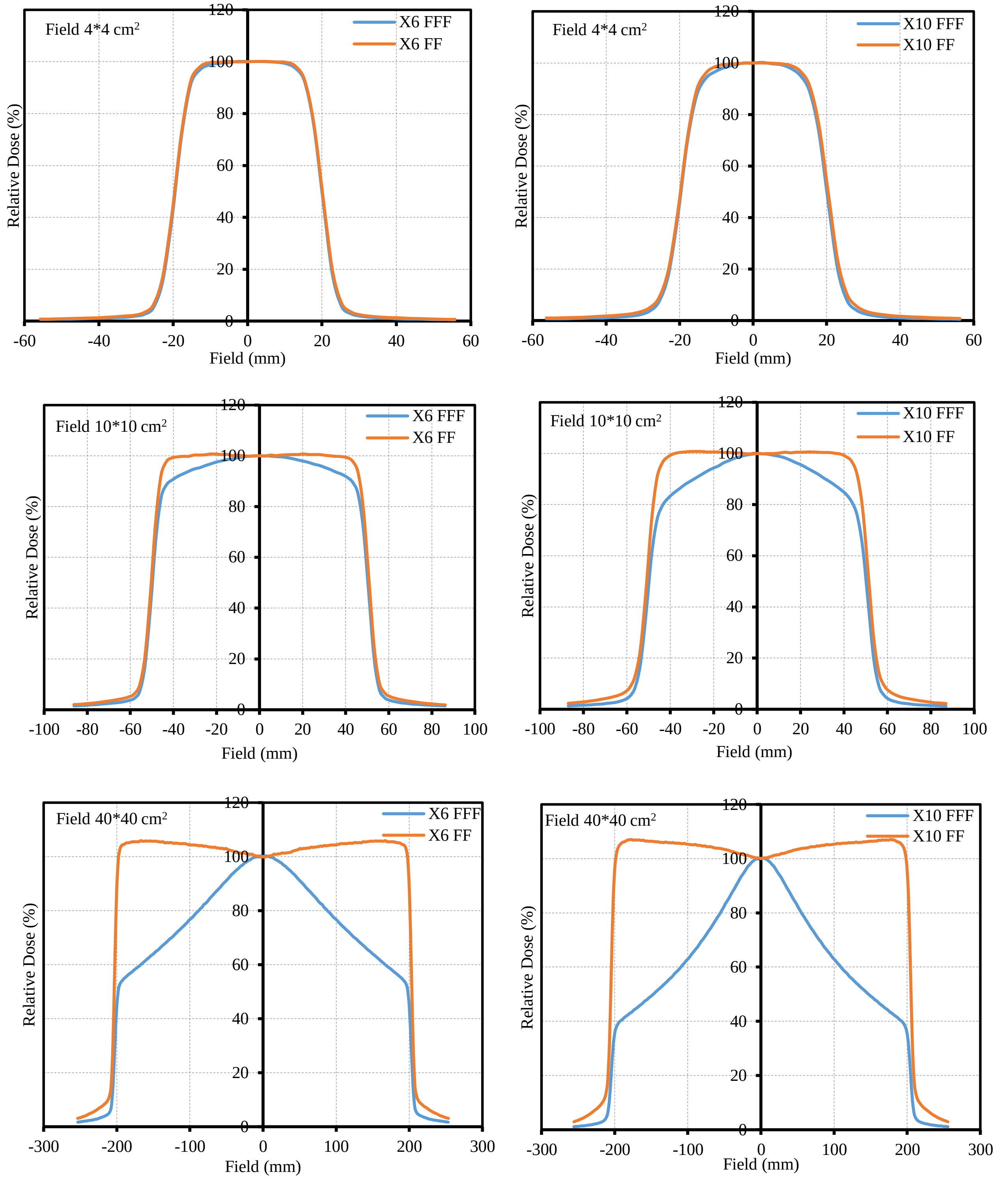

Figure 7. Comparison of profile curves for 6MV beam vs 6_{FFF}MV beam and 10MV vs 10_{FFF}MV using various field size of 4×4cm^2, 10×10cm^2 and 40×40cm^2

Furthermore, the PDD depends on the beam quality [22] that is defined mainly by energy, radiation field size and shape, SSD, and collimation of the beam. Transversal and diagonal beam profiles were measured for all available beam energies of previously specified field sizes at depths of (D_{max}, 5, 10, 20, and 30cm). The diagonal was determined only for the largest field size (i.e. 40×40cm^2). The flatness of the field is calculated as a maximum deviation from the average dose intensity administered in 80% of the full width at half maximum (FWHM) of the profile in a plane transverse to the beam axis measured at 100cm SSD. At a depth of 10cm, the mean corresponds to the average of the maximum and minimum intensity points in 80% of the FWHM area.

The flatness is given by:

$$Flatness = \frac{Dmax - Dmin}{2} \times 100\ \% \quad (2)$$

where D_{max} and D_{min} are the maximum and minimum dose values in the central 80% of the dose profile, respectively. The flatness parameter is not applicable to FFF beams. The parameter related to the FFF beams (known as the unflatness) is the ratio between the dose level at the central axis of the beam (D_{cax}) and the dose level at a predefined distance from the central axis ($D_{x\ off\ axis}$) or at the corner of the field area measured at 100cm SSD at a depth of 10cm.

The unflatness is given by:

$$Unflatness = \frac{Dcax}{Dx\ off\ axis} \quad (3)$$

Symmetry is defined as the maximum variation of the integrated dose between two corresponding equidistant points from the centerline of the beam in the central field width of 80% of the main transverse axes (Crossplane), it is a parameter that checks the level of equality between the left and right sides of a profile.

$$Symmetry = \frac{D(x) - D(-x)}{2} \times 100\ \% \quad (4)$$

Output Factor

The OF may be determined as the ratio of the corrected dosimeter readings of the absorbed dose in water $Dw_{(x,\ y)}$ on the axis of the beam at a defined depth Z_{ref} for (x,y) field, the absorbed dose in water $Dw_{(10,\ 10)}$ at the same depth, and distance for the reference field $10\times10cm^2$. The OF was measured for squared and rectangular field sizes ranging from $3\times3\ cm^2$ to $40\times40cm^2$ for all photon energies. Relative OF measurement data were obtained using an isocentric configuration at a depth of 5 cm (95 cm SSD) for 6MV and 6MV FFF, and at a depth of 10 cm (90 cm SSD) for 10MV, 10MV FFF, 15MV and 18MV. A Semiflex 0.125 cm^3 ionization chamber was used to measure the field sizes ranging from $3\times3\ cm^2$ to $40\times40\ cm^2$. The total reading output factor was normalized to $10\times10\ cm^2$ for all measured field sizes. The obtained results were then averaged and compared to obtain the OF tables for all TrueBeam STx® energies.

Quality Index, Tissue Phantom Ratio $_{(20, 10)}$

The quality index tissue phantom ratio $_{(20,\ 10)}$ (TPR) is determined using the measured PDD_{20cm} and PDD_{10cm} data through an empirical approximation relationship [18] as $TPR_{(20,\ 10)} = 1.2661\ PDD_{(20,\ 10)} - 0.0595$.

Where $PDD_{(20,\ 10)}$ is the ratio of the percent depth doses at 20 cm and 10 cm depths [5]. Moreover, it can be measured directly in the phantom $D_{(20,\ 10)}$ in isocentric configuration for reference field $10\times10\ cm^2$ at depth values of 10 and 20 cm. The value is measured for all available energies of the photon beam and compared with the values obtained from the empirical formula [18]

Multileaf Collimator Leaf Transmission Factor

To measure the transmission factor of high definition multileaf collimator (HDMLC), the Farmer $0.6cm^3$ ionization chamber, model 30013 (PTW-Freiburg, Germany), was placed in water at the depth of 10cm at the isocenter and field size of $10\times10cm^2$. The open field reading values were recorded, and subsequently, the closed A and B MLC banks reading values were obtained by placing the ionization chamber below MLC leaves which was more than 2cm from the field center. The same procedure was repeated by moving the other bank of the MLC. The ratio between the reading value obtained from the closed and open MLC fields is defined as the MLC transmission factor[23].

Dosimetric Leaf Gap

A rounded leaf tip characterize Varian MLC system. The physical difference between the light field and the irradiation field formed by the MLC is defined as DLG [24]. During commissioning, the DLG parameter is set individually for each energy available on the TrueBeam linear accelerator [19, 25]. To measure the DLG of the HDMLC, the ionization chamber (Semiflex 31010) $0.125cm^3$ was placed in water at the depth of 10cm at the isocenter. The DLGs were measured as per the Varian procedure by sweeping gap fields of varying widths [14]. A plan was created in Eclipse TPS (Varian Medical Systems, USA) consisting of programmed sliding MLC field gaps of (2, 4, 6, 10, 14, 16 and 20mm). A reference field size of $10\times10cm^2$ was set by the X and Y jaws for all the above fields, which will hereafter be referred to as DLG fields. Each sweeping gap travelled across this reference field, and had a control point for every centimeter [26]. The concept of the plot suggested by Varian and the fact that the DLG is the intercept of the fit generated from that plot.

Results

Truebeam Percentage Depth Dose

The PDD data were measured for various jaw settings for all the energy modes. a range of field size from 3×3, to $40\times40cm^2$ and the measurement depth range from 0 to 30cm (Figures 1- 3). Figure 1 illustrates the PDDs curves of these field settings for X6MV, $X6_{FFF}$MV, X10MV, $X10_{FFF}$MV, X15MV and X18MV. The PDD curves normalized to the corresponding D_{max} depth for each field size. Figure 2 shows the variation of the PDDs as a function of energy for the reference field $10\times10cm^2$. The values of the PDD parameters (D_{max}, PDD_5, and the $TPR_{(20,\ 10)}$) increased with the energy. On the other hand, Table 2 tabulates a decrease in the dose to the surface D_s with increasing energy.

Table 1. The percentage depth dose parameters for the various energies of flattening filter beams (X6MV, X10MV, X15MV, and X18MV) vs $X6_{FFF}$MV, and $X10_{FFF}$MV

Energies (MV)	Fields (cm^2)	D_{max} (cm)	PDD_5 (%)	PDD_{10} (%)	PDD_{20} (%)	$TPR_{20/10}$ (QI)
X6 MV	4 × 4	1.49	83.59	61.60	33.20	0.622
	10 × 10	1.4	86.06	66.17	37.81	0.664
	40 × 40	1.20	87.97	71.27	44.92	0.738
$X6_{FFF}$ MV	4 × 4	1.20	81.37	58.31	30.13	0.594
	10 × 10	1.30	84.38	63.25	34.55	0.632
	40 × 40	1.29	86.42	67.58	39.95	0.689
X10 MV	4 × 4	2.49	90.57	70.56	42.59	0.704
	10 × 10	2.30	91.38	73.33	46.21	0.738
	40 × 40	1.90	91.12	75.44	50.23	0.783
$X10_{FFF}$ MV	4 × 4	2.20	89.20	67.73	39.28	0.674
	10 × 10	2.29	90.32	70.89	42.71	0.703
	40 × 40	2.10	90.71	72.74	45.93	0.739
X15 MV	4 × 4	2.99	94.12	74.70	46.64	0.731
	10 × 10	2.80	94.24	76.40	49.55	0.761
	40 × 40	2.00	91.90	76.70	52.34	0.704
X18 MV	4 × 4	3.40	96.86	78.25	50.28	0.754
	10 × 10	3.20	96.45	79.57	52.67	0.778
	40 × 40	2.10	92.22	77.12	53.31	0.815

Table 2.TrueBeam measured analyses and comparison parameters (Profiles curves, Ds, dosimetric leaf gaps and multileaf collimator transmission factors) for flattening filter beams and flattening filter-free beams

Parameters	Fields (cm^2)	X6 MV	$X6_{FFF}$ MV	X10 MV	$X10_{FFF}$ MV	X15 MV	X18 MV
Symmetry Crossplane at (D_{max}/10cm) depth (%)	4 × 4	2.6 / 0.9	0.3 / 0.5	2.1 / 1.2	0.9 / 0.6	1.7 / 1.0	1.5/1.2
	10 × 10	0.3 / 0.3	0.7 / 0.8	0.4 / 0.2	1.1 / 1.3	0.6 / 0.5	0.4 / 0.4
	40 × 40	0.8 / 0.9	1.2 / 1.3	0.7 / 0.8	1.6 / 1.85	1.1 / 1.0	1.0 / 1.1
Flatness at (D_{max} / 10cm) depth (%)	4 × 4	6.3 / 6.5	-	7.5 / 7.7	-	7.8 / 7.9	8.3 / 8.7
	10 × 10	0.8 / 2.3	-	1.1 / 2.1	-	1.4 / 2.0	1.57 / 2.1
	40 × 40	2.9 / 1.4	-	3.4 / 1.5	-	3.1 / 2.4	2.8 / 2.6
Unflatness at (D_{max} / 10cm) depth (%)	4 × 4	-	1.0 / 1.0	-	1.0 / 1.0	-	-
	10 × 10	-	1.1 / 1.1	-	1.2 / 1.2	-	-
	40 × 40	-	1.6 / 1.6	-	2.1 / 2.1	-	-
Surface Dose (%)	4 × 4	50.63	60.00	31.72	42.94	27.47	34.31
	10 × 10	55.21	63.31	38.69	47.08	35.79	33.48
	40 × 40	71.55	72.16	60.58	56.24	60.26	60.62
Dosimetric leaf gaps (cm)		0.032	0.026	0.041	0.037	0.042	0.038
Multileaf collimator transmission at depth of 10cm (%)		1.21	1.03	1.36	1.22	1.33	1.21

Quality Index Tissue Phantom Ratio$_{(20,10)}$

The $TPR_{(20,10)}$ values of the FF beam at the depths of 20 and 10 cm are X6, 0.664; X10, 0.738; X15, 0.761; and X18, 0.778). (Table 1). Moreover, the $TPR_{(20,10)}$ values of FFF beam at the depths of 20 and 10 cm includes 0.632 and 0.703 for $X6_{FFF}$MV and $X10_{FFF}$MV, respectively (Table 1).

Surface dose

For the flattened and unflattend beams, the surface dose decreases with increasing energy, and increases with increasing field size. Surface dose in a reference field 10×10cm^2 FF beams are 55.21%, 38.69%, 35.79% and 33.38% for X6, X10, X15 and X18, respectively (Table 2). The reference field of 10×10cm^2 FFF beams has lower mean energy and a higher surface dose than that of the FF beams (i.e., 63.31% for X6MV and 47.08% for X10MV).

As shown in Table 2, the surface dose for 40×40cm^2 X10MV flattened beams is higher than that for X10MV unflattened beams (10×10cm^2).

Truebeam Profiles

The beam profiles were measured at 100cm SSD and different depths, along the transverse, in addition, the diagonal directions for a range of field dimensions were from 3×3, to 40×40cm^2 (Figure 4). Moreover, the measurements were performed at five different depths (D_{max}, 5, 10, 20, and 30cm) for all the field sizes. Figure 5 illustrates the profiles measured at five different depths for the reference field size of 10×10cm^2. Hemi diagonal profiles were also measured for a field size of 40×40cm^2 following the same conditions above (Figure 6). All the profiles were normalized to the corresponding central axis for each field size.

Symmetry, Flatness and Unflattens.

Symmetry, flatness, and unflattenss values of FF beam and FFF beam are shown in Table 2. According to Varian specification, FF Beam symmetry, flatness of the reference field size (10×10cm^2), and the max field size at 10cm depth are within the tolerance intervals (flatness < ± 3%, Unflattens < ± 2%, Symmetry <2%).

For 10×10cm^2 field size:

The values of FF beam symmetry were 0.3%, 0.2%, 0.5% and 0.4% for X6MV, X10MV, X15MV and X18MV respectively. Moreover, the values of flatness obtained at 2.3%, 2.1%, 2.0% , and 2.1% for X6MV, X10MV, X15MV and X18MV respectively. On the other hand, the values of FFF beam symmetry were 0.8% and 1.3% for $X6_{FFF}$MV and $X10_{FFF}$MV, respectively, and the corresponding values for unflattenss were estimated at 1.1% and 1.2% for $X6_{FFF}$MV and $X10_{FFF}$MV, respectively.

For 40×40cm^2 field size:

The values of FF beam symmetry were 0.9%, 0.8%, 1.0% and 1.1% for X6MV, X10MV, X15MV and X18MV respectively. Additionally the values of flatness were determined at 1.4%, 1.5%, 2.4% and 2.6% for X6MV, X10MV, X15MV and X18MV, respectively, On the other hand, the values of FFF beam symmetry were 1.3% and 1.8% for $X6_{FFF}$MV and $X10_{FFF}$MV, respectively, and the corresponding values for unflattenss were obtained at 1.6% and 2.1% for $X6_{FFF}$MV and $X10_{FFF}$MV, respectively.

Penumbra

The mean penumbra values of cross-plane flattened photon beams at collimator angle of 0◦ were determined from 7.84±0.01 to 8.79±0.01mm and from 6 to 18MV at 10cm depth with a field size of 10×10cm^2. Moreover, the mean penumbra values of cross-plane beams at the collimator angle of 0° were estimated at 7.57±0.04 and 7.81±0.08mm for $X6_{FFF}$MV and $X10_{FFF}$MV, respectively, at 10cm depth with a field size of 10×10cm^2 (Table 3).

Table 3. Radiation Penumbra measured for flattening filter beams and flattening filter-free beams in terms of low, medium, and high field sizes (4×4cm^2, 10×10cm^2, and 40×40cm^2)

Energies (MV)	Fields size (cm^2)	$Penumbra_{(Dmax)}$ (mm)	$Penumbra_{(5)}$ (mm)	$Penumbra_{(10)}$ (mm)	$Penumbra_{(20)}$ (mm)	$Penumbra_{(30)}$ (mm)
X6 MV	4 × 4	5.61 ± 0.07	5.99 ± 0.03	6.38 ± 0.04	6.98 ± 0.08	7.32 ± 0.12
	10 × 10	5.97 ± 0.01	6.81 ± 0.00	7.84 ± 0.01	9.37 ± 0.01	10.71 ± 0.04
	40 × 40	6.14 ± 0.00	7.25 ± 0.00	9.82 ± 0.00	18.92 ± 0.00	37.67 ± 0.00
$X6_{FFF}$ MV	4 × 4	5.38 ± 0.11	5.84 ± 0.04	6.23 ± 0.04	6.80 ± 0.04	6.32 ± 0.02
	10 × 10	5.50 ± 0.02	6.46 ± 0.05	7.57 ± 0.04	9.38 ± 0.04	10.83 ± 0.04
	40 × 40	5.93 ± 0.00	7.23 ± 0.00	10.27 ± 0.00	20.89 ± 0.00	37.94 ± 0.00
X10 MV	4 × 4	6.40 ± 0.04	6.80 ± 0.02	7.18 ± 0.02	7.77 ± 0.01	8.20 ± 0.02
	10 × 10	6.88 ± 0.05	7.43 ± 0.04	8.24 ± 0.04	9.59 ± 0.02	10.73 ± 0.02
	40 × 40	6.77 ± 0.00	7.47 ± 0.00	9.48 ± 0.00	14.71 ± 0.00	25.12 ± 0.00
$X10_{FFF}$ MV	4 × 4	6.08 ± 0.10	6.43 ± 0.05	6.90 ± 0.09	7.46 ± 0.13	7.91 ± 0.12
	10 × 10	6.30 ± 0.07	6.90 ± 0.10	7.81 ± 0.08	9.22 ± 0.07	10.52 ± 0.06
	40 × 40	6.61 ± 0.00	7.51 ± 0.00	9.41 ± 0.00	14.75 ± 0.00	24.16 ± 0.00
X15 MV	4 × 4	6.57 ± 0.01	6.99 ± 0.00	7.40 ± 0.01	7.90 ± 0.02	8.32 ± 0.05
	10 × 10	7.10 ± 0.05	7.52 ± 0.00	8.21 ± 0.01	9.39 ± 0.00	10.34 ± 0.03
	40 × 40	7.18 ± 0.00	7.55 ± 0.00	9.10 ± 0.00	12.84 ± 0.00	17.01 ± 0.00
X18 MV	4 × 4	7.11 ± 0.02	7.51 ± 0.02	7.95 ± 0.01	8.52 ± 0.01	9.00 ± 0.02
	10 × 10	7.76 ± 0.08	8.12 ± 0.06	8.79 ± 0.01	9.95 ± 0.05	10.87 ± 0.07
	40 × 40	7.91 ± 0.00	7.87 ± 0.00	9.40 ± 0.00	12.51 ± 0.00	15.22 ± 0.00

Truebeam Output Factor

The OF increases with the field size (Table 4). The OF values of the FF beam ranged between 0.842 for small fields of 3×3cm^2 to 1.099 for a large fields 40×40cm^2. Moreover, the corresponding values for the FFF beam were from 0.898 and 0.889 for $X6_{FFF}$ and $X10_{FFF}$, respectively, (a small field 3×3cm^2) to 1.06 and 1.056 (a large field of 40×40cm^2) (Figure 8). For all beams, it was observed that the same field size of the OF decreases with increasing the energy from 6 to 18MV (Figure 8, 9).

Table 4. Output Factors at 95cm source to surface distance (SSD) and 90cm (SSD) for X6, X10, X15, and X18 energies of flattening filter beams and flattening filter-free beams

	Output Factor at 95cm source to surface distance (SSD) and 90cm (SSD) respectively for X6, X10, X15, and X18 energies Flattening filter and flattening filter-free beams					
Field size (cm × cm)	X6 MV	$X6_{FFF}$ MV	X10 MV	$X10_{FFF}$ MV	X15 MV	X18 MV
3 × 3	0.882	0.898	0.853	0.889	0.853	0.842
4 × 4	0.906	0.921	0.887	0.919	0.893	0.890
6 × 6	0.947	0.957	0.936	0.957	0.943	0.944
10 × 10	1.000	1.000	1.000	1.000	1.000	1.000
20 × 20	1.061	1.046	1.071	1.042	1.060	1.053
30 × 30	1.088	1.063	1.099	1.058	1.083	1.074
40 × 40	1.084	1.060	1.099	1.056	1.081	1.068

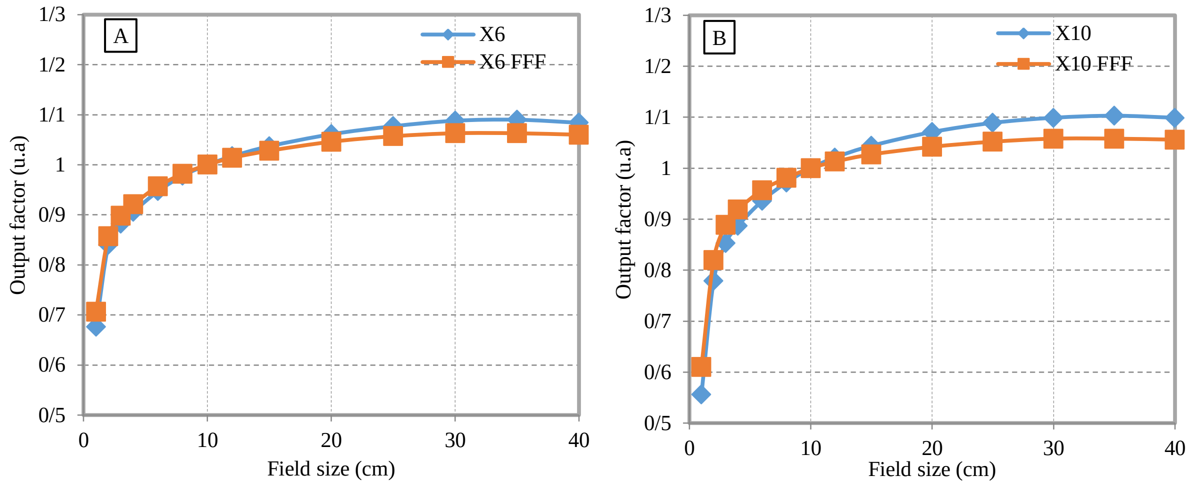

Figure 8. Output factors for symmetric fields for X6 and $X6_{FFF}$MV (A), X10 as well as $X10_{FFF}$ MV (B).

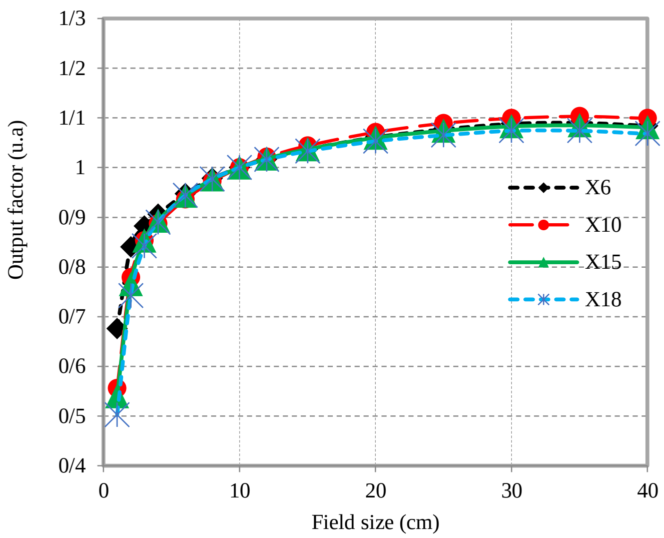

Figure 9. Photon output factors for flattening filter photon energies, X6, X10, X15 and X18 MV

Multileaf Collimator Transmission and Dosimetric Leaf Gaps Factors

Regarding the HDMLC, the MLC transmissions and DLG factors were 0.0121, 0.0103, 0.0136, 0.0122, 0.0133, and 0.0121 as well as 0.32, 0.26, 0.41, 0.37, 0.42, and 0.38mm, for X6 MV, $X6_{FFF}$ MV, X10 MV, $X10_{FFF}$ MV, X15 MV, X18 MV, respectively (Figure 10, Table 2).

Discussion

Depth Dose Curves and Profiles

After comparing FF with FFF ((Figure 3) it was revealed that the mean energy levels of FFF beams are lower than those of the FF beams (Table 2). Moreover, the FFF beams had a D_{max} located closer to the surface. Since beam hardening does not occur at FFF beams, their depth dose curves have more rapid fall-off with a slight difference in D_{max}; accordingly, small FFF energies have a higher surface dose. With increasing field size, the D_{max} is closer to the surface for the flattened beams; however, this effect is less pronounced for FFF beams. Moreover, the surface dose of 10×10cm^2 field size increases by 8.1% and 8.39% for 6_{FFF}MV and 10_{FFF}MV, respectively.

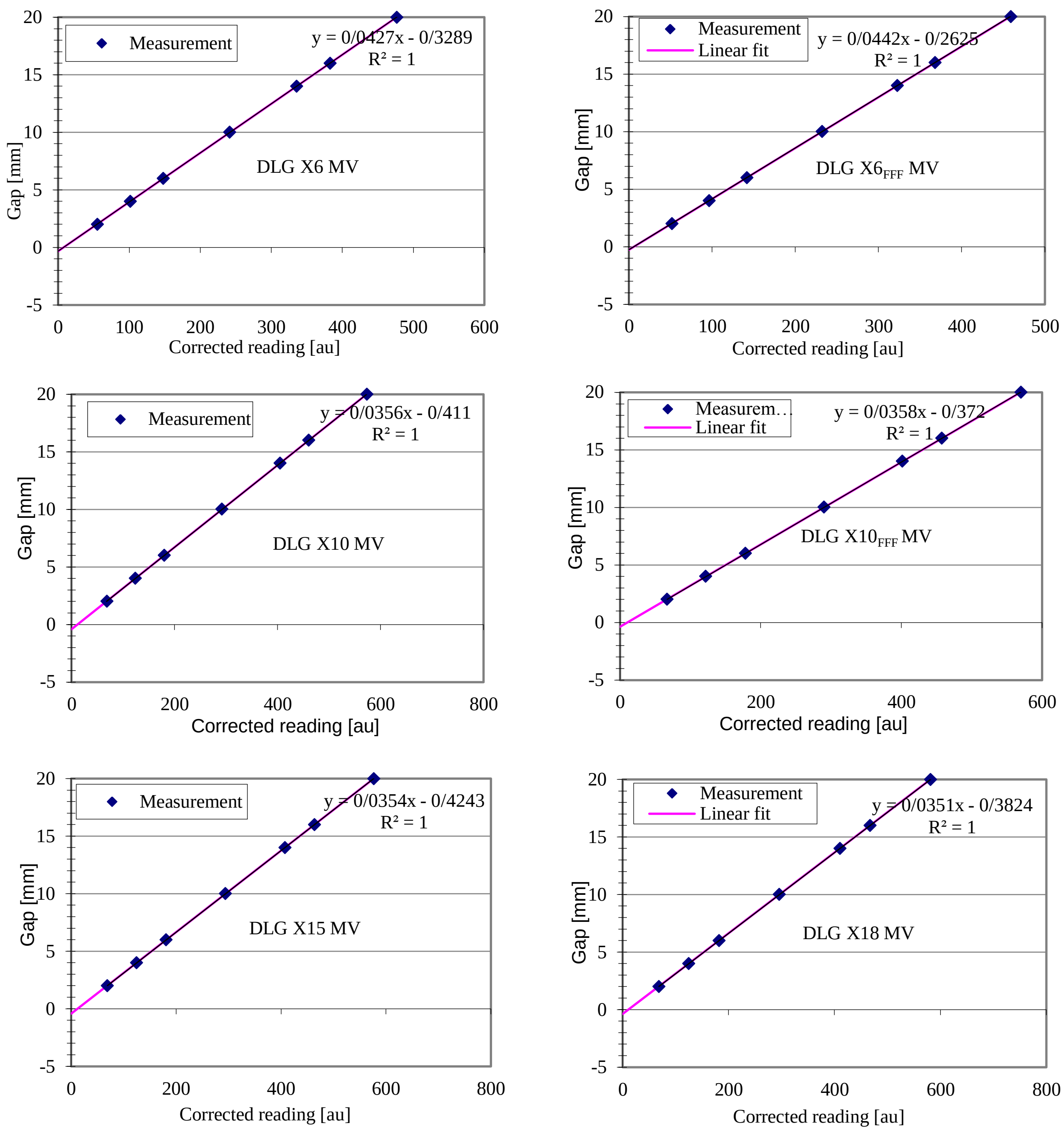

Figure 10. The dosimetric leaf gap graphs obtained from the dynamic light scattering measurements procedure for X6 MV, $X6_{FFF}$ MV, X10 MV, $X10_{FFF}$ MV, X15 MV and X18 MV.

An increase (8%) in the surface dose was noticed between the FF and FFF beams due to the removal of flattening filter that caused different electron contamination and lower photon energy spectrum. Similarly, the fractional dose effect was the strongest on the central axis of the beam due to the beam hardening effect of the flattening filter, which helped reduce surface or skin dose.

Surface dose decreases in FF beams (approximately 20%), and it decreases with increasing energy from 6 to 18MV. Moreover, it increases with increasing field size (Table 1, 2).The unflattened profiles have the maximum dose on the central axis, and decrease gradually toward the field edge. This unflattened form becomes more pronounced with increasing field size and beam energy. Up to a field size of 4×4cm^2, the in-field part of a profile is practically the same for X6 and X6FFF, as well as for X10 and X10FFF (Figure 4, 5, 6, 7).

The unflattenss increases with energy, and up to 4×4cm^2, the difference in the profile for FF and FFF beams is neglectable. When beam energy increased from 6MV to 10MV, the dose reduction effect of the unflattened beam was greater, compared to the FF beam in the out-of-field area. This process clarifies the improved dose saving effect of the unflattened beam. This is very important clinically for cases receiving a high dose and having a variety of healthy tissue structures found in the head and neck area.

Output Factor

The OF at lower field sizes is slightly smaller in FF, compared to FFF beams, and in the same field size, the OF of the FF beam increases with decreasing the energy from 18 to 6 MV. (Figure 8, 9). The head scatter component of a FFF beam varies from that of the flattened beam due to the lack of the flattening filter. In these conditions, the variation in OF are more important for FF beams.

Dosimetric Leaf Gaps and Multileaf Collimator Transmission Transmission Factor

The DLG for the HDMLC was less than 1mm for all energies and smaller in FFF beams (Figure 10, Table 2).

Generally, MLC transmission increases with increasing energy. On the same analogy, it has been found that DLG also increases with increasing energy due to increased transmission across a round leaf gap of MLC.

Conclusion

Photon beam reference dosimetric characteristics of TrueBeam STx® Linear Accelerator were successfully obtained in this study to be utilized by the Eclipse TPS. Moreover, after comparing the results from the Varian model, good compliance was achieved according to vendor-specific recommendations.

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