Monte Carlo investigation into feasibility and dosimetry of flat flattening filter free beams

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Abstract

Flattening filter free (FFF) beams due to their non-uniformity, are sub-optimal for larger field sizes. The purpose of this study was to investigate the incident electron beam distributions that would produce flat FFF (F4) beams without the use of a flattening filter (FF). Monte Carlo (MC) simulations with BEAMnrc and DOSXYZnrc codes have been performed to evaluate feasibility of this approach. The dose distributions in water for open 6 MV beams were simulated using the Varian 21EX linac head model, which will be called the FF model. The FF was then removed from the FF model, and MC simulations were performed using (1) 6 MeV electrons incident on the target and (2) a 6 MeV electron beam with electron angular distributions optimized to provide as flat dose profiles as possible. Configuration (1) represents FFF beam while configuration (2) allowed producing a F4 beam. Optimizations have also been performed to produce flattest profiles for a set of dose rates (DRs) in the range from 1.25 to 2.4 of the DR of FF beam. Profiles and percentage depth doses (PDDs) from 6 MV F4 beams have been calculated and compared to those from the FF beam. Calculated profiles demonstrated improved flatness of the FFF beams. In fact, up to field sizes within the circle of 35 cm diameter the flatness of F4 beam at $d_{\text{max}}$ was better or comparable to that of FF beam. At 20 cm off-axis the dose increased from 52% for FFF to 92% for F4 beam. Also, profiles of F4 beams did not change considerably with depth. PDDs from F4 beams were similar to those of the FFF beam. The DR for the largest modeled (44 cm diameter) F4 beam was higher than the DR from FF beam by a factor of 1.25. It was shown that the DR can be increased while maintaining beam flatness, but at the cost of reduced field size.

(Some figures may appear in colour only in the online journal)
Introduction

Recent research and introduction of the flattening filter free (FFF) beams to clinical practice generated considerable interest in radiotherapy with most publications highlighting advantages of FFF beams as compared to traditional FF beams. These include increased efficiency of the dose delivery, reduced out-of-field dose by about a factor of two, over 70% reduced leakage dose in the patient plane (Titt et al 2006a, 2006b, Vassiliev et al 2006a, 2007, Kry et al 2010, Duan et al 2011, Georg et al 2011, Stevens et al 2011, Almberg et al 2012, Dzierna et al 2012).

These benefits result from removing attenuation of the primary beam as well as removing scatter radiation originating from the flattening filter (FF). Reduction of the head scatter improves dosimetry of the FFF beams resulting in reduced variation of all field size dependent parameters (Ponisch et al 2006, Zhu et al 2006, Kragl et al 2009, Dalaryd et al 2010).

Lower value of leaf transmission as well as less transmission variation off-axis was reported (Hrbacek et al 2011). It has also been reported that FFF beams will be easier to model in treatment planning algorithms potentially resulting in increased accuracy of the dose calculations (Cashmore 2008, Georg et al 2011, Kragl et al 2011, Cashmore et al 2012) or improved calculation speed.

In addition, FFF beams demonstrated far less dosimetric sensitivity to variations in the beam steering (Cashmore 2008). In experiments, reported by Cashmore, artificially introduced steering currents did not change the shape of the beam but only slightly shifted the beam position, while in traditional FF beams the same changes resulted in considerable asymmetry of the delivered dose.

Treatment planning studies have been reported using FFF beams to treat various treatment sites such as the prostate (Vassiliev et al 2007, Zwahlen et al 2012), lung (Stevens et al 2011, Navarria et al 2012, Verbakel et al 2012), breast (Stevens et al 2011, Thomas et al 2012, Xie et al 2012), larynx (Stevens et al 2011), head-and-neck (Abacioglu et al 2012, Wu et al 2012), pancreas (Atwood et al 2011), liver (Arcangeli et al 2012), brain (Kim et al 2012, Thomas et al 2012), spine (Thomas et al 2012, Verbakel et al 2012), esophagus (Nicolini et al 2012), and cervix (Thomas et al 2012). Most often FFF beams were used with stereotactic body radiotherapy technique, though use of these beams with IMRT and VMAT have also been evaluated. These studies report that for smaller volumes FFF beams provided adequate PTV coverage combined with increased treatment efficiency.

However, considerable limitations associated with clinical use of FFF beams have also been reported. It proved increasingly difficult to obtain adequate coverage of larger volumes with FFF beams, and such plans were generally under dosing peripheral regions of larger lung and breast PTVs (Stevens et al 2011). Use of FFF fields also resulted in increased MUs for IMRT and VMAT plans (Duan et al 2011, Zhang et al 2011, Almberg et al 2012, Cashmore et al 2012). This is because medium and large un-flattened fields require extra modulation in order to achieve required dose uniformity. Simple conformal plans, if re-planned for FFF beams, would require use of IMRT techniques resulting in higher MUs and also necessitating extra work load associated with these techniques in clinical setting.

These limitations of FFF beams inspired investigations into improving their flatness. Chofor et al (2011) proposed a ‘direction-selective filter’ (DSF) to partly compensate for shortcomings of existing FFF. As a matter of fact the ‘DSF’ is a re-designed flattening filter that has been moved up to the level of target assembly. The DSF allowed achieving flatness for the fields with diagonal size not exceeding 15 cm in any direction, which includes fields such as $10 \times 10 \text{ cm}^2$, $4 \times 14.5 \text{ cm}^2$ or less.

Tsiamas et al studied the effect of electron angular spread on the dose profile flatness (Tsiamas et al 2011). They performed Monte Carlo (MC) simulations where angular spread
of the electrons incident on the target was set to 5° and 10°. This resulted in improved beam flatness and flattening of the photon beam for the field sizes between 10 × 10 cm² and 15 × 15 cm² and partial flattening for field sizes from 15 × 15 cm² to 30 × 30 cm².

This paper aims to determine the optimal angular distribution of incident electrons that would produce as flat dose distribution as possible without the use of FF. It investigates improvement of beam flatness as well as dose rates (DRs) that could be achieved from such incident electrons and also evaluates the basic dosimetry of achieved beams.

Materials and methods

Terminology

The following terminology will be used through the paper: flattening filter free (FFF) beam; beams with a flattening filter present will be referred to as flattening filter (FF) beams; relative dose rate (RDR) refers to the dose rate at the beam’s central axis, the DR relative to FF beam will be referred to as RDRFF, the DR relative to FFF beam will be referred to as RDRFFF; flat FFF will be used interchangeably with F4 beam; the ‘convergence angle’ of the incident electron beam is defined in figure 2 as angle θ; the angular distribution of incident electrons will imply the distribution of convergence angles as azimuthal symmetry of the beam is assumed.

Monte Carlo modeling

For MC modeling of radiation transport through a linac head into water BEAMnrc/DOSXYZnrc package (Rogers et al 2009) was used within the Vancouver Island MC system (Zavgorodni et al 2007, Bush et al 2008) environment. DOSXYZnrc code used BEAMnrc as a shared library particle source utilizing directional bremsstrahlung splitting (Kawrakow et al 2004) for improved efficiency. Our model of a standard 21EX linac head (schematically shown in figure 1(a)) has been well benchmarked previously (Zavgorodni et al 2005, Gagné and Zavgorodni, 2007, Bush et al 2009, 2011, Basran et al 2010). For this project

Figure 1. Diagram demonstrating geometries of (a) standard 6 MV beam with FF beam, (b) geometry of FFF model used in this paper, and (c) geometry of FFF beam combined with convergent electron beam incident on the target.
Figure 2. Electron beams incident on a target within small solid angles with different convergence angles \( \theta_i \). Two out of the modeled twenty one solid angles are shown.

Modifications to the shielding geometry (not shown in figure 1) have been added to the model to improve agreement of measured and calculated dose profiles for \( 40 \times 40 \) cm\(^2\) fields along diagonal directions. This model will be called the FF model further in this paper.

In order to produce a MC model with a FFF beam, the FF has been removed from the FF linac model while all other model components remained intact. MC simulations were then performed with (1) the FFF model using electrons with the same 6 MeV beam parameters as in the FF model and, (2) convergent 6 MeV electron beams (figure 1). Figure 1(b) represents (FFF) beam while figure 1(c) shows the FFF model with convergent beam of incident electrons. It is expected that, unlike FF beams, radial spread of the incident electron beams will not be an important factor in forming the shape of the dose profile (Cashmore 2008). In this paper all electrons were converging into a circle of 1 mm radius on the target.

The dose distributions were calculated in a \( 60 \times 60 \times 40 \) cm\(^3\) water phantom with voxel sizes variable in all directions from 0.2 to 1 cm with smaller dimensions being along the regions with expected steep dose gradients such as build up region and beam penumbra. The source to surface distance (SSD) of 100 cm was used in the calculations and dose uncertainty of less than 0.5% was achieved for in-field voxels at \( d_{\text{max}} \).

Angular distribution of electrons, incident on the target, to produce flat FFF beam

In order to determine optimal the angular distribution of electrons to produce a flat diagonal dose profile for \( 40 \times 40 \) cm\(^2\) field in the geometry of figure 1(c), we modeled a set of dose distributions generated by convergent electron beams with different angles of convergence \( \theta_i \) (figure 2). For every angle of convergence \( \theta_i \) the electrons entered the target within a narrow (1\(^\circ\)) solid angle. Twenty one angles of convergence \( \theta_i \) in the range from 0\(^\circ\) to 20\(^\circ\) were used providing 21 dose distributions. Diagonal profiles \( D_i(r) \), normalized at the central axis, as well as the dose per incident electron at the central axis \( D_i(r_0) \) (Gy/e\(^{-}\)) were extracted from these dose distributions and stored to be used by optimization algorithm.

A simulated annealing optimization algorithm was then employed to optimize weights \( w_i \) of the scored dose distributions to receive as flat profile \( D_{\text{opt}}(r) \) as possible while maintaining highest possible dose per incident electron. The optimal angular distribution of the incident convergent electrons then corresponds to the distribution of optimized weights \( w_i \). Given that we are aiming for a perfectly flat dose profile, which implies relative dose off-axis being a unit, the objective function to be minimized becomes

\[
F_{\text{obj}} = \sum_{i=1}^{N} w_i \sum_{j=1}^{M} (1 - D(r_j))^2.
\]
where $N$ is the number of convergence angles and $M$ is the number of radial dose profile points used in optimization. An optimization constraint was applied for the $\text{RDR}_{\text{FF}}$ to be set greater than required minimum $\text{RDR}_\text{min}$.

These optimizations were repeated for a set of $\text{RDR}_\text{min}$ values in the range between $\text{RDR}_{\text{FF}}$ and $\text{RDR}_\text{FFF}$. For each $\text{RDR}_\text{min}$ value the radius of 90% dose level within $D_{\text{opt}}(r)$ was found and used to quantify the size of flat area of the dose distribution. This value of the dose level was chosen as an indication of the field size that would provide $\pm 5\%$ dose uniformity in the high dose region.

Similar approach has been previously used by our group in order to optimize the shape of electron profiles (Bush et al 2009) that provided the best match of modeled and measured dose distributions in water.

**Comparing characteristics of F4 beams to those of FF and FFF beams**

Using the optimal angular distribution of electrons on the target, that provided the flattest diagonal profile for $40 \times 40$ cm$^2$ field, the dose distributions in water were calculated for $4 \times 4$, $10 \times 10$, $20 \times 20$ and $40 \times 40$ cm$^2$ fields, and transverse profiles as well as percentage depth doses (PDDs) were extracted for comparison with profiles from the standard FF beam.

**Results**

**Validation of MC model**

Figure 3 shows measured and MC calculated diagonal dose profiles for 6 MV $40 \times 40$ cm$^2$ field. Un-smoothed measured data were used deliberately to demonstrate that
Figure 4. PDD from a 40 × 40 cm² field calculated for conventional FF, FFF and F4 beams. A measured PDD from 21EX Varian linac is also shown. All PDDs were normalized at the depth of 10 cm.

The agreement of calculated profiles with measurement is within combined measurement and statistical uncertainties. This figure also demonstrates very close agreement of measured and modeled beam penumbras beyond 25 cm off-axis. Good agreement in this region confirms accurate modeling of the beam shielding structures. Note that large field profiles are notoriously difficult to match to experimental data (Chibani et al 2011). Diagonal profiles of 40 × 40 cm² are the largest possible profiles capturing a considerably larger fraction of the particle fluence than any other measurable profile. These profiles are not commonly shown in MC model validation results potentially due to increasing difficulty of obtaining satisfactory agreement with measured data for such large fields. This figure provides a very solid validation of our MC model for the 21EX linac that was used as a basis for FFF and F4 modeling in this paper. Also shown in this figure are profiles for FFF and flattest achieved (F4) beams.

Figure 4 shows the PDD for 40 × 40 cm² field from conventional FF beam as compared to the measured PDD as well as PDDs of FFF and F4 beams. This figure again shows very close agreement with measurement of modeled FF beam PDD that is known to be difficult to model for this large field.

These results confirm validity of our 21EX model. Figure 4 also demonstrates that PDDs for FFF and F4 fields are very similar (F4 is slightly harder) and both less penetrating than standard FF beam.

Optimal angular distribution of electrons, incident on the target, to produce F4 beam

Seven out of twenty one calculated diagonal profiles that were used in optimization of the angular distribution of incident electrons are shown in figure 5. This figure shows that as convergence angle \( \theta \) increases, the dose profile flattens but the flattening saturates once the convergence angle reaches 15°. Expectedly, the DR at the central axis also drops (figure 6) with an increase of convergence angle because the beam energy gets re-distributed into a wider phantom area. An increasingly higher fraction of the beam energy is also getting absorbed in the primary collimator as the bremsstrahlung lobe diverges from the central axis.

With flatness improving as convergence angle increases, it is expected that higher convergence angles provide flatter dose. However, with the DR being an optimization
constraint and dropping with increase of convergence angle, the algorithm is searching for a combination of angles that provides the flattest summary profile while maintaining the required DR. Therefore some forward directed component of the electron beam can be expected to maintain the DR. Optimization results show that when the DR over about 1.5 times of $R_{DR_{FF}}$, was requested, the angular distribution contained a forward (zero angle) component as well as oblique convergence angles. However, if lower DR was used as optimization constraint, a narrow distribution of oblique angles provided optimal solution. Solution space was found to be rather broad with multiple distributions providing similar profiles. In fact only oblique angles, with no forward component, provided near-optimal distributions as well. Optimized angular electron distributions for a set of five $R_{DR_{min}}$ values are shown in figure 7.

The radii of 90% dose level in the optimized dose profiles $D_{opt}(r)$ are shown in figure 8. As expected, these radii reduce with increase of achievable DR. However the plot shows that the field size as large as 44 cm in diameter is potentially achievable with the DR 25% higher than that of FF linac. The field of 24 cm diameter that covers majority of the modern conformal field sizes could potentially be achieved with the DR that is 80% higher than that of FF fields. Larger fields, apart from increased DRs, would still have the benefits associated with the absence of FF in these beams.
Characteristics of F4 beams as compared to FF and FFF beams

Figure 9 shows diagonal profiles at the depth of maximum dose ($d_{\text{max}}$) as well as the depth of 10 cm modeled for FF, FFF and F4 beams. These profiles are normalized at the beam central axis and demonstrate that convergent electrons greatly improved flatness of the FFF beam. For example, for profiles calculated at 20 cm off-axis the dose increased from 52% for FFF beam to 92% for F4. At 15 cm off-axis the dose increased from 62% to 96%. In fact, at $d_{\text{max}}$ for the area within the radius of 18 cm, the F4 beam is actually flatter than the FF beam.

Figure 9 also shows diagonal profiles for these beams at the depth of 10 cm. This figure demonstrates that profiles of F4 and FFF beams do not change considerably with depth, unlike profiles of conventional FF beams. This has been previously reported for FFF beams (Titt et al. 2006a, Vassiliev et al. 2006b, Kragl et al. 2009), and is expected, as very little off-axis photon spectral variation exists in these beams (Dalaryd et al. 2010).

Also, compared to the FF beam, the out-of-field dose (figure 10) was reduced for the F4 beam as it was for the FFF beam. This dose reduction has been previously reported for FFF beams (Kry et al. 2010, Almberg et al. 2012, Cashmore et al. 2012) and figure 10 confirms this for F4 beams. The magnitude of this reduction varies with the distance from the edge of the field as seen in this figure. It also varies with field size and, for the 20 × 20 cm$^2$ field, off-axis the dose from F4 actually exceeded that of the FF beam (see figure 13 below). Detailed investigation of off-axis dose for F4 fields is a subject of future investigation.
Figure 9. Diagonal dose profiles in water calculated using our MC model of 21EX linac for an open 40 × 40 cm² 6 MV FF beam, open 40 × 40 cm² 6 MV FFF beam, an open 40 × 40 cm² 6 MV FFF beam and a convergent electron beam incident on the target (F4 beam). The profiles were calculated for the water phantom positioned at 100 cm SSD and taken at the depth of \(d_{\text{max}}\) (1.5 cm) as well as 10 cm.

Figure 10. Off-axis fractions of 40 × 40 cm² diagonal profiles demonstrate out-of-field dose for FFF and F4 beams as compared to FF beam from 21 EX model.

Figures 11–13 show the dose profiles calculated at the depths of \(d_{\text{max}}\) as well as 10 cm for 4 × 4, 10 × 10 and 20 × 20 cm² fields of FF and F4 beams. For the small fields of 4 × 4 cm² there is no considerable difference between FF and F4 profiles. For 10 × 10 cm² fields F4 profiles at both depths are similar to FF profiles at 10 cm depth and would probably perform as well in clinical, including IMRT, situations. For 20 × 20 cm² fields F4 profiles are \(\sim 2-3\%\) lower than FF profile at 10 cm depth but still rather flat and are most likely to be acceptable for IMRT and VMAT treatments.


**Figure 11.** 6 MV, 4 × 4 cm² dose profiles at d\(_{\text{max}}\) as well as the depth of 10 cm (d\(_{10}\)) calculated for conventional FF and F4 beams. All profiles are normalized at CAX.

**Table 1.** PDD data for 6 MV FF and FF beams of different field sizes at 10 and 20 cm depth.

| Field size (cm²) | 10 cm depth (d\(_{10}\)) | 20 cm depth (d\(_{20}\)) |
|-----------------|--------------------------|--------------------------|
|                 | 4 × 4                    | 10 × 10                  |
|                 | 20 × 20                  | 40 × 40                  |
| FF              | 62.0                     | 66.7                     |
|                 | 20 × 20                  | 40 × 40                  |
| F4              | 54.3                     | 59.5                     |
|                 | 66.0                     | 66.0                     |
|                 | 4 × 4                    | 10 × 10                  |
|                 | 33.8                     | 38.7                     |
|                 | 40 × 40                  | 40 × 40                  |

Finally, figure 14 and table 1 show depth dose data calculated for FF and F4 6 MV beams with field sizes ranging from 4 × 4 to 40 × 40 cm². All F4 PDDs are less penetrating compared to PDDs from the conventional FF beam. As in the case of FFF beams, this is indeed due to lack of beam hardening in the FF. Similar to FFF, F4 beams also produce steeper build-up and higher surface dose, as expected from the softer beams.

**Discussion**

This paper, using MC calculations combined with simulated annealing optimization, evaluated angular distributions of incident electrons that are capable of providing flat dose profiles, from a FFF accelerator. No specifics of actual production of such electron distributions have been investigated. The beam collimation system of Varian 21EX linac was used in this study for the sake of simplicity; however different linac model and beam energies would produce qualitatively similar results. This study shows that it is possible to achieve the dose profile at d\(_{\text{max}}\) that is about as flat as the profile of conventional FF beam (though the dose off-axis is reduced rather than increased as it is for a FF beam), and the flatness is not much reduced at the depth of 10 cm. Further dosimetry improvements would likely be achieved if the target thickness/composition and beam collimation system were tailored to optimize F4 beam performance.

Although all data in this study have been produced using convergent electrons incident on the target, divergent beams have also been modeled. Divergent beams have been modeled by simply moving the beam convergence point a few millimeters above the target. As electrons cross over the convergence point in air, a divergent beam enters the target. Characteristics of
such beam were very similar (though profiles slightly less flat) to those presented in this paper and therefore are not shown.

Electron beams, modeled in this paper, provided flatter fields than those achievable from de-focusing of the electrons incident on the target (Tsiamas et al 2011). The dose profiles shown by Tsiamas et al (only profiles for $20 \times 20$ cm$^2$ field size are shown, see figure 4, (Tsiamas et al 2011)) indicate that for $20 \times 20$ cm$^2$ field the flattest profile which was produced by a 14° electron beam angular spread resulted in $\sim92\%$ dose at 8.5 cm off-axis. Our $20 \times 20$ cm$^2$ profile (figure 9) provided 95% of the CAX dose demonstrating more efficient flattening capabilities of the beams modeled in this study. Our study also shows the feasibility of achieving $\pm 5\%$ flat dose profiles within 22 cm off-axis from $40 \times 40$ cm$^2$ FFF fields.

Figure 10 shows that $40 \times 40$ cm$^2$ F4 beam considerably reduced scattered radiation from the treatment head compared to FF, a phenomenon which has been previously reported
for FFF beams. In general, the properties of F4 beams such as softer x-ray spectra with less penetrating PDDs, reduced leakage and scattered radiation are very similar to those of FFF beams. This is expected, as geometries of these beams are very similar, indeed. In addition, similarly to that of FFF beams, F4 beams have near no spectral variability of the beam off-axis which reduces variation in field-size dependent dosimetric parameters. This should simplify modeling of such beams within treatment planning systems resulting in more accurate dose calculations.

As the convergence angle of the incident electron beam increases, an increasingly larger fraction of the forward-peaked bremsstrahlung lobe hits the primary collimator and gets absorbed, resulting in reduced DR. The size of flat area of the beam therefore becomes a function of the maximum achievable DR (figure 8), and it is foreseeable to utilize this effect and use different angular distributions of the incident electrons at different field size settings to maintain the flat dose while producing the highest achievable DRs.

Flat dose distributions have been previously achieved with a racetrack accelerator that had no FF through the use of scanning magnets as was proposed by Brahme et al (1980). The authors of this and subsequent papers on racetrack MM50 (Karlsson et al 1993, Satherberg and Karlsson 1998) discussed scan patterns that produce uniform dose from 50 MeV incident electrons. In fact their pattern qualitatively resembles the optimal angular distributions derived in this paper. Similar to our forward and oblique components of the incident electron distribution (figure 7), their scanning pattern also had central component as well as a peripheral circular pattern (figure 2 in Karlsson et al (1993)). However, flat dose distributions were only achievable from MM50 when using high energy electrons. At the energies of 10 MV and for small fields at 20 MV, a cone-shaped graphite absorber was used to provide extra beam flattening as well as absorption of primary electrons.

This paper therefore presents the first study investigating extent of potential capabilities of low (6 MeV) energy electron beams in achieving flat dose profiles from FFF beams. In order to produce F4 beams, investigated in this paper through the beam scanning technology, the electrons incident on the target would have to be scanned dynamically in a sweeping...
motion providing azimuthally uniform electron fluence. For applications with sliding window IMRT treatments the frequency of this scanning would have to be high enough to maintain the cone of electrons for any dosimetrically significant motion of MLCs. Alternative methods for achieving convergent electron beams could be applied similar to technologies used in high current electron accelerators. It remains to be seen which of these technologies might find its way to clinical practice.

Dosimetric properties of F4 compared to FF beams would be most beneficial for treatments that require large fields such as head-and-neck IMRT and VMAT. F4 beams could also be used in conformal treatments. They provide higher efficiency with similar target coverage as FF beams and would not require as high number of monitor units for these treatments as FFF beams do. Compared to FF beam, lower leakage, scatter and out-of-field dose would also be expected.

One of the disadvantages of F4 as compared to FF beams is reduced penetration and increased surface dose (see figures 4, 14 and table 1). However it is likely to be possible to match 6 MV beam penetration by increasing the energy of F4 incident electrons as it was reported for FFF beams (Almberg et al. 2012, Huang et al. 2012). These reports achieved very similar PDDs to those from FF beams while the DR further increased. Detailed investigation of these beam modifications will be performed in our future study.

Conclusions

This preliminary research has shown potential for achieving F4 beams. Dosimetry of such beams has been evaluated. These beams are shown to combine dosimetric advantages of FF and FFF beams potentially offering more efficient treatments with less scatter, less leakage radiation and less monitor units required to deliver the dose.

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