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Small-field Dosimetry of 6- and 10-MV Flattening Filter-free and Flattening Filter Photon Beams for Therapeutic Use

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This investigation aimed to measure and commission small unflat photon beams using the detectors described in our previous study[10]. Furthermore, the dosimetric parameters of small-field unflat and flat photon beams were compared to provide a better interpretation of beam energy and spectrum. The TrueBeam linear accelerator (TrueBeam LINAC, Varian Medical Systems) was employed in this study. The 10 and 6 MV unflat and flat photon beams were used to measure the output factor, depth dose, and beam profile of small-fields ranging in size from 1 cm × 1 cm to 6 cm × 6 cm. All measurements were performed according to the TRS-483 protocols established by the International Atomic Energy Agency. For both 10 and 6 MV, the output factors in unflat beam were significantly higher than in flat beam. The study found that unflat beam penumbras were slightly smaller than flat beam penumbras for both photon energies, which may improve tumor conformity and reduce doses to normal organs. The unflat photon beams had higher suface doses and lower depth doses at 10 cm than the flat photon beams for both energies, leading to considerably more beam energy degradation for unflat beams. The findings of this work are consistent with previously published data, and they will be useful for future research and LINAC commissioning.

Keywords: Small-field dosimetry; flattening filter free beam; Output Factor; Penumbra; Surface dose

1 Introduction

Modern medical linear accelerators (LINACs) are equipped with both unflat (flattening filter-free, FFF) and flat (with flattening filter, FF) photon beam modes to deliver homogenous and non-homogeneous dose distributions for radiotherapy, respectively. In the past, radiotherapy was administered using flat beam mode for both broad beam and small beam scenarios. However, modern radiotherapy techniques such as stereotactic radiosurgery (SRS), stereotactic radiotherapy (SRT), and stereotactic body radiotherapy (SBRT), which utilise both small radiation fields and non-uniform dose distribution, may not work well with flat beam. In addition, these techniques employ high fraction doses to treat tumors, necessitating a high dose rate. In comparison to flat beams, unflat beams are non-homogeneous, forward-peaked, and 2–4 times more intense in terms of dose rate, with less head scattering[1–4]. Therefore, unflat beams are especially advantageous in these cutting-edge radiotherapy techniques.

In recent years, SRS, SRT, and SBRT have seen increased use as treatment options for a variety of small tumors. Small unflat beams with a high dose rate are particularly beneficial in these advanced techniques, as it reduces beam duration as well as inter- and intra-fractional setup errors. As a result, the significance of successfully commissioning small unflat beams has grown. Nevertheless, when using standard detectors, which expand the penumbra, it is challenging to measure small beams that have a steep dose gradient region. In general, large volume detectors have the effect of broadening the penumbra, whereas small volume detectors result in noisier signal production. Therefore, selecting an appropriate detector for measuring the specific dosimetric parameter of a small beam is challenging for radiotherapy dosimetry[5]. Several studies were reported in past and most of them focuses on the small flat photon beams[6–10].

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As a result, the main purpose of this investigation was to measure and commission the small unflat beams using the detectors described in our previous study[11]. This was done to increase the amount of dosimetric data that is currently available on small unflat photon beams. In addition, the dosimetric parameters of small-field unflat and flat photon beams were compared to get a better interpretation of beam energy and spectrum. The dosimetric parameters investigated in this study were beam output, penumbra ($d_{20\text{-}80}$), percentage depth dose (PDD) at 10 cm (D_{10}) and percentage surfaces dose (D_S) for 10 and 6 MV small unflat and flat photon beams.

2 Materials and methods

2.1 Measurement setup and detector selection

The True Beam LINAC (Varian Medical Systems, Inc., Palo Alto, CA, USA) was used in this study. This machine can generate photon beams in both unflat and flat modes. The 10 and 6 MV unflat and flat beams were employed to measure the PDD, beam profile, and output factor of small-fields ranging in size from 1×1 cm^2 to 6×6 cm^2. The TRS 483 procedure was used to adjust the nominal small-field widths to the equivalent square small-fields. The dose rate of 600 MU/min (monitor units/minute) was used for both 10 and 6 MV flat beams, while the dose rates of 2400 MU/min and 1400 MU/min were used for the 10 and 6 MV unflat beams, respectively. During the measurement of the beam data, the LINAC's collimator, gantry, and couch angles were all adjusted to zero degrees. The detectors and measuring techniques were chosen based on the findings of our previous investigation[10]. As shown in the Fig. 1, the PinPoint ionization chamber (PTW 31014) was employed to measure PDD at 10 cm and output factor, while the Gafchromic EBT3 films (Ashland Advanced Materials) and diode based EDGE detector (Sun Nuclear Corporation) were employed to measure beam profile and surface dose, respectively. The three-dimensional (3D) radiation field analyzer (RFA, Sun Nuclear Corporation) and SNC dosimetry software were utilized to measure small-field beam data (beam profile, PDD, and output factor). The properties of the above detectors were shown in the Table 1. The experimental setup used for measurement was shown in the Fig. 2.

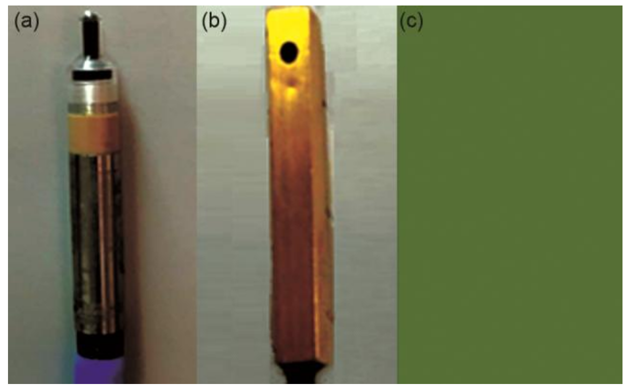

Fig. 1 — Photographs of (a) PinPoint (b) EDGE (c) EBT3 detectors.

Fig. 2 — Experimental setup used for measurement of unflat (FFF) and flat (FF) photon beams.

Table 1 — Features of the various dosimeters employed in this investigation.

Properties	EDGE detector	PinPoint chamber	EBT3 film
Detector	Shielded Diode	Ion Chamber with air filled	Radiochromic Film
Make	Sun Nuclear	PTW	Ashland Advanced Materials
Sensitive volume (mm)	Diameter: 0.8 Thickness : 0.03	Diameter: 2 Length of the cavity: 5	N/A
Active Volume	0.0019 mm^3	0.015 cm^3	N/A
Effective point	0.5 mm	0.6r	Film surface
Material	Silicon Brass	Electrode: Aluminium Wall: Graphite	Diacetylene monomer-based active layer with polyester coating

2.2 Output factor, PDD and beam profile measurement

The method described in TRS 483 was used to calculate the output factors for small-fields. We followed a similar approach to that used in other investigations[12-14] to assess the experimental uncertainties related to measuring output factors using the PinPoint detector. The source-to-axis setup was used during measurement. PDDs were acquired by scanning the detector along the beam's central axis, and cross-line profiles were obtained at 10 cm depth. In order to apply the definition of penumbra for flat beams to unflat beams, we rescaled the measured beam profiles as recommended in a previous work[4]. The gap between the 80% and the 20% dose points on a beam profile is called the penumbra of the flat beam. The surface dose is the quotient of the dose at 0.5 mm depth and the dose at the depth of maximum dose, and it was evaluated using a PDD curve. The Schematic descriptions of the $d_{20\text{-}80}$, D_{10} and D_S were shown in the Figs. 3 & 4, respectively.

3 Results and discussions

3.1 Output factor

The output correction factors proposed in previous literature[12–15] were multiplied by the quotient of detector meter readings according to the TRS 483 guidelines for calculating the output factor for small beams. The output factors were significantly higher in unflat than in flat beams for both 10 and 6 MV. The variation in the output factor measured using 6 MV flat beam relative to that obtained with 6 MV unflat beam was -5.6% and -3.3% for a field size of 1×1 cm^2 and 2×2 cm^2. The differences in the other fields, on the other hand, were determined to be within 3%. The output factor variation between 10 MV unflat and flat was -6.8% and -4.2% for a field size of 1×1 cm^2 and 2×2 cm^2, while the differences in the other fields were within 3.5%. The estimated experimental error (k = 2, 95% CI) associated with PinPoint for nominal square fields of size 1×1 cm^2, 2×2 cm^2, 3×3 cm^2, 4×4 cm^2, and 6×6 cm^2 were 2.5, 1.1, 1.0, 0.9, and 0.6, respectively. For 10 and 6 MV unflat and flat beams, the output factors are plotted in Fig. 5. The results agree with previously published data[11,16,17].

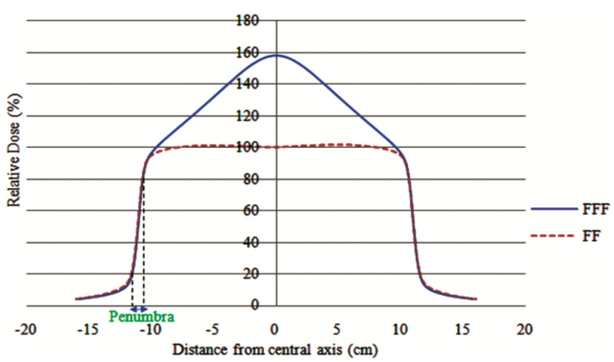

Fig. 3 — Schematic descriptions of the penumbra ($d_{20\text{-}80}$) for unflat (FFF) and flat (FF) beam profiles.

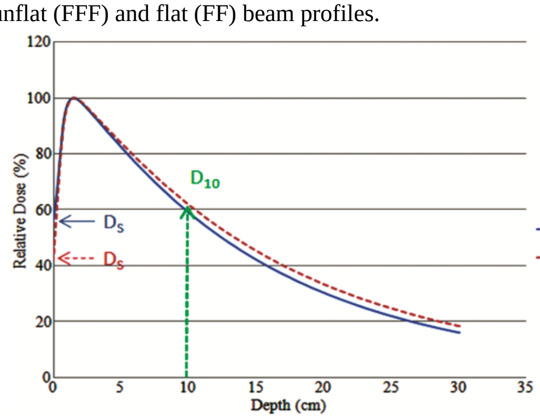

Fig. 4 — Schematic descriptions of the D_{10} and D_S in depth dose curves of unflat (FFF) and flat (FF) beams.

3.2 Penumbra ($d_{20\text{-}80}$)

The variation in penumbra (average of the right and left penumbra) of small-fields in 6 MV unflat and flat beams was less than 1 mm, but it was within 0.5 mm between 10 MV unflat and flat beams. For both unflat and flat beams, the penumbra increased with field size. The penumbras of unflat beams were slightly smaller compared to the flat beams for both photon energies. The results also showed that the penumbra increases with increasing photon beam energy due to an increase in secondary electron range. The penumbras of the profiles were highly dependent on the chamber type and sensitive volume. The study found that unflat beams have a smaller penumbra than flat beams, which could lead to better dose

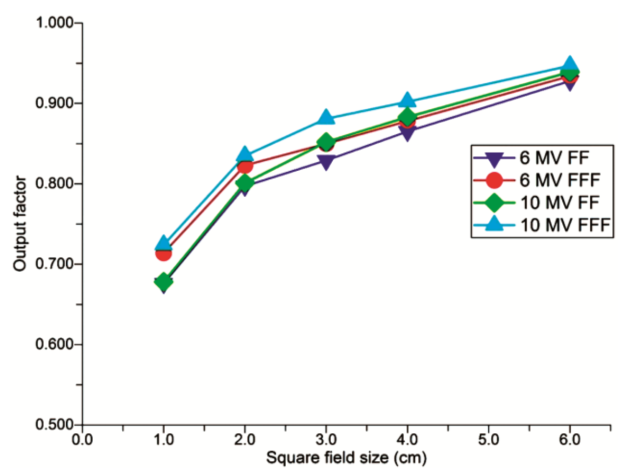

Fig. 5 — Output factor versus field size for 10 and 6 MV unflat (FFF) and flat (FF) beams.

distribution conformity and homogeneity to the tumor volume while minimizing doses into healthy organs[18,19]. In general, dose fall-off is a limiting factor when it comes to minimizing exposure to critical structures lying nearby during advanced radiotherapy treatments[20]. As a result, decreasing the penumbra width with unflat beams may improve clinical outcomes, especially for SRS, SRT, and SBRT. Fig. 6 shows the penumbra versus field size for 10 and 6 MV unflat and flat beams.

3.3 PDD at 10 cm (D_{10})

The flattening filter removal resulted in a substantial reshaping of the depth dose curve, despite the fact that the beam control parameters remained the same. The unflat beam depth doses showed a sharp dose drop-off in the exponential area when compared to flat beams. For both energies, unflat photon beams were determined to have a lower D_{10} than flat photon beams, indicating an apparent reduction in beam energy. The percent difference in D_{10} between a 6 MV unflat and flat beams was 6.5% for 1×1 cm^2 field size, 5.5-5.9% for 2×2 cm^2 to 4×4 cm^2 field size, and 5% for 6×6 cm^2 field size. The percent difference in D_{10} between a 10 MV unflat and flat beams was 6% for 1×1 cm^2 field size, 5.5-5.6% for 2×2 cm^2 to 4×4 cm^2 field size, and 4.6% for 6×6 cm^2 field size. As field size increases for both energies, the percent difference in D_{10} between unflat and flat beams decreases. Fig. 7 illustrates the PDD curves for 10 and 6 MV unflat and flat beams. The measured data is consistent with previous studies[17,21,22].

3.4 Percentage Surfaces Dose (D_S)

For both energies, unflat photon beams were shown to have higher surface doses than flat photon beams. The percent variation in surface dose between the 6 MV unflat and flat beams was -7.67% for 1×1 cm^2 field size, -8.3 to -8.9% for 2×2 cm^2 to 4×4 cm^2 field size, and -7.3% for 6×6 cm^2 field size. The percent variation in surface dose between a 10 MV unflat and flat beam was -15.5% for 1×1cm^2 field size, -14.4 to -19.1% for 2×2 cm^2 to 4×4 cm^2 field size, and -11.7% for 6 cm × 6 cm field size. The variation in surface dose is greater at 10 MV than at 6 MV. The surface dose is dependent on beam quality and was found to be higher at lower photon energies. Due to a lower energy spectrum and different electron contamination, percentage surface doses of unflat photon beams were found to be different from flat beams. Fig. 8 shows the percentage surface doses for 6 and 10 MV unflat and flat beams. These findings agree with the data that have been presented in earlier publications [23–26].

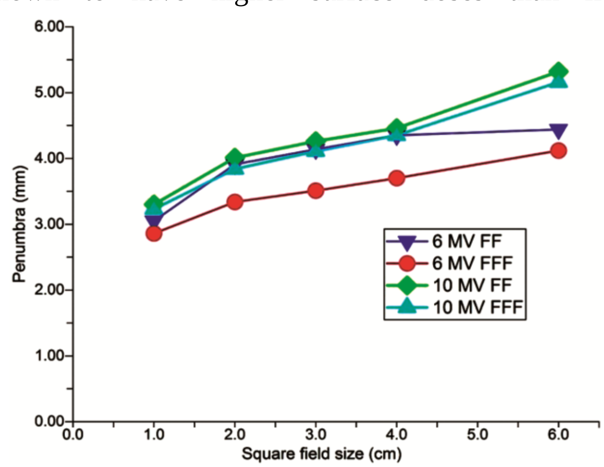

Fig. 6 — Penumbra versus field size for 10 and 6 MV unflat (FFF) and flat (FF) beams.

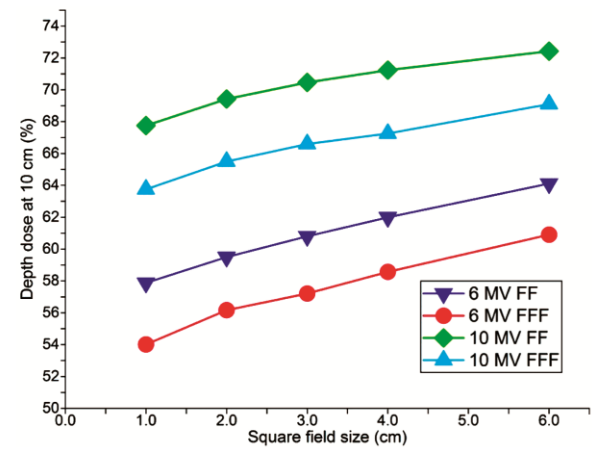

Fig. 7 — Depth dose at 10 cm versus field size for 10 and 6 MV unflat (FFF) and flat (FF) beams.

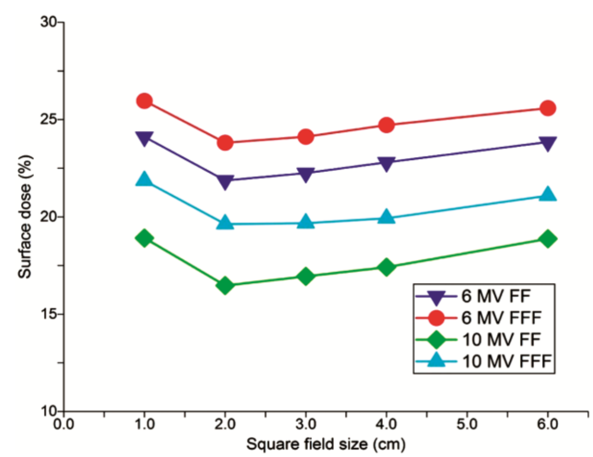

Fig. 8 — Percentage surface dose versus field size for 10 and 6 MV unflat (FFF) and flat (FF) beams.

4 Conclusions

In this study, the output factor, penumbra, PDD at 10 cm, and surface doses of small-fields in 10 and 6 MV unflat and flat photon beams were evaluated. For both energies, the output factors were found to be significantly greater in unflat than in flat photon beams. According to the findings, unflat photon beams have less penumbral than flat beams, which may improve tumor conformity and reduce doses to normal organs. A similar effect was achieved by utilising photons of lower energy, which decreased the beam's penumbra while still allowing for adequate skin sparing and beam penetration. The results of the study indicate that unflat beams have higher surface doses and lower PDD than the flat beams, resulting in relatively more beam energy degradation in unflat beams. The findings of this investigation are consistent with previously published data, and they will be beneficial for future research and commissioning of LINAC.

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