Optimisation of 12 MeV electron beam simulation using variance reduction technique

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Abstract. Monte Carlo (MC) simulation for electron beam radiotherapy consumes a long computation time. An algorithm called variance reduction technique (VRT) in MC was implemented to speed up this duration. This work focused on optimisation of VRT parameter which refers to electron range rejection and particle history. EGSnrc MC source code was used to simulate (BEAMnrc code) and validate (DOSXYZnrc code) the Siemens Primus linear accelerator model with the non-VRT parameter. The validated MC model simulation was repeated by applying VRT parameter (electron range rejection) that controlled by global electron cut-off energy 1, 2 and 5 MeV using 20 x 10⁷ particle history. 5 MeV range rejection generated the fastest MC simulation with 50% reduction in computation time compared to non-VRT simulation. Thus, 5 MeV electron range rejection utilized in particle history analysis ranged from 7.5 x 10⁷ to 20 x 10⁷. In this study, 5 MeV electron cut-off with 10 x 10⁷ particle history, the simulation was four times faster than non-VRT calculation with 1% deviation. Proper understanding and use of VRT can significantly reduce MC electron beam calculation duration at the same time preserving its accuracy.

1. Introduction
Monte Carlo (MC) simulation is an algorithmic calculation uses a random sampling method to model a system with its specific geometry [1]. In radiotherapy application, MC is a fundamental tool to simulate a virtual model of radiation source and radiation transport in the system [2]. Advantage of MC is able to carry out dosimetry study in a challenging experiment setup which is not easily accessible in actual situation during treatment delivery [3, 4]. There are plenty of MC codes that have been used for radiotherapy applications, including Monte Carlo N-Particle (MCNP) [5], Geometry and Tracking (GEANT)[6], Electron Gamma Shower (EGS)[7] and PENELOPE[8]. However, the common MC code used for linear accelerator simulation and patient dose calculation are BEAMnrc and DOSXYZnrc where both codes were based on EGSnrc which is widely used for radiotherapy applications[9, 10]. The advantage of using EGSnrc code includes its ability for simulation three to five times faster than PENELOPE and GEANT because of its simple geometry[11].

In radiotherapy, the dose distribution in electron beams is more complex than that in photon beam[12]. Furthermore, the MC simulation of electron beam requires a long simulation time as compared to photon beam. Due to its prolonged computation time, an algorithm called VRT in BEAMnrc code was studied
in this work to speed up calculation duration to run the MC simulation. The VRT parameters in EGSnrc code are range rejection, bremsstrahlung cross section involvement, Russian roulette, Bremsstrahlung splitting, interaction forcing [1, 9, 13]. VRT parameters suggested in this study are electron range rejection and particle histories. This study uses VRT parameters on evaluating simulation time on Siemens Primus linac treatment head.

2. Materials and Methods

2.1. Monte Carlo Modelling and Simulation

The treatment head of Siemens Primus linear accelerator was generated by using precise geometry provided by Siemens Medical System, USA. The accelerator head was comprised of eight component modules, which are primary scattering foil, primary collimator, secondary flattening foil, ionisation chamber, mirror, upper and lower jaws and applicator, as shown in Figure 1(a). A 12 MeV electron beam model was developed from BEAMnrc with 10 x 10 cm² field size and source-to-surface distance (SSD) of 100 cm by using 20 x 10⁷ particle history.

Simulation runs with default EGSnrc transport parameter (non-VRT method) and used AE = ECUT = 0.7 MeV for electron and AP = PCUT = 0.01 MeV for photon energy by using 700icru. pegs4 data file. AP and AE represent the low-energy threshold for secondary Bremsstrahlung photons generation. PCUT and ECUT are defined as the global cut-off energy for electron and photon transport. A phase space file generated from BEAMnrc simulation comprised of all the data of particles, which exited from the treatment head. This file was used as an input radiation source file to DOSXYZnrc simulation for dose calculation in homogeneous water phantom. The DOSXYZnrc was used to simulate the deposited dose (central axis depth dose) in voxelised 3-D water phantom with a volume of 14 x 14 x 12 cm³ and the voxel size is 0.5 x 0.5 x 0.2 cm³.

Figure 1 (b) shows the model of 3-D water phantom with voxel X, Y, Z axis. The volume of 3-D voxel phantom was proportional to the reference phantom. In DOSXYZnrc, 5.0 x 10⁷ particles history was used to simulate the electron transport in 3-D water phantom. The output file from DOSXYZnrc used STATDOSE interface to extract the dose information. This data was analysed and normalized based on PDD calculation as indicated in the following equation:

\[
PDD = \frac{D_d}{D_{d0}} \times 100 \%
\]

where, \(D_d\) is the absorbed dose at any depth and \(D_{d0}\) dose at reference depth [14]. Ion chamber measurements were collected and compared with calculated PDD value from the MC model.

2.2. Variance Reduction Technique

MC simulation required the calculation of efficiency in the VRT application. The efficiency, \(\eta\) is defined as:

\[
\eta = \frac{1}{\sigma^2 T}
\]

where, \(\sigma^2\) is variance and \(T\) is the total CPU time used for processing \(N\) history number [13]. The variance is proportional to the inverse of the \(N\), thus, efficiency of VRT is not reliable to the number of histories. However, it increases CPU computation time per history.
2.3 Range Rejection of VRT
The VRT technique applied in this study was the range rejection for 12 MeV electron beam. The fundamental of range rejection is to eliminate electron history below a selected energy level to speed up MC simulation. Furthermore, VRT can be applied in conjunction with other techniques to improve the efficiency of MC calculation. Thus, the range rejection in this study was initialised in conjunction with number of particle history to obtain the best simulation time for EGSnrc without influencing the outcome.

The electron range rejection was turned on in BEAMnrc code by applying ESAVE global electron cut off as 1, 2 and 5 MeV. This parameter was governed in BEAMnrc to determine the energy of the electron. CPU computation time for BEAMnrc was then recorded. The phase space file generated from this simulation was used in DOSXYZnrc code for dosimetry analysis. DOSXYZnrc code runs simulation with 5.0 x 10^7 particle history to calculate dose in 3-D voxel phantom as shown in Figure 1(b). Simulation time was recorded and 3dDose output file was analysed using STATDOSE interface. PDD evaluation was performed to ensure that range rejection has no influence on dosimetry output. This result was compared to ionisation chamber measurement in 3-D water phantom. The range rejection that provided shorter simulation time with unbiased result was chosen to be in conjunction with particle history. The particle history values was reduced from 20.0 x 10^7 to 7.5 x 10^7 and the analysis was done on computation time and PDD.

3. Results and Discussion

3.1. Phase space file validation
The phase space generated from BEAMnrc was evaluated in beamdp.gui by using spectral distribution and particle scatters plot. The spectral distribution from the treatment head simulation at 11.5 MeV in Figure 2(a) was found to be the closest to represent 12 MeV electron beams. Also, Figure 2(b) shows maximum intensity of scatter particle at range between -5 cm to +5 cm in x and y-axis agrees well with treatment head simulation defined at 10 x 10 cm^2 field size. Therefore, these results had acknowledged the validation of phase space file for 12 MeV electron beam simulation and further analysed in DOSXYZnrc code.
3.2. Dose Calculation Validation

The phase space file generated from BEAMnrc code was used further in DOSXYZnrc simulation and the results were compared with experimental measurement using ionisation chamber. The STATDOSE interface was utilised to derive PDD value for voxel phantom created in DOSXYZnrc. The MC calculation result matched well with ion chamber measurement with less than 2% error in buildup region as shown in Figure 3. This signifies that linac model for 12 MeV beam was simulated accurately using EGSnrc code compared with non-VRT method.

![Figure 3. 12 MeV electron beam validation for MC calculation using PDD measurement](image)

3.3 Electron Range Rejection Measurement

The non-VRT simulation time observed for BEAMnrc was 26.8 hours and DOSXYZnrc was 0.8 hours by using $20 \times 10^7$ particle history and result a total computation time of 27.6 hours. The results showed that the 5 MeV electrons cut-off energy able to reduce the total simulation time of BEAMnrc and DOSXYZnrc from 27.6 hours to 13.8 hours when the electron range rejection was applied. Figure 4(a) showed that total simulation time decreased as the electron cut-off energy value increased. The range rejection showed no substantial difference on DOSXYZnrc simulation time. The result showed that the 5 MeV electrons cut-off energy was the best range rejection to reduce the computation time. The PDD values show good agreement and explain well that the output did not influence the electron range rejection as shown in Figure 4(b). The interactions occurred (as in figure 2 (a)) below the electron cut-off energy (5 MeV in this case) were not simulated and hence reduced calculation time expressively by using VRT method. The uncertainties between both simulations were not affected as cut-off energy value 5 MeV is lesser to simulate electron energy of 12 MeV due to monoenergetic peak electron beam profile generated by linac as shown in Figure 2.
Figure 4. (a) Simulation time using different electron cut-off energy shows 5 MeV reduce simulation time to 13.7 hours. (b) PDD of simulation using different electron cut-off energy with less than 1% errors was observed.

3.4. Number of Particle History Analysis

The electron range rejection at 5 MeV from the previous study was referred to investigate the effect of particle history on total computation time. The results showed that the simulation time decreases by lowering the number of particle history in Figure 5 (a). Particle history of $7.5 \times 10^7$ yields the lowest simulation time of 5.8 hours. However, PDD analysis in Figure 5 (b) showed that $7.5 \times 10^7$ particle history deviated by 7.4% from the measured PDD result and this outcome is unacceptable as the error is more than 2%. The number of histories used in BEAMnrc must be more than $5.0 \times 10^7$ to achieve 1% statistical uncertainty in dose calculation for 6 MeV electron beam[15]. On the other hand, this result showed that minimum number of particle history that to be chosen in this study is $10 \times 10^7$ with a total simulation time of 7.3 hours to produce a PDD output with a 1% dose error for 12 MeV electron beam. The cut-off range must be corresponded to required spatial resolution to conserve the final outcome. This indicated that the simulation time depended on both electron range rejection and particle history.

Figure 5. (a) Simulation time using different particle history, where $7.5 \times 10^7$ gives shorter simulation time. (b) Percentage error of different particle history with non-VRT calculation, shows $7.5 \times 10^7$ particle history having unacceptable dose discrepancy of 7.4%

4. Conclusion

The electron range rejection for Siemens Primus linear accelerator 12 MeV electron beam energy was optimised. The electron range rejection together with number of particle history used in BEAMnrc code able to give accurate results and good computation time. 5 MeV global electron cut-off in range rejection for $10 \times 10^7$ particle history yields the fastest simulation time of 7.3 hours with unbiased outcome in radiation interaction. Limitation in particle history with lower than $10 \times 10^7$ influences the output from treatment head and deviates PDD result. In addition, this study also proved that the use of electron range
rejection did not influence time required to run DOSXYZnrc. Future work to investigate ESAVE more than 5 MeV for different electron energies is suggested.

5. References

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