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Monte Carlo study on electron contamination and output factors of small field dosimetry in 6 MV photon beam

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ABSTRACT

The purpose of this study was to investigate the characteristics of electron contamination and Output Factors (OFs) from Varian Trilogy Clinac iX 6 MV photon beam at small field sizes. EGSnrc Monte Carlo (MC) code system was used to model the photon beam for this Linear Accelerator (Linac) head and analyze the electron contamination and OFs from this treatment head. The electron contamination was analyzed for field sizes of 1×1 , 2×2 , 3×3 , 4×4 , and 5×5 cm². The number of electron contamination increases with increasing field sizes, but the maximum energy of the electron contamination stays constant (at around 1.87 MeV for each field size). The contaminants contribute to the dose at the surface of the water phantom (1–5 cm from the surface) for field size 4×4 and 5×5 cm² and this dose decreases with depth. The OFs are simulated by EGSnrc code system and have a good agreement with measurement (deviation 3.45, 1.76, and 0.86 for field of 2, 3 and 4, respectively). This study presented that MC methods have great potential to accurately predict the electron contamination and OFs for 6 MV photon beam.

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1. Introduction

Teletherapy treatment techniques such as volumetric modulated arc therapy, stereotactic radiosurgery, Gamma Knife, and Cyberknife use small field sizes to treat tumors and spare normal structures. Using small radiation fields allows the dose to be placed accurately in the target volume and to spare healthy tissue that can be within close proximity. There is an increasing demand to characterize small field dosimetry in some treatment techniques.

One of the challenges in dosimetry is how to reduce the statistical uncertainty in treatment. Accurate dosimetry within photon beam can be difficult because the radiation

particles released by the linear accelerator not only contain primary photons and secondary photons but also particle contamination (e.g. electrons and positrons). Particle contamination, especially electrons, is produced in a Linac by the interaction of a photon with the photon beam head components. This particle contamination influences the dose distribution in a target (patient or phantom).^[1,2] This effect is not negligible in the phantom surface and becomes a major contribution in the build-up region. The primary dose distribution of electron contamination in the build-up region originates mostly from the primary photon interaction with components of the accelerator

head, such as the secondary JAWS, as well as the air column between the treatment head and patient surface. A secondary contribution arises from the backscattering of the photons inside the patient's body. To investigate these characteristics of particle contamination, detailed information about the geometries and material of each component in the head Linac should be known. There are three methods to determine electron contamination, namely direct measurement with a magnet [3,4] or helium bag,[5,6] an analytical method,[5,7] and Monte Carlo (MC) simulation.[2,5,8] The electron contamination in photon beam can produce a 'skin sparing' effect whereby more dose is deposited at depth than in the skin tissue region. The contaminant can shift the $D_{\max}$ to the shallow depth and give the contribution to the surface dose in a patient.[2]

Various researchers have reported the feasibility of MC to calculate some parameters such as electron contamination, Output Factors (OFs), and small field.[2,5,9–11] It show that MC techniques was more accurate than conventional methods. In the present paper, we investigate the electron contamination for large field sizes by MC simulation. The energy of electron contamination for different field sizes is not changed, but the amount of contamination increases with enlarged field size. Electron contamination dose decreases with depth. In this research, we investigate the characteristics of electron contamination and OFs from Varian Clinac iX 6 MV photon beam with various small field sizes (1×1 , 2×2 , 3×3 , 4×4 , and 5×5 cm²) with SSD 100 cm in water phantom. In order to estimate the accuracy of the dose calculation in MC simulation achieved by the MC model of the linear accelerator head, we will compare the results with direct measurements in a hospital (during the commissioning process and OFs) to obtain the appropriate energy and full width at half maximum (FWHM) for use in simulation.

2. Methods

EGSnrc Monte Carlo code system is a well-known code used to simulate the history of photons and electrons through a medium. In this study, the radiation transport software packages of BEAMnrc and DOSXYZnrc, based on the EGSnrc code, were used to perform this simulation. [12] For dosimetry, the Varian Trilogy Clinac iX 6 MV photon beam with 60 leaf pairs Millenium MLC (Varian Medical Systems, Palo Alto, CA) installed in Tan Tock Seng Hospital, Singapore for clinical treatment and operating at nominal energies of 6 MV was used. Measurement of PDD, profile dose, and OFs were performed in a water phantom 3D scanner (Sun Nuclear Corporation, Melbourne, FL) with 67.6 cm diameter. An ion chamber

Figure 1. Sketch of setup geometry in the Monte Carlo simulations for 6 MV photon beam and water phantom.

semiflex 0.125 cc (PTW-Freiburg, type 4801) was used as detector.

The linear accelerator head was simulated successfully by BEAMnrc code [13] in the commissioning process for a field size 10×10 cm². [14] This treatment head is simulated in two parts, e.g. patient-dependent (part 1) and independent (part 2) components to reduce the simulation time. Figure 1 shows the setup of the simulated geometry for the head of Varian Trilogy Clinac iX 6 MV photon beam for this simulation. The component modules used in this study to model the Linac were FLATFLIT for target, primary collimator, vacuum window and flattening filter, CHAMBER for ionizing chamber, JAWS for secondary collimators (Y1, Y2, X1, and X2), DYNMLC for Multileaf Collimator (MLC), and SLABS for the air gap between the MLC and phantom surface at Source to Skin Distance (SSD) 100 cm.

The particles after being transported in the head of the linear accelerator using this code were scored on the scoring plane in phase space files (phsp). The phsp file contains the information on all particles in the scoring plane (charge, energy, direction, etc.) analyzed by BEAMDP (BEAMnrc Data Processor) to calculate the energy spectra, the mean energy profiles, and the fluence profiles of the photon beam at the surface of phantom. [13] This phsp file becomes the input on DOSXYZnrc to measure the absorbed dose in

Table 1. Number of particles from source and in phase space (phsp) file with different field sizes (energy of incident electron 6.4 MeV and SSD 100 cm).

Field sizes	Capacity (GB)	Number of Particles			
		In phsp file			From source
		Photon	Electron	All particles	
1 × 1	0.541	9865937	47872	9913809	52561997824
2 × 2	0.632	11426366	53690	11480054	47541731328
3 × 3	0.725	19332125	70277	19402402	39310626816
4 × 4	0.829	23234785	82465	23317250	30433665024
5 × 5	1.002	36502716	155041	36657757	26076995584

water phantom ($40 \times 40 \times 40 \text{ cm}^3$). The arrangement of the voxel sizes in the phantom for measured percentage depth dose (PDD) and profile dose are different. All measured absorbed dose curves (PDD and profile dose) were normalized at the depth of maximum dose on the central axis. PDD and lateral dose profile curves from MC simulation by DOSXYZnrc [15] were compared with the experimental measurements from the Tan Tock Seng Hospital (TTSH) Singapore to validate our MC model.

The voxel size arrangements for PDD and dose profile are different. The accuracy, deviation (measurement and simulation), and statistical uncertainty are dependent on this factor.[16,17] There was good agreement between the measurements and simulations for beam profile and PDD curves (deviation less than 5%). For beam profiles, maximum local differences less than 2%, were seen for flat regions, but they increased to 13% for regions located out of field for the deepest considered depth of 20 cm. The incident electron fluence onto the target of this linear accelerator was modeled as centrally symmetric with a Gaussian distribution of FWHM 1.0 mm and energy 6.4 MeV. The Linac geometry was used as input to the MC code with specifications obtained from the vendor of the accelerator. This Monte Carlo simulation was implemented under the same condition as the measurement (American Association of Physicists in Medicine (AAPM), TG-105).[18]

In this study, we investigated electron contamination in the Varian Clinac iX 6 MV photon beam with variable small fields. The contaminant electrons were analyzed at different field sizes (1×1 , 2×2 , 3×3 , 4×4 , and $5 \times 5 \text{ cm}^2$) with SSD 100 cm. In this study, the data included mlc-defined nominal field sizes. For the calculation, the photon and electron cut-off energy was set to 0.521 and 0.01 MeV, respectively. The number of histories for the Monte Carlo calculation in part 2 was 3×10^{10} particles, resulting in 4×10^8 particles in phase space after the Linac head. The number of particles that hit the phantom surface equals the number of histories (5×10^8 particles). The large number of particles can reduce the statistical uncertainty. All materials used in MC simulation were extracted from the 521ICRU PEGS4 (processor for Electron Gamma

Shower) cross section data available in BEAMnrc and DOSXYZnrc, and met the specifications for the Linac as provided by the manufacturer.

The OFs were simulated at a depth of 10 cm (beam direction) in a $40 \times 40 \times 40 \text{ cm}^3$ water phantom for square field sizes with side lengths ranging from 1 to 5 cm in 1 cm increments. The OFs were calculated by normalizing the dose per incident particle from each field size to the dose per incident particle with the 10 cm field size. The simulation in BEAMnrc was split up between 11 PCs with 4 or 8 cores, making the simulation 11 times faster than if only one PC was used. The original input file were split up into an arbitrary number of input files, between 1 and 99, each with a unique pair of seeds. For each different pair of seeds, an independent random number sequence was generated. At the end of the simulation, the output files had to be collected and combined into one using BEAMDP. When simulating dose distributions in a water phantom with DOSXYZnrc, we used only one computer.

3. Results

3.1. Beam characteristics

The simulation output in the phantom surface was in the form of a phase space file of size 1.002 GB for a $5 \times 5 \text{ cm}^2$ field. The number of electrons in phsp file was about 0.35% of all the number of particles. The detailed number of particles from source and in the phsp file for different field sizes is shown in Table 1. The amount of photon and electron contamination in the phsp file depends on the field width. The maximum number of particles that can be stored in a phase space file is $2^{31}-1$ or 2.14 GB.[16] Every bit in phsp file stores the particles information. The small field size that allows many particles did not reach the phsp area (blocked by mlc). So, the simulation should be repeated many times with different seed number to obtain the large capacity of phsp file. This repeated simulation affects the simulation time.

On analyzing the file using BEAMDP, we found that the number of incident particles from the source from the end

Figure 2. The energy fluence (up) and angular distribution (down) of all particles at the phantom surface (defined at SSD = 100 cm and incident electron energy 6.4 MeV) inside field sizes 1×1 , 2×2 , 3×3 , 4×4 , and 5×5 cm².

of patient-dependent component Linac was more than 2.6×10^{10} . The total number of particles in the phsp file was 3.6×10^7 , which includes 3.5×10^7 photons with the rest being electrons. Unfortunately, these numbers are not sufficient to obtain the simulation with the desired statistical precision in the PDDs and dose profiles (less than 2%). So, the number of history that used DOSXYZnrc simulation (phantom) should be recycled more than 10 times.

We need to consider the number and energy of all particles released from photon beam stored in phsp file. The photon beam characteristics, e.g. energy fluence, spectral distribution, angular distribution, and mean energy (Figures 2 and 3) can be used to investigate the particles. [13] The mean energy profile was used to verify the flattening filter shape (inside field). This profile presents that the mean energy inside the field is lower than outside the field. The mean energy (Figure 3) has close relationship with fluence (Figure 2). This figure remains flat inside the field due to the hardening effect in flattening filter. The electron and scattered photon contributed to the increase in mean energies in off-axis distance.

Figure 3. The mean energy and spectral distribution all particles at the phantom surface (defined at SSD = 100 cm and incident electron energy 6.4 MeV) inside the field sizes 1×1 , 2×2 , 3×3 , 4×4 , and 5×5 cm².

Figure 4. Measured (black line) and MC (dash dot line) PDD at phantom surface for 6 MV photon beam for 4×4 cm² field size.

3.2. Dosimetric parameters

PDD values were calculated from the dose obtained at different depths in water phantom for different field sizes. The PDD data were plotted along Z axis. A comparative

Figure 5. Normalized dose of percent depth (up) and profile dose (down) curve for all particles at 100 cm SSD for various field sizes.

Figure 6. The mean energies of all particles, photons, and electrons at the phantom surface as a function of off-axis distance for 5×5 cm² field size at SSD = 100 cm.

plot shows good agreement between measurement and MC simulation for 4×4 cm² field in water phantom, with differences less than 5% (Figure 4). The dosimetric parameters such as depth of dose maximum, PDD, and dose profile obtained in this simulation match well with the measurement data.

Fields can be defined by JAWS or MLC. In this study, small fields defined by the Millenium MLC with JAWS setting at 10×10 cm² were calculated and the resulting PDDs and dose profiles obtained. There is special interest in small field dosimetry because of the capabilities of the Linac under study with the 120-leaf Millenium MLC. Figures 5 and 6 show PDDs and dose profiles for 1×1 , 2×2 , 3×3 , 4×4 , and 5×5 cm² defined by the Millenium MLC. All measured PDD curves were normalized at the depth of maximum dose on the central axis. And the lateral profile curve was scored at a depth of 1.5 cm.

Figure 7. The angular distribution and fluence for all particles, photons, and electrons at the phantom surface (defined at SSD 100 cm) inside the field sizes 5×5 cm².

Figure 8. Percent depth and lateral dose profile curve for all particles, photons, and contaminant electrons at SSD = 100 cm for $4 \times 4 \text{ cm}^2$ (up) and $5 \times 5 \text{ cm}^2$ (down) field sizes.

3.3. Electron contamination

The angular and spectral distribution and mean energy extracted from the phsp file using BEAMDP was plotted as Figures 6 and 7. Figure 6 shows the mean energy of particles in the phsp file. The cube, round, and triangle line represents mean energy of all particles, photons, and electrons in the phsp file, respectively. The mean energy of photons was relatively flat inside the $5 \times 5 \text{ cm}^2$ field (1.75 MeV on the central axis) and shows a sharp fall-off at the edge of the field (1.3 MeV) as shown in Figure 6. The mean energy of electrons (as shown in Figure 6) decreased gradually outside the field (from 1.8 MeV in the central axis to 1.4 MeV at the field border). The angular distribution curve (Figure 7(a)) shows that the scatter angle of the electrons is bigger than the primary photon angle for a $5 \times 5 \text{ cm}^2$ field. Figure 8 shows the contribution of electron contamination for surface dose in PDD and profile dose for water phantom.

Figure 9. OFs in the water phantom given by square fields. All factors were normalized to a field size of 10 cm.

3.4. Output factors (OFs)

The OF is the ratio of dose value for any field size to the dose value for a reference field sizes in the water phantom, at the same observed depth and Source to Surface Distance (SSD). In this study, the reference field is a square field of $10 \times 10 \text{ cm}^2$ at SSD of 100 cm.

Figure 9 represents the different fields measured in the water phantom and their OFs associated for small fields in the Varian Trilogy Clinac iX 6 MV photon beam. The figure shows that OFs for MC with 0.1 voxel size and simulation for all field was less than 1.0. The agreement between MC calculation and measurement data for all fields was found to less than 4%. At field sizes smaller than 3 cm, lateral electronic disequilibrium caused a reduction in phantom scatter. The rate of change in lateral electronic disequilibrium was small above field sizes of 3 cm (OFs was equal to 0.77 and 0.81 at field sizes of 1 and 2 cm, respectively). At field sizes below 10 cm, lateral electronic disequilibrium increased sharply with decreasing field size. Maximum deviation was observed 3.45% for $2 \times 2 \text{ cm}^2$. And deviation for field size of 3 and 4 cm is 1.76 and 0.86%, respectively.

4. Discussion

The number of particles per MeV per incident particles at the phantom surface (fluence energy) peaks at 1.30 MeV for all field sizes (Figure 2). There is then a sharp drop, a slight decrease in number and then a slight increase resulting from the mean energy of photons at the larger off-axis distances (Figure 3). The increase was due to the hardening effect of the flattening filter, since the photons transferred through the 3.75 cm thick copper (density 8.52 g/cm^3) had much higher energies. Allahverdi et al. [2] reported similar results.

Figure 5 shows five representative percentage dose and dose profile curves for 1×1 , 2×2 , 3×3 , 4×4 , and 5×5 cm² fields for the 6 MV photon beam. All measurement results were normalized to maximum depth (1.5 cm). In general, when working with small fields, it is more important to precisely characterize the penumbra width. The variation of penumbra width at the surface were investigated as a function of field size. For the field sizes roughly below 3×3 cm², the field consists almost only of penumbra. The penumbra width, e.g. the spatial distance between 80 and 20% dose, is smaller in small fields. This increases the curvature and hence the volume effect in the penumbra region. This penumbra width was influenced by curved leaf end of MLC.[19] The results indicated that the beam profile and penumbra width were nearly independent of field size.

Electron contamination is normally an unwanted dose for radiotherapy due to the low energy of these electrons. The number of contaminating electrons depends on the field sizes. Decreasing field sizes reduces the amount of electron contamination and surface dose. The contaminating electrons have an energy spectrum that changes rapidly with depth. The total electron contamination of the spectrum depends on field size and was 0.42% for a 5×5 cm² field. This study presents calculated depth-dose components from different particles as well as the calculated surface dose and contribution from different particles to surface dose across the field. It was shown that the increase in surface dose with the increase in the field size is mainly due to the increase in incident contaminant charged particles.

The Monte Carlo calculated PDD across the 4×4 and 5×5 cm² fields are shown in Figures 8 (a) and (b). The surface dose was the average dose in each voxel referred to a depth of 5 cm. This data indicate that the contaminant electron dose has a maximum value along the central axis and it gradually decreases with depth, while the photon dose shows an increase toward the field border followed by a sharp fall-off. It is also seen that the contaminant electrons comprise the majority contribution of the surface dose outside from the field edge. This study found that the amount of electron contamination for the Varian Trilogy Clinac iX 6 MV photon beam accelerator ranges from 0.3 to 0.5% for 6 MV photon beams. This corresponds to 1.4 and 3.9% surface dose, respectively, depending on field sizes. There was some difference between our MC results and another study because different SSD, series of Linac, energy, and field sizes.[1,2,5] Allahverdi et al. (2011) reported that the contribution of contaminant electron in surface dose was 6.1% for field size 5×5 cm² for 18 MV photon beam.[2]

In small fields, the energy spectrum of the primary photons and electron contamination can change with the field size. Also, the mean energy of photons and electron

contamination in the phsp file decreased with increasing field sizes. The maximum energy of the photons and electrons in the phsp file are 6.391 and 0.01 MeV, respectively. This energy is constant at every field size.

OFs, especially for small fields, are known to tend to errors, since the dose distribution is not uniform at the point of measurement in the central axis. Therefore, accurate methods of predicting and measuring the OFs for photon beam need to be available to the clinical physicist especially in small field. The ability to predict the OFs' use has been improved over the years for clinical photon beams. Recently, Monte Carlo code was used by some investigators to calculate OFs for photon beams. The consensus among investigators is that Monte Carlo algorithm has the potential to accurately predict the electron contamination and OFs for photon beams. Nevertheless, in clinical practice, it is required that accurate OFs values be readily available without the need for users to specify the geometry of the field and run the corresponding simulations.[20–23]

5. Conclusions

This study increased our knowledge of the clinical photon beams and associated contaminant electrons for small fields. It demonstrated the accuracy of the Monte Carlo technique in simulating the electron contamination and OFs in photon beam. In the future, the contribution of each Linac's components on electron contamination will be studied.

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