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Monte Carlo study of a free flattening filter to increase surface dose on 12 MV photon beam

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ABSTRACT

Background: Several investigations reported the dosimetric properties of flattening filter free photon beams to enhance the entrance dose in the surface and build up region. This paper was aimed to investigate the effect of the flattening filter free to enhance the dose at the surface and buildup region. ***Materials and Methods:*** A 12 MV photon beam of a linear accelerator was modeled and developed in both flattening filter and flattening filter free modes using the Monte Carlo BEAMnrc code. For both modes, the beam dosimetric features, including central axis absorbed doses and photon energy spectra were investigated. ***Results:*** A remarkable increase in the dose rate on the surface and build up region were attained with the flattening filter free mode. At the depth of 0 mm on 2×2 cm^2, 4×4 cm^2, 5 × 5 cm^2, and 10×10 cm^2 field sizes, the surface doses between flattening filter mode and flattening filter free mode were augmented from 27.33% to 33.78%, from 28.89% to 35.75%, from 29.44% to 36.39%, and finally from 35.10% to 47.46%, respectively. At the depth of 25 mm for field size from 2×2 cm^2 to 10×10 cm^2, the buildup doses for flattening filter mode and flattening filter free mode were augmented from 124.89% to 136.72% and from 132.21% to 142.67%, respectively. ***Conclusion:*** A significant increase in the entrance and buildup dose rate was observed when using an unflattened photon beam, which can be a benefit for the treatment of some skin cancers.

***Keywords**: Monte Carlo, surface dose, linac, flattening filter free.*

INTRODUCTION

After the discovery of X-rays by Wilhelm Conrad Roentgen in 1895, the X-rays has been used in the diagnostic and treatment of the cancer (1). Currently, external radiation therapy is most usually carried out by linear accelerators (linac) for high energy X-rays. This external radiation therapy is used in treatment of various skin cancers; cancers of the mouth, nasal cavity, pharynx, larynx, brain tumours, leukaemia, breast, prostate, and lung cancers (1). Unfortunately, This X-ray can also cause some sides effects as heart, pulmonary and skin toxicity (2-4). For skin reactions induced by particles charged, such as erythema and fibrosis, the depths between 0.1 and 2 mm have been considered to be most relevant (5-6). In external radiotherapy (RT), the accumulated dose in the surface area is coming from different radiations as; primaries photons; backscattered and scattered radiations (electrons contaminations and photons induced in collimator, flattening filter, and air). Further, the angle of beam incidence, field size, source surface distance (SSD), and beam energy can influence this accumulated skin dose. As a result of this factors, a deviation of 15% has been registered between calculated and measured surface dose (7-8). Accurate and precise measurement of the dose at the surface and the buildup region for photon beams isn't an easy operation, but an important task owing to its effects in some clinical case in skin dose. The size of the dosimeter along the beam direction should be as small as possible to obtain accurate measurements. Several studies were realized for this purpose to measure accurately the absorbed dose at the surface and build up region by using small dosimeter; the parallel plane chambers, diodes; optically stimulated luminescence (OSL) [9]; radiochromic films [10]; and a metal oxide field effect transistor (MOSFET) detector.

In the last years, the unflattened beams have become an emerging technology in RT for the vendors. These vendors should do an important works by amelioration dedicated treatment units with the flattening filter-free (FFF) mode in the future linacs generation. There has been an increasing interest in the use of FFF photon beams in the field of RT. When the flattening filter (FF) is removed from the head's linac, photon production should be far more efficient and dose rate should increase substantially at the entrance of treatment patient, which is especially advantageous for high-dose-per fraction delivery techniques such as stereotactic radiosurgery (SRS) and stereotactic body radiation therapy (SBRT) [11]. It has also been reported with a study by Kry *et al.* [4],that operating an FFF linac generally has a reduced neutron production [12]. Many research groups have predicted on commercially available modern accelerators that the skin dose with FFF beams contain more low-energy components and have softer energy spectra than the corresponding flattened beams which can lead to increased surface dose. Furthermore, there is evidence that the use of FFF beams lead to a shorter treatment delivery time which can have clinical significance [13-14]. In addition, the absence of the FF can decrease the out-of-field doses to the patient which leading to the possibility of inducing secondary cancer [15]. However, one of the disadvantages of using FFF beams in breast RT is the higher degree of modulation needed when uniform dose distribution is required, that requiring more monitor units (MUs) to achieve the uniform dose distribution [13-14].

The dose in the buildup region was defined like the dose region between the surface of the water phantom or the patient (depth z = 0 cm) and the maximum depth dose ($z = z_{max}$) in external megavoltage photon beams.

Contamination electrons are produced by Compton scatter in the accelerator components or in air and contribute to increase the surface dose [16]. Typical values of surface dose for a 10 × 10 cm^2 field are: 100% superficial and orthovoltage; 30% cobalt-60 gamma rays; 15% 6 MV X-ray beams; 10% 18 MV X-ray beams [1]. The surface dose or skin dose, as a part of patient quality assurance in external beam radiation therapy, is still clinically important because a basic knowledge of the build-up effect, can facilitate the delivery of an accurate dose to superficial target volumes. The Monte Carlo (MC) techniques are often applied to superficial dose analysis [13]. MC simulations are the most techniques to determine precisely the superficial dose deposited in tissue based on the actual algorithm for the transport radiation physics.

In this study, our goal was to quantify and investigate in detail the increasing absorbed dose in the buildup and surface region and photon fluence with a FFF mode by investigating depths measurement positions for 2×2, 4×4, 5×5, and 10×10 cm^2 squares field sizes on a Saturne 43 linear accelerator 12 MV (CEA, LNHB, France) using BEAMnrc MC code.

MATERIALS AND METHODS

The experimental dosimetry data was provided by the laboratory LNHB (National Laboratory Henery Becquerel, CEA, France). These Dosimetric data included the percentage depth dose was measured in a cubic water tank with the x, y, and z dimension 40 × 40 x 40 cm^3 by means of a cylindrical ionization chamber PTW-3100. The tank is placed so that: its front face is at a distance of 90 cm from the tungsten target; and the generation of a field size of 10 x 10 cm^2 was considered in 100 cm from the target [17-18]. Water is recommended by the IAEA as the reference medium for dosimetry in radiotherapy because the human tissues are made up of more than 80% of water [17-18].

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Monte Carlo modeling of a 12 MV linac

The model constructed of a head's linac is not an easy work due to its complexity of the geometry and material. That required a necessity of a precise modeling to obtain a discrepancy dose calculation between MC and experimental results in the gamma index method within 1.5% /1.5mm.

We used the BEAMnrc [19] MC code to create and score the phase space distributions produced by the pair jaws for both FF and FFF modes on different square fields sizes. At the first step of this work, we modeled the head's linac geometry of Saturne 43 on FF mode accordingly to the manufacturer's detail as shown in the figure 1, and on FFF mode (removing the FF component from the head's linac). In second step of this simulation, we utilized the DOSXYZnrc [20] MC code to compute the surface dose and build-up dose distribution on a water phantom using the phase space file (PSF) scored by BEAMnrc MC code at z = 50 cm for both FF and FFF modes. Our water phantom was modeled under the treatment head at the SSD of 90 cm with a dimension of 40 × 40 × 40 cm^3 in x, y and z direction, respectively. The jaws were modified to create various fields' sizes: 10×10 cm^2, 5×5 cm^2, 4×4 cm^2, and 2×2 cm^2 at 10 cm depth inside the cubic water phantom. The voxels dimensions of the cubic water phantom modeled with the DOSXYZnrc MC code were 1×1×0.1 cm^3 for depth dose calculation. The parameters simulation used on BEAMnrc and DOSXYZnrc MC user codes for photon and electron low-energy cutoffs were 0.01 MV and 0.521 MeV, respectively.

The photon energy spectra was obtained by using the BEAMDP (BEAM Data Processor) [21] user code analyzing the scored PSF generated by the BEAMnrc user code at the depth z=50 cm below the pair jaws for the fields sizes from 2×2 to 10×10 cm^2 on both FF and FFF modes using a 100 energy bins. The graphs were plotted using the QT-GRACE software.

The initials histories used in the BEAMnrc simulations were: 3×10^9 particles for 10×10 cm^2, 1×10^9 particles for 5×5 cm^2, 1×10^9 particles for 4×4 cm^2, and 1×10^9 particles for 2×2 cm^2. All the simulations used for both FF and FFF modes were run on a desktop core i7 CPU with 8 GHz RAM on Ubuntu 14.04 system.

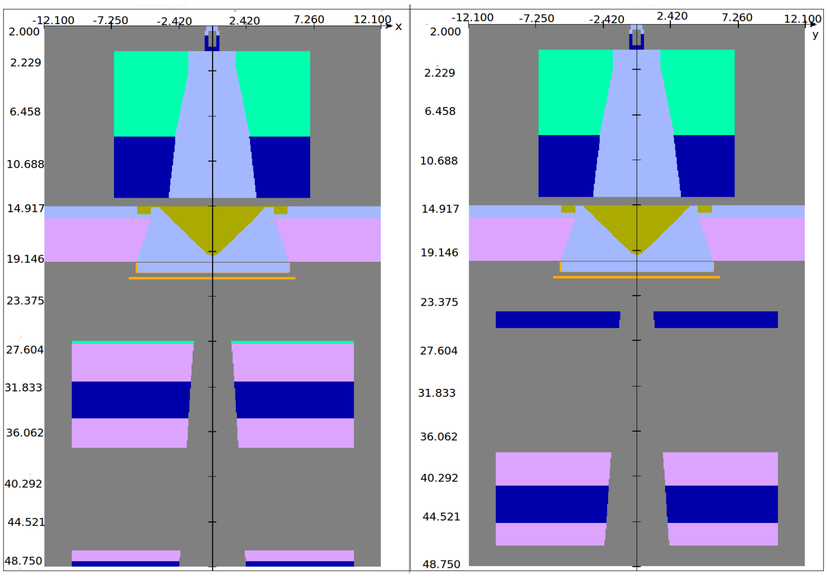

Figure 1. The two-dimensional XZ and YZ section of the head Saturne 43 modelling by BEAMnrc.

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Surface dose ratios

Absolute surface dosimetry is difficult to measure; therefore, relative surface dose measurements were made by normalizing surface dose values to those at the depth of 10 cm for each field size from 2×2 cm^2 to 10×10 cm^2 (i.e., D_{surf} / D_{d10}) and will herein be referred to simply as relative surface dose. We choose the depth of 10 cm as depth of normalization of surface dose rather than depth of dose maximum (d_{max}) because the depth 10 cm, is closer to the clinically meaningful prescription point. We calculated the ratio of surface doses as: $(D_{surf}$ / $D_{d10})_{FFF}$ / $(D_{surf}/D_{d10})_{FF}$, enabling investigation into the effects of field size on FF and FFF modes [22].

RESULTS

All the statistical uncertainty in our MC results was less than 1% (calculated by DOSXYZnrc MC user code). The surface and build-up dose was increased with the field size for both the FF and FFF modes within the buildup region. We were only interested in the relative dose in the buildup region to compare the difference between FFF and FF modes, where all the radiation measurements were normalized to a standard 10×10 cm^2 at the depth 10 cm. Absolute surface dosimetry is difficult, relative surface dose measurements were made by normalizing D_{surf} (surface dose) to those at D_{d10} (dose at depth z=10 cm) for each field size (i.e., D_{surf} / D_{d10}) and will herein be referred to simply as relative surface dose.

Figure 2 shows a comparison of MC calculated and experimental PDD for FF mode on a water phantom with the field size of 10×10 cm^2 for 12 MV beam. A good agreement was obtained between MC calculated and experimental PDD and the gamma index was 1.5% / 1.5mm.

Table 1 shows the results of PDDs (%) at 0 mm depth (normalized to the dose absorbed locally at 10 cm depth) for 12 MV beam linac on different filed sizes. It could be showed that, the relative surface dose D_{surf} / D_{d10} were: 27.33%, 28.89%, 29.44%, and 35.10% for 2×2, 4×4, 5×5, and 10×10 cm^2 with FF mode, respectively. For FFF mode, the relative surface dose D_{surf} / D_{d10} were: 33.78%, 35.75%, 36.39%, and 47.46% on 2×2, 4×4, 5×5, and 10×10 cm^2, respectively.

Table 2 shows the PDD (%) at 5 mm depth (normalized to the dose absorbed locally at 10 cm depth) for 12 MV FF and FFF modes with different field size. The results were indicated that 97.27, 96.37, 96.04, and 94.57 on 10×10, 5×5, 4×4, and 2×2 cm^2 with FF mode, respectively. For FFF mode, the results were 112.74, 97.47, 97.34, and 97.27 on 10×10, 5×5, 4×4, and 2×2 cm^2, respectively.

Table 3 shows the PDD (%) at 25 mm depth (normalized to the dose absorbed locally at 10 cm depth) for 12 MV beam linac. These results were demonstrated that, D_{surf} / D_{d10} were: 136.72%, 126.32%, 125.77%, and 124.89% on 10×10, 5×5, 4×4, and 2×2 cm^2 field sizes with FF mode, respectively. When the FFF mode was used, the results were 142.67%, 132.62%, 132.38%, and 132.21% on 1× 10, 5×5, 4×4, and 2×2 cm^2 with FF mode, respectively.

Figure 3 shows a comparison of MC calculated PDD in build-up and surface region for FF and FFF mode on a water phantom with the field size of 10×10 cm^2 for 12 MV beam.

Figure 4 shows a comparison of MC calculated PDD in build and surface region for FF mode and FFF mode on a water phantom with the field size of 10×10 cm^2, 5×5 cm^2, 4×4 cm^2, and 2×2 cm^2 for 12 MV beam.

Figures 5 and 6 show photon energy spectra for FF and FFF modes below the bottom jaws of Saturne 43 head's linac with the field size of 10×10 cm^2, and 2×2 cm^2, respectively.

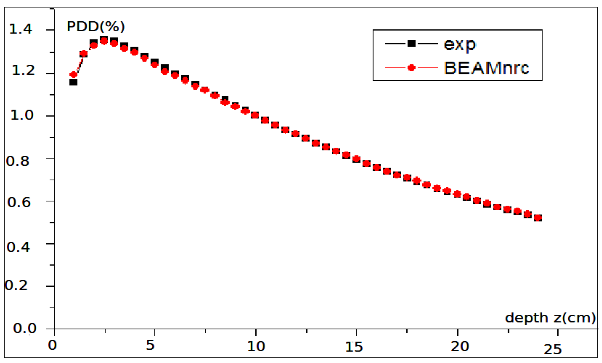

Figure 2. BEAMnrc and experimental PDD curve in the water phantom for 10×10 cm2 field size for 12 MV beam.

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Table 1. PDDs for the centrally positioned fields at 0 mm depth (normalized to the dose absorbed locally at 10 cm depth) for 12 MV beam linac.

	Central PDD (%) at 0 mm			
Field (cm^2)	FF	uncertainty	FFF	uncertainty
10 × 10	35.10	0.8 %	47.46	0.9 %
5 × 5	29.44	0.3 %	36.39	0.7 %
4 × 4	28.89	0.3 %	35.75	0.7 %
2 × 2	27.33	0.2 %	33.78	0.4 %

Table 2. PDDs for the centrally positioned fields at 5 mm depth (normalized to the dose absorbed locally at 10 cm depth) for 12 MV beam linac.

	Central PDD (%) at 5 mm			
Field (cm^2)	FF	uncertainty	FFF	uncertainty
10 × 10	97.27	0.5 %	112.74	0.5 %
5 × 5	96.37	0.2 %	97.47	0.5 %
4 × 4	96.04	0.2 %	97.34	0.6 %
2 × 2	94.27	0.2 %	97.27	0.3 %

Table 3. PDDs for the centrally positioned fields at 25 mm depth (normalized to the dose absorbed locally at 10 cm depth) for 12 MV beam linac.

	Central PDD (%) at 25 mm			
Field(cm^2)	FF	uncertainty	FFF	Uncertainty
10 × 10	136.72	0.4 %	142.67	0.3 %
5 × 5	126.32	0.2 %	132.62	0.4 %
4 × 4	125.77	0.2 %	132.38	0.5 %
2 × 2	124.89	0.2 %	132.21	0.3 %

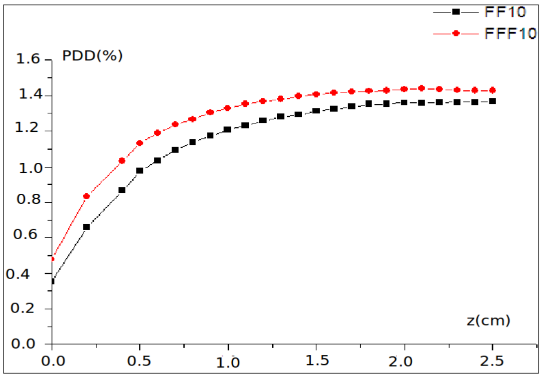

Figure 3. Comparison between MC PDD curve for FF and FFF modes in the buildup region for 12 MV beam with a 10 × 10 cm^2 field size.

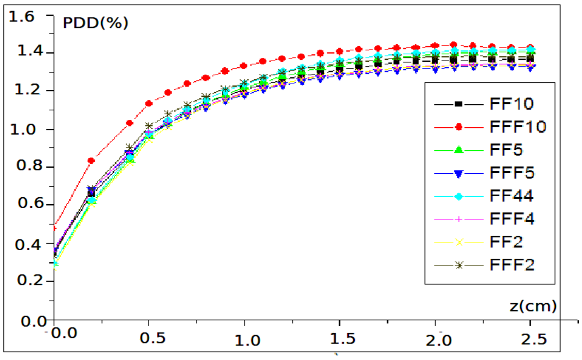

Figure 4. Comparison between MC PDD curve for FF and FFF modes in the buildup region on 10 × 10, 5 × 5, 4 × 4, and 2 × 2 cm^2 fields sizes for a 12 MV beams.

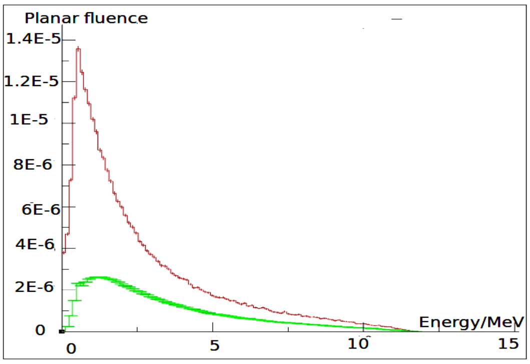

Figure 5. Photon fluence spectra; red line-FFF mode, and Green line-FF mode on 10 × 10 cm^2.

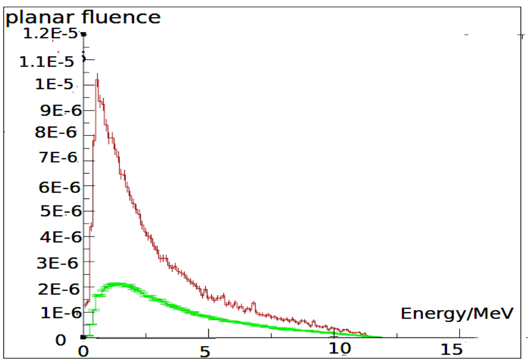

Figure 6. Photon fluence spectra; red line-FFF mode; Green line-FF mode on 2 × 2 cm^2.

DISCUSSION

In practice, increasing field size is a well-known effect of the increase in surface dose [9-10]. This augmentation was contributed by low photon energy and electrons contaminations from collimators, phantom surface, and treatment head [23]. Some works have interested to the tray, which generates more electrons and raising skin doses. Others studies have interested to SSD and found that using shorter SSD, had a significant rise in surface dose. Gursoy *et al*. have been interested to study the effect of carbon fibre tabletop in surface dose and found that, the surface dose was increased from 12.87% on 10×10 cm² field to 22.27% on 20×20 cm² filed for 6 MV and from 8.72% on 10×10 cm² field to 18.73% on 20×20 cm² filed for 18 MV [23]. Removal of the FF has been shown many potential benefits (lower out-field dose, reducing in leakage radiation from linac head's, short on-beam treatment time, and increased fraction surface dose) over conventionally filtered beams for the delivery of treatments techniques such as SRT, SBRT, VMAT, and IMRT [5-6,14]. Also, it has been shown with other study, which operating an FFF linac (removing FF) generally has a decrease in neutron production [12].

The fractional surface dose, which was the surface dose at a depth of 0 cm (D_{surf}) at any field size divided by the dose at the depth of 10 cm (D_{d10}) [22], was observed to be greater for the FFF mode than for the corresponding conventional FF beams.

Annemieke *et al*., and Cashmore have simulated the Elekta Precise Linac and found that the buildup and the surface dose of the FFF beam increased with the depth in solid water [24-25]. Vassiliev *et al*. [26] have reported the buildup dose measurement using the Varian Clinac 21EX at a depth of 0.3 cm of 6-MV flat and FFF X-rays, where the surface dose ratios of FFF to flat beams were 1.2 for a 4 × 4 cm² field size and 1.16 for a 10 × 10 cm² field size. Another study, using the Varian TrueBeam Linac have found that the surface dose ratios of FFF to flat beams were 1.14 and 1.10, respectively [26]. As it is obtained in table 1, our results at the depth 0 mm, were 1.23 for 2×2 cm² field size, 1.24 for 4 × 4 cm² field size, 1.24 for 5×5 cm² field size, and 1.35 for a 10×10 cm² field size on Saturne 43 linac on 12 MV. It is shown that, the ratio $(D_{surf} / D_{d10})_{FFF} / (D_{surf}/D_{d10})_{FF}$ was augmented from 1.23 for 2×2 cm² field size to 1.35 for field size 10×10 cm².

The buildup dose as shown in figure 4 for FFF mode was slightly larger than that of the FF mode for different build-up depths with the field size of 2×2 cm², 4×4 cm², 5×5 cm² and 10×10 cm². It is shown that in table 3 that, the build-up dose at depth of 25 mm was increased from 124.89 % to 136.72 % for FF mode and from 132.21 % to 142.67 % for FFF mode on field sizes 2×2 cm² and 10×10 cm², respectively.

The results in table 2 at depth of 5 mm with the different field sizes 2×2 cm², 4×4 cm², 5×5 cm² and 10×10 cm² indicated that, the buildup doses for FFF mode was augmented from 97.27% on 2×2 cm² to 112.74% on 10×10 cm², and from 94.27% on 2×2 cm² to 97.27% on 10×10 cm² for FF mode.

Our results are semblables with those of the previous published studies, which demonstrated the rising of the surface and the build-up dose for the FFF mode. Our previous obtained results established that, the surface and the build-up dose with FFF mode was higher compared with the FF mode on different field sizes.

The photon fluence spectra as shown in figures 5 and 6 for FFF mode, was slightly higher than that of the FF mode for field size of 2×2 cm², and 10×10 cm². These findings are also consistent with the known increase in the contribution of low energy photons in a FFF delivery.

CONCLUSION

A BEAMnrc MC model was successfully developed for the Saturne 43 head's linac on 12-MV photon beam with FF and FFF modes. The obtained results showed that the FFF mode may cause a substantially increased surface and build up dose. The obtained calculations showed that an increase in the ratio $(D_{surf} / D_{d10})_{FFF} / (D_{surf}/D_{d10})_{FF}$ were 1.23 for 2×2 cm² field size and 1.35

for field size 10×10 cm^2. Our study showed also that the photon fluence spectra was considerably higher for the FFF mode.

Conflicts of interest: *Declared none.*

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