EXAMINATION OF OUT-OF-FIELD DOSE AND PENUMBRAL WIDTH OF FLATTENING FILTER FREE BEAMS IN MEDICAL LINEAR ACCELERATORS

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Abstract

Until recently, medical linear accelerators (LINACS) have been equipped with a flattening filter in the beam line in order to make the intensity of the photon beam uniform at a specified depth. This makes calculation of patient dose simpler, but has the drawback of introducing additional scatter in peripheral regions of the photon field, leading to increased dose in regions outside the primary target and enhanced risk of developing secondary malignancies and other complications. All leading manufacturers of linacs have introduced a Flattening Filter Free (FFF) mode in their most recent linacs, with the flattening filter completely removed from the beam-line. We show that the FFF modes on a TrueBeam™ linac (Varian Medical Systems, Palo Alto, CA) exhibit a clinically relevant reduction in peripheral and out-of-field dose when compared to flattened beams with similar depth-dose distributions.

INTRODUCTION

Flattening Filter Free beams are a relatively new modality in radiation oncology, with Varian Medical systems releasing the TrueBeam™ medical linear accelerator with FFF options in 2010 and Elekta (Stockholm, Sweden) following with the Versa HD in 2013. The use of flattening filters was traditionally favoured due to the uniformity of the intensity of the photon beam they produce, resulting in "flat" dose profiles; the introduction of intensity-modulated radiotherapy (IMRT) and multi-leaf collimation (MLC), however, have allowed physicians to generate unique fields that modulate photon fluence to achieve optimal dose distributions without using a flattening filter.

Removal of the flattening filter generates beams that are characterized by a "peaked" profile, with a higher photon intensity towards the center of the beam and a lower intensity towards the periphery. Because the beam is unflattened, the average energy of the photon spectra is lower; for this reason, an FFF beam with nominal energy of 10 MV will have a similar depth-dose distribution to a flattened (FF) beam with nominal energy 6 MV. FFF beams are capable of delivering a higher dose rate by upwards of a factor of 2.3 for 6 MV beams and 5.5 for 18 MV beams, allowing treatment times to be reduced and thus reducing the opportunity for intrafractional variation due to patient movement; additionally, the removal of a flattening filter greatly reduces the amount of scattered and leakage radiation generated during treatment [1].

Previous studies have demonstrated through the use of Monte Carlo models and measurements that FFF beams have the potential to reduce dose in peripheral regions of the photon field [2][3]. It is believed that this effect could be a result of the reduction in scatter caused by elimination of the flattening filter. We investigated various profile measurements from the Varian Representative Data set, examining penumbral width (distance between 80% and 20% central axis dose) and relative dose at various distances from the field edge (defined as 50% central axis dose) in this study.

For this investigation, we compared beam profiles for the energy pairing of 10 MV FFF and 6 MV FF. This beam energy pairing was chosen in order to compare the standard of care (6 MV FF) to a beam of similar depth dose distribution. Profiles were compared for field sizes of 3x3 cm^2, 4x4 cm^2, 6x6 cm^2, 8x8 cm^2, and 10x10 cm^2. Each field size was also examined at depths in water of 5 cm, 10 cm, 20 cm, and 30 cm. Relative dose was examined at distances of 2 mm, 5 mm, 10 mm, 30 mm, and 50 mm from the field edge.

NORMALIZATION OF PROFILES

Because of the different shapes of the FF and FFF profiles, normalization of FFF beams had to be done in such a way that the penumbral regions of the FF and FFF beams could be more fairly compared. Methods for normalizing FFF beams have been developed using both the inflection point of the FFF profile as well as the spatial differences between the doses at 80% and 20% of the normalized central axis FF dose; however, these methods either fail to achieve optimal coverage of a target or result in excessive dose along the central axis of the FFF beam [4], [5]. For this reason, we normalized the FF profiles such that central axis dose was 110%; the dose of the FFF beam at the location of 100% FF dose was then used to normalize the FFF beam. This allowed us to examine the profiles and penumbra under clinically relevant conditions, as the hypothetical target volume would be neither underdosed nor overdosed using this method.

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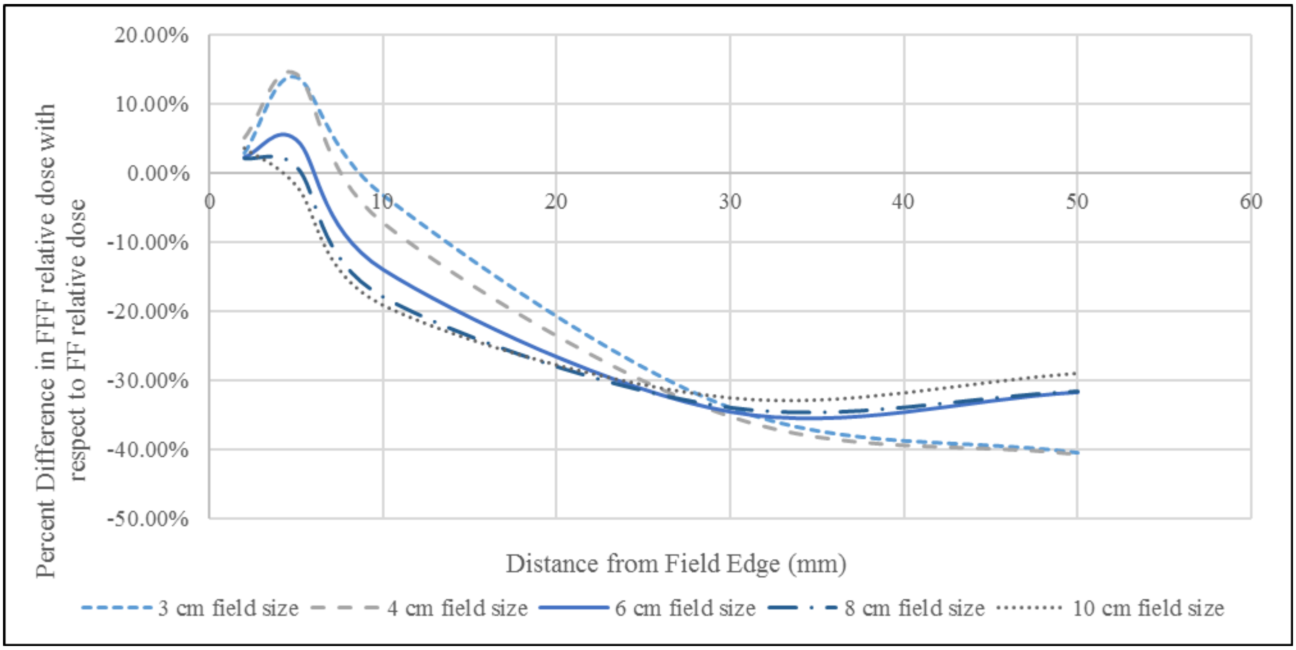

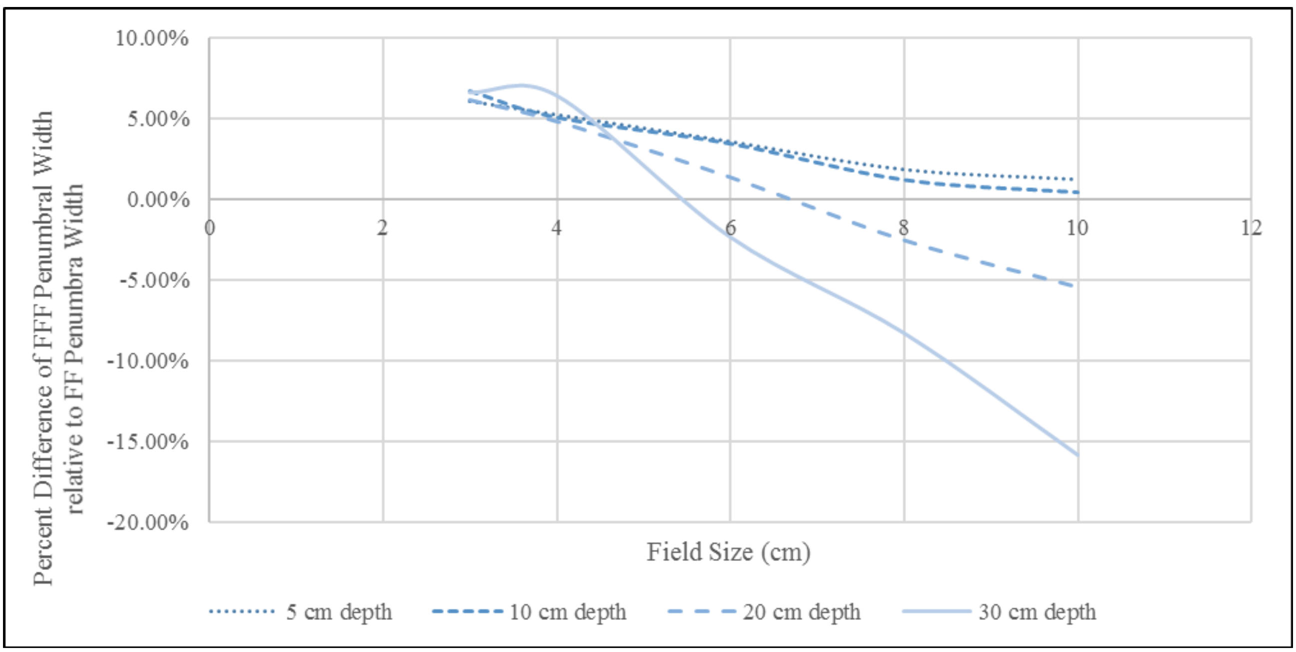

Figure 1 (top): Percent difference in dose relative to central axis between FFF beams and FF beams. Negative values indicate that relative dose for the FFF beam was lower than relative dose for the FF beam at the same location.

Figure 2 (bottom): Percent difference in penumbral width of FFF beam with respect to FF beam. The x-axis indicates the length of one side of a square field.

RESULTS

Relative Dose in Profile Periphery

Relative dose in the peripheral and out-of-field regions of the profiles showed a favourable reduction of dose for the FFF beams compared to the FF beams. The difference between FFF beams and FF beams was seen to become larger with increasing distance from the field edge (see Fig.1); no discernible difference due to change in field size was observed in this data set. At regions closer to the field edge, relative dose was generally higher for the FFF beam than for the FF beam.

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Penumbral Width

The penumbral width of the FFF beam relative to that of the FF beam was seen to decrease with increasing field size; this may be seen in Fig. 2 (above). Penumbral width tended to decrease with increasing depth of measurement; additionally, the rate of decrease tended to increase with increasing depth of measurement, as the slopes of linear fits of the data at each depth became increasingly negative at -0.0073, -0.009, -0.017, and -0.0335 for depths of 5 cm, 10 cm, 20 cm, and 30 cm respectively.

SUMMARY AND CONCLUSIONS

Dose profiles were examined and compared for 6 MV flattened beams and 10 MV flattening filter free beams to determine the difference in dose relative to central axis dose of the FF beam. Profiles were studied at depths of 5 cm, 10 cm, 20 cm, and 30 cm and for field sizes of 3 x 3 cm^2, 4 x 4 cm^2, 6 x 6 cm^2, 8 x 8 cm^2, and 10 x 10 cm^2. Measurements of the profiles indicate a general trend for lower relative dose for FFF beams compared to FF beams at the same depth and field size. Penumbral width tended to be higher for FFF beams but tended to decrease with increasing field size and depth.

The results of this study suggest that FFF beams may reduce dose in regions beyond 1 cm of the field edge. This suggests that out-of-field dose may be substantially reduced when using a flattening filter free beam compared to a flattened beam with similar depth-dose distributions, potentially diminishing the risk of secondary malignancies and other complications in cancer patients undergoing radiotherapy. Future work may include measuring and examining profiles for different beam energy pairings (such as 10 MV FF and 15 MV FFF).

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