Original Article

Spatial Mesh-Based Surface Source Model for the Electron Contamination of an 18 MV Photon Beams

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Abstract

Background: Source modeling is an approach to reduce computational burden in Monte Carlo simulations but at the cost of reduced accuracy. Although this method can be effective, one component of the source model that is exceptionally difficult to model is the electron contamination, a significant contributor to the skin and shallow dose. **Aims and Objectives:** To improve the accuracy for the electron contamination component of the overall source model, we have generated a spatial mesh based surface source model. **Methods and Materials:** The source model is located downstream from the flattening filter and mirror but upstream from the movable jaws. A typical phase space file uses around ten parameters per particle, but this method simplifies this number to five components. By using only the electron distance from the central axis, angles from the central axis and energy, the computational time and disk space required is greatly reduced. **Results and Conclusion:** Despite the simplification in the source model, the electron contamination is still accurate to within 1.5%.

Keywords: 18 MV photon beams, electron contamination, Monte Carlo, source model

Received on: 20-04-2020 **Review completed on:** 14-10-2020 **Accepted on:** 02-11-2020 **Published on:** 02-02-2021

Introduction

It is well established that Monte Carlo (MC) simulations allow for accurate modeling of linear accelerators (linacs).[1] These simulations provide an inexpensive and safe means of calculating radiation doses around linacs without having to actually run the machine or irradiate any patients. The downside to MC simulations is that to achieve a high degree of accuracy, the time required to run the simulation can be on the order of days or weeks.[2] To accelerate the calculation process, it is possible to model the various aspects of the radiation emitted from the linac rather than run a complete simulation.[3-6] Although this is a promising solution, the uncertainty is increased unless each specific component of the radiation beam is accurately modelled.[7]

One important component in the beam emitted from a linac is electron contamination. Electron contamination is the creation of scattered electrons from photon interactions in the head of the linac and in the air. These electrons contribute significantly to the surface dose in a patient and are critical to generate an accurate beam model. Although electron contamination is a significant contributor to patient dose, it is difficult to generate an acceptable contamination model, as demonstrated in the literature. Sikora and Alber formulated a virtual source model for electron contamination using mathematical equations,[4] which they combined with their previous photon model.[3] Using this method, they showed that their overall accuracy was acceptable, but they did not report specifically on the accuracy of the electron contamination portion of the model.[4] González, *et al*. took a similar approach using a virtual source model based on mathematical equations, but their results show deviations up to 15% for the electron contamination.[6]

In this work, rather than model the electron contamination mathematically to generate a virtual source model, a spatial mesh-based surface source (SMBSS) was used to improve the accuracy. In addition, the major source of electron contamination is the flattening filter and mirror, so the source model is immediately downstream to these components to eliminate additional uncertainties. Not only is accuracy

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Quick Response Code:	**Website:** www.jmp.org.in
	DOI: 10.4103/jmp.JMP_29_20

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How to cite this article: Ezzati AO, Studenski MT, Gohari M. Spatial mesh-based surface source model for the electron contamination of an 18 MV photon beams. J Med Phys 2020;45:221-5.

increased, but this approach reduces the disk space required and is still independent from patient setup.

Materials and Methods

Linac simulation validation

Varian 2100C/D linear accelerator was simulated in MCNPX2.4. Open literature[8] data and manufacturer blueprints were used in the simulation set up. Extra care was given while modeling the flattening filter to increase the MC model dose calculations accuracy in large photon fields (sizes >20 cm × 20 cm). Pena, *et al.*'s method[9] was used to tune electron beam energy incident on the target. 2×10^9 histories were run and a photon electron energy deposition mesh tally was used to calculate the dose in a simulated water phantom. The cut-off energy of the electrons was 0.2 MeV in all simulations.

To validate the linac simulations, profiles and percent depth dose (PDD) curves for varying field sized were measured using a Physikalisch-Technische Werkstatten (PTW) farmer-type 0.6 cc ion chamber in a water tank. The measured profiles and PDDs were compared to the data from the linac simulations.

Electron contamination phase space file

Approximately 4×10^7 electrons are required to obtain accurate spatial and energy probability distributions to model electron contamination. Even using the maximum allowed histories in MCNP (2×10^9), the number of electrons incident on the phase space plane (25 cm downstream from the target and mirror) is only around 1.3×10^6, an order of magnitude lower than required [Figure 1]. To solve the problem, we utilized the geometry splitting variance reduction technique to increase the number of electrons from 1.3×10^6 to 4×10^7.[10] The spatial and energy distributions of these electrons were collected in a phase space file (PSF) which was converted from binary (MCNP default) to ASCII format and was read into MATLAB to generate the new SMBSS model.

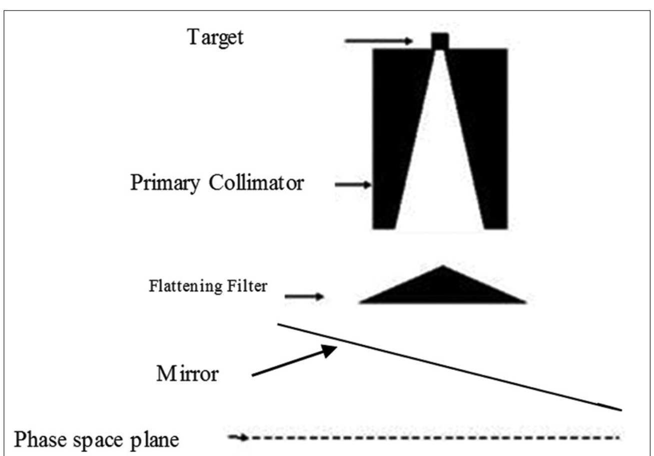

Figure 1: Schematic view of the patient independent and cylindrically asymmetric part of the Linac for obtaining the phase space file

Electron contamination source model

The MCNP source code was modified as described in a previous publication for reading and sampling large number of distributions.[11] The PSF contains 10 parameters for each particle that crosses the phase space plane. These parameters include x, y, z, *u*, *v*, *w*, energy, weight, and time. The *u, v,* and *w* are the cosines between the *x*-axis, y-axis, z-axis, and particle direction, respectively. All the particles that cross the phase space plane have the same z-coordinate, which is ignored in the PSF analysis. Because the PSF was located upstream of the movable jaws, it is azimuthally symmetric, the Ezzati, *et al.* method[12] was used to replace x and y with a single parameter R. The particle weight can be excluded since all particles have the same weight using the geometry splitting technique. The simulation was not time dependent and it can be also ignored. By these simplifications, each particle was described by R, *u*, *v, w,* and energy parameters.

Due to large angular scatterings and deflections of electrons, the SMBSS approach was used to model the parameters of the electron contamination in the PSF.[11,12] The electron parameters were sampled or calculated sequentially as: (1) sample distance to accelerator central axis (R), (2) for given R, sample directional cosine with respect to accelerator central axis (*w*), (3) for given R and *w*, sample direction with respect to x-axis cosine (*u*), (4) for given R, *w* and *u*, sample energy, (5) calculate y-axis direction cosine (*v*), (6) rotate the particle around accelerator central axis randomly [Figure 2].

Electron contamination source model validation

To assess the accuracy of the electron contamination source model, profiles and PDDs were obtained for various field sizes. As it is impossible to measure electron contamination alone in a clinical beam, the electron contamination source model calculations were compared to calculations using the PSF alone with 4×10^7 histories. This comparison also provided a means to calculate the speed up factor to assess the time savings of using the source model instead of the full MC simulation.

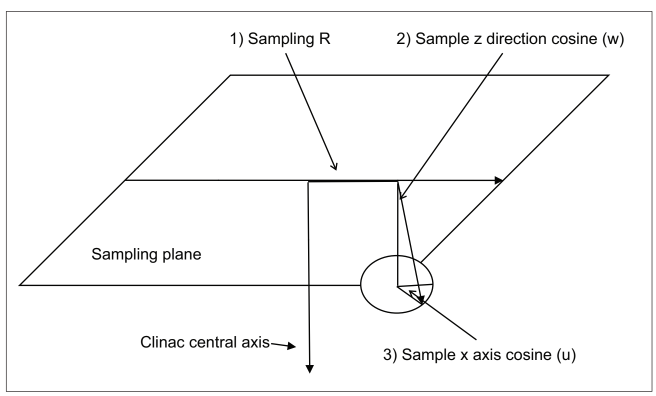

Figure 2: Sequence of particle sampling in spatial mesh based surface source

Results

Linac simulation validation

Figure 3 illustrates measured and simulated PDDs at 100 cm source-skin distance (SSD) for 10 cm × 10 cm, 20 cm × 20 cm, 30 cm × 30 cm and 40 cm × 40 cm field sizes. Uncertainty of the calculations for most of the points and 1 standard deviation was <0.5%. Simulated and measured PDDs differences are <2% demonstrating an accurate model. Figure 4 displays profiles for 10 cm × 10 cm, 20 cm × 20 cm, 30 cm × 30 cm and 40 cm × 40 cm field sizes in water phantom at 4 and 15 cm depths and 100 cm SSD. Agreement between simulated and measured profiles is <2% or 2 mm distance-to-agreement.

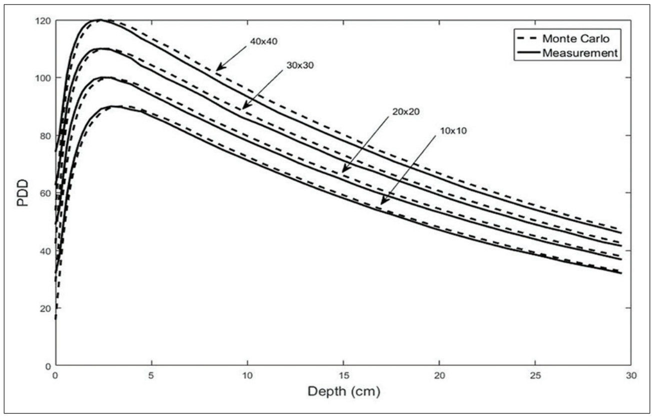

Figure 3: Calculated and measured percent depth dose at 100 cm source-skin distance

Beam characteristic histograms

Figures 5a-d show some SMBSS histograms for describing the electron contamination PSF: radial histogram, histograms of z-direction for three different radii, histograms of x-direction for two different z-direction intervals and 5 cm radius and energy distributions for two arbitrary intervals of x-direction. For each radial interval shown in Figure 5a, a z-direction distribution was calculated [Figure 5b]. For each interval of the z-direction bin, an x-direction histogram was obtained [Figure 5c]. For each interval of the x-direction bin, an energy histogram was calculated [Figure 5d]. Figure 5b shows that increasing the radius shifts the histogram of z-direction. Figure 5c reveals that particle distribution probability decreases by increasing the x-direction

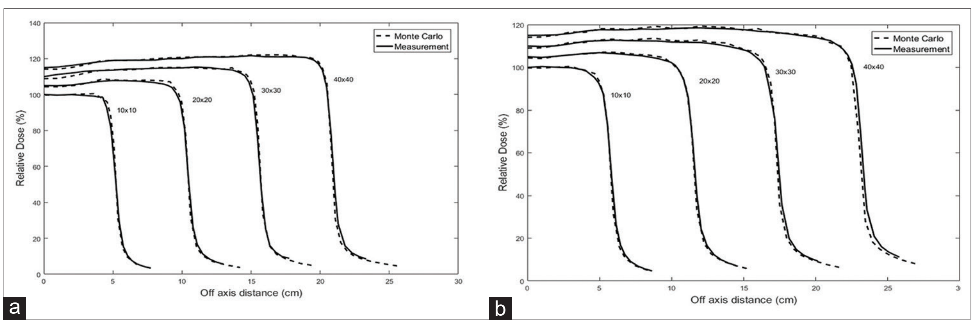

Figure 4: Calculated and measured profiles at two depths: (a) 4 cm and (b) 15 cm

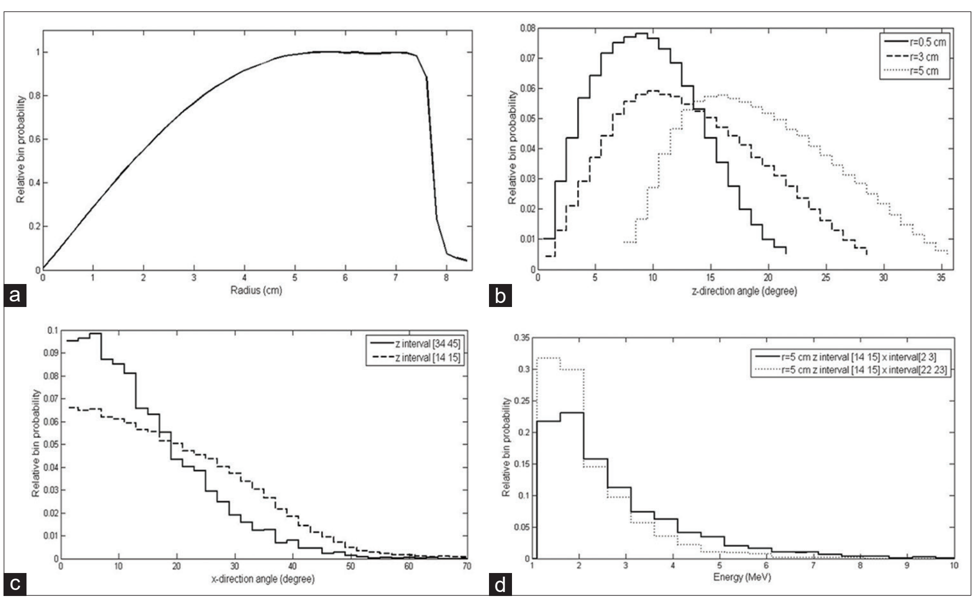

Figure 5: Spatial mesh based surface source histograms for the phase space file: (a) radial histogram, (b) histograms of z-direction, (c) histograms of x-direction, and (d) energy histogram

angle. It can be seen from Figure 5d by increasing the x-direction angle energy distribution was shifted to low energies.

Electron contamination source model validation

Figure 6 shows calculated PDDs using the PSF and source model. Agreement between the PSF and source model was within 0.5% for each field size with an associated uncertainty of 0.5%. Figure 7a and b shows profiles at the surface and 4 cm depth, respectively, for varying field sizes. Agreement between PSF and source model profiles is <1.5% of each profile maximum.

Spatial mesh based surface source speed up factors

Table 1 shows the SMBSS speed up factors with respect to full linac simulations. These factors were calculated by the mythology that was described in.[10-13] This table shows that when the field size is increased, the speed-up factor increases.

Electron contamination energy spectrum and mean energy

Figure 8 shows the energy spectrum of the electron contamination at 100 cm SSD on the linear accelerator central axis. The spectrum trend is the same as 6 and 15 MV photon beams electron contamination that were calculated by Sikora and Alber.[4] The mean energy of electrons was 3.44, 3.95 and 4.18 MeV at phase space plane, collimator exit and phantom surface, respectively.

Table 1: Spatial mesh based surface source speed up factors with respect to whole linac simulation

Field size	Speed up factor
10×10	800
20×10	1000
30×30	1100
40×40	1400

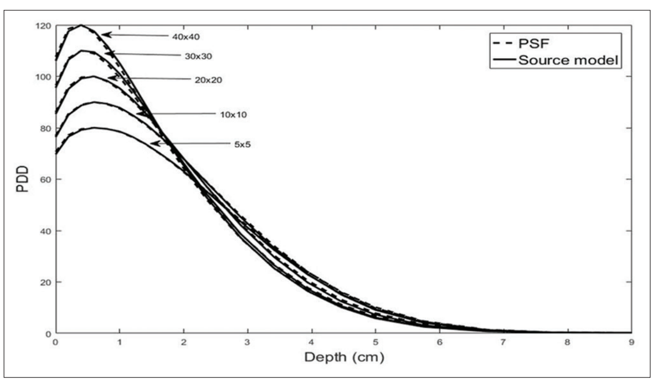

Figure 6: Simulated percent depth dose using the phase space file and spatial mesh based surface source at 100 cm source-skin distance

Discussion

Electron contamination is an unavoidable component of clinical linac photon beams and must be modeled accurately as it is a significant contributor to skin and shallow radiation dose. Although electron contamination is a significant contributor to patient dose, it is difficult to generate an acceptable contamination model due to the relatively low contamination electron production in the head of the linac and the inherently large scattering angles of electrons. These physical properties can be simulated accurately in a full MC simulation but at the significant cost of computational time and disk space. Here, we have demonstrated a novel method to create a source model for the electron contamination that is accurate while reducing the disk space required for the calculation.

Other groups have looked at using mathematical models to generate a source model for electron contamination. The source model generated by Sikora and Alber has difference up to 24.5% with respect to PSF near the surface due to the inaccuracy of the electron contamination component.[4] Another source model that was developed by González, *et al*. has difference up to 15% with respect to PSF related to the same issue.[6] These models use some simplifications that reduce the overall accuracy of the model but speed up computation time. In one model, the assumption is made that any interaction in the secondary collimator results in full absorption of contamination electrons, while in reality, there is a scatter component.[4] In another model, air interactions are omitted by considering only accounting for their effects in the source definition.[6]

To overcome these limitations, the approach of using an SMBSS model was taken instead of a mathematical model. Our approach was different in that we used correlated histograms to generate our model. In addition, the location of our phase space plane was downstream of the flattening filter and mirror but upstream of the movable jaws in the linac. With this approach, electron interactions in the secondary collimator and in air are fully simulated. The overall result of more accurate modeling

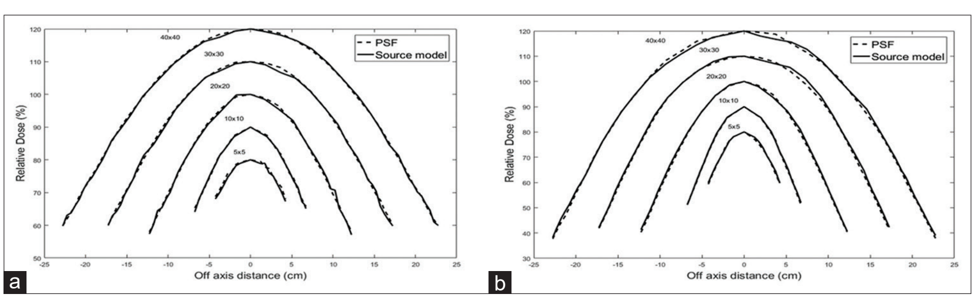

Figure 7: Simulated profiles using the phase space file and source model at (a) surface and (b) depth of 4 cm

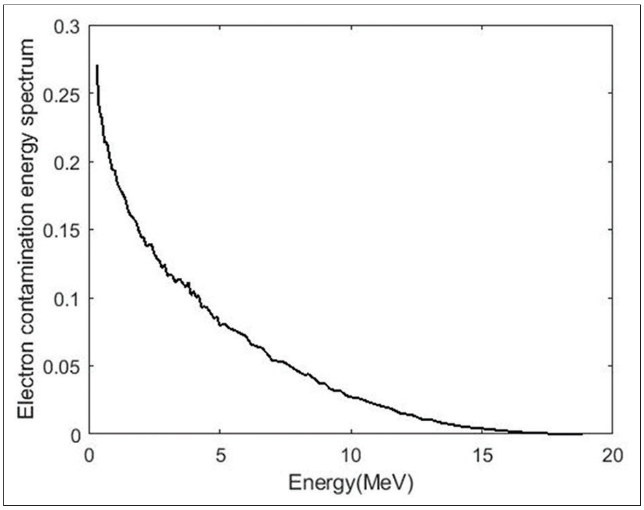

Figure 8: Electron contamination energy spectrum at 100 cm source-skin distance on the linac central axis

only deviates by 1.5% with respect to PSF, a significant improvement over previous works.

Conclusions

In this study, an SMBSS model was developed for electron contamination that is accurate to within 1.5% for all field sizes. The improved accuracy directly correlates to more accurate dose calculation for clinical research and treatment.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Financial support and sponsorship

Nil.

Conflicts of interest

There are no conflicts of interest.

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