A method to reduce the statistical uncertainty caused by high-energy cutoffs in Monte Carlo treatment planning

J S Li and C-M Ma

Fox Chase Cancer Center, 333 Cottman Ave., Philadelphia, PA, 19002, USA
E-mail: Jinsheng.li@fccc.edu

Abstract. The effects of high electron energy cutoff (ECUT) have been investigated and a method to reduce the dose statistical uncertainty caused by high ECUT was implemented in this work. In EGS4 Monte Carlo simulations, an electron is discarded and its energy is deposited locally when its total energy is lower than ECUT. The deposited energy can be significantly higher than the energy loss calculated using the CSDA model with the corresponding stopping powers in a low-density medium. This will create higher statistical uncertainties in the dose distributions, especially in air and lung tissues. In this work, a new method was implemented to continuously transport a discarded electron without considering multiple scattering or secondary particle generation. The energy loss is calculated based on the mass collision stopping powers in the local medium with an additional energy loss (70%) to account for the effect of approximations made in transporting the electron in a straight line rather than a curved path. The new method can significantly reduce the dose statistical uncertainty and thus improve the simulation efficiency even though the new method requires about 2% more CPU time. Our results showed that the statistical uncertainty of the dose in air cavities of a head-and-neck patient was reduced from 39% to about 2%. The dose distribution for the head and neck patient was significantly improved without losing dose accuracy and simulation efficiency.

1. Introduction

It has been widely accepted that the Monte Carlo method is the most accurate method for radiation therapy dose calculation. However, the effect of statistical uncertainties on Monte Carlo dose calculation must be considered for its clinical implementation because the Monte Carlo method is a statistical simulation method based on random samplings. This effect can be reduced by simulating a large number of radiation particles which requires tremendous computing power and a long simulation time. Previous investigators have studied the effect of statistical uncertainties on the dose distribution [1, 2], dose-volume-histograms (DVHs) [1, 3] and inverse planning [4]. Methods to remove or reduce the effects, such as denoising [5, 6] and DVH deconvolution [3], were also developed. It was also shown that for patient dose calculation, the cutoff energy for electron transport (ECUT in EGS4) can be as high as 1.0 MeV for head & neck and lung patient and 2.5 MeV for other part of the body without losing dose accuracy at the high dose region [7]. High ECUT values can reduce the simulation time in general. However, it may result in large statistical uncertainties in dose distributions especially in low-density media. One example is the air cavities in the simulation geometry and sometime even in the treatment target volumes for head and neck treatments, or for prostate treatments and treatments with the use of bolus. The statistical uncertainty of the dose in the air cavity can be much higher than...
that in other tissues because the air density is very low. When an electron is discarded because its energy is below ECUT it will deposit all its energy in the voxel where it is terminated. Because the dose is calculated as the energy deposited in the voxel divided by the mass of the voxel, the dose in an air cavity will be 1000 times higher than that in a tissue voxel for the same energy deposition when an electron is discarded this way. The high dose uncertainty in the air regions will make the dose distribution very confusing and it will affect the optimization efficiency in the planning process for intensity-modulated radiation therapy (IMRT). It will take a much longer time to reduce the statistical uncertainty in the air cavity to a certain level by simply simulating more particles. Different codes may treat the track-end electron differently after its energy is lower than ECUT to reduce the statistical uncertainties. The XVMC code [9] treats the track-ends as “normal” condensed history steps, which implies that a hinged step is taken with a randomly selected hinge point. It was mentioned that this technique associates with a 10-25% increase in CPU time per history and 30-40% increase in simulation efficiency with increased ECUT.

In this work, the effects of high ECUT on the dose distribution and simulation efficiency were investigated for the EGS4 (Electron Gamma Shower version 4) Monte Carlo system [8]. A method was developed to reduce the dose statistical uncertainty caused by high ECUT by simulating the particle to a very low energy after its energy is lower than ECUT in a different way as described in Ref. [9].

2. Material and method

2.1. Effects of high ECUT on dose statistical uncertainty

The low energy thresholds for knock-on electron and soft bremsstrahlung production (AE and AP in EGS4 [8]) and the energy cutoffs for electron and photon transport (ECUT and PCUT in EGS4), are very important parameters for Monte Carlo simulations. They can affect the accuracy of the simulation results and the simulation time significantly. A 0.7MeV ECUT (total energy) and a 0.01MeV PCUT are usually used as cutoff energies for radiation therapy dose calculation. Previous studies showed that the cutoff energy could be much higher without changing the dose distribution in soft tissues [7]. High-energy cutoffs will generally increase the statistical uncertainty of a dose distribution for the same number of particle histories, especially in low-density regions, such as air cavities. This is because the energy deposited in an air voxel by a discarded electron when its energy is below ECUT is significantly higher than the energy loss calculated using a CSDA (continuous slowing-down approximation) model with the corresponding unrestricted stopping powers for the same electron transversing the air voxel. Dose calculations for a prostate patient, a lung patient and a head and neck patient with air cavities were performed with different ECUT values. The simulation efficiency and statistical uncertainty in different regions were compared and the effects on dose distributions at these regions were investigated for different ECUT values.

2.2. Technique to reduce the dose statistical uncertainty caused by high ECUT

The higher statistical uncertainty in an air cavity is caused by the large energies deposited by electrons discarded in the air cavity when their energies are below ECUT. A lower cutoff energy for electron transport will generally improve the situation but the simulation will take much longer time. It is known that the dose accuracy is acceptable for radiation therapy dose calculation with an electron cutoff energy as high as 1MeV in soft tissues. However, new methods are needed to keep the statistical uncertainty low and the dose distribution accurate for simulation geometries that include air cavities and low-density media.
In this work, a method named non-stop electron transport is developed. In this method, electrons are transported continuously after their energies are lower than ECUT. The electrons are transported along a straight line and the energy deposition is calculated based on their unrestricted mass collision stopping powers. The energy deposition was further increased empirically by 70%, based on our simulation results, to ensure the local dose accuracy because the real electron path length is much longer than a straight line due to electron multiple scattering. The unrestricted mass collision stopping powers for bone, tissue and air for electrons under 2MeV were taken from the ICRU report 35 [10].

The new method has been implemented in the MCSIM code [11], an EGS4/PRESTA [8, 12] based Monte Carlo treatment planning system with several variance reduction techniques. The implementation was validated by calculating the dose distributions in a prostate patient, a lung patient and a head and neck patient and compared with the previous results without applying this new method. The AE was set to 0.7MeV and AP and PCUT were set to 0.01MeV for all the simulations. A history-based method was used to compute the statistical uncertainty (σ) and the CPU time (T) was recorded for each Monte Carlo simulation. The simulation efficiency, 1/(σ²T), with and without the new method was evaluated for different ECUT values.

3. Results

Monte Carlo dose calculations were performed for a prostate patient using different ECUT values with and without the new method. No other variance reduction techniques were applied in all the simulations. There were no significant differences in the dose distribution for ECUT up to 2MeV. The CPU time and the dose statistical uncertainty are shown in table 1.

Table 1. Monte Carlo dose calculation efficiency for a prostate patient with different ECUT values. The same number of particles was used for all the simulations. The simulation efficiency is relative to the case calculated with a 0.7MeV ECUT.

| ECUT(MeV) | Without the New Method | With the New Method |
|-----------|------------------------|---------------------|
|           | CPU Time(h) | %Uncertainty | Efficiency | CPU Time(h) | %Uncertainty | Efficiency |
| 0.7       | 6.76        | 1.4          | 1.00       | 6.80        | 1.4          | 0.99       |
| 1.0       | 5.02        | 1.5          | 1.17       | 5.12        | 1.4          | 1.32       |
| 1.5       | 4.26        | 1.7          | 1.08       | 4.33        | 1.5          | 1.36       |
| 2.0       | 3.88        | 2.0          | 0.85       | 3.99        | 1.5          | 1.48       |

The Monte Carlo simulation time is significantly reduced with higher ECUT but the simulation efficiency is not improved as much or even reduced without employing the new method because the statistical uncertainty may increase with ECUT. The new method can reduce the dose statistical uncertainty to the same level for a 0.7MeV ECUT and thus improves the efficiency by up to 74% for high ECUT simulations even though the total CPU time taken for a simulation is slightly longer (2%). The voxel size for this case was 3.8 x 3.8 x 5.9mm³. The effects will be more significant for smaller voxels. The results for the lung case showed similar trends. The new method could reduce the statistical uncertainty significantly when higher ECUT was used for simulation and it improved the simulation efficiency by up to 2 times for a 1.0MeV ECUT and up to 3 times for a 1.5MeV ECUT.

Monte Carlo dose calculations with and without the new method were also performed for a head & neck patient treated with intensity modulated 6MV photon beams. Air cavities were present in the treatment region and some of them were included in the treatment target volume. A 0.7MeV ECUT was used for both Monte Carlo simulations. The comparison of results in figure 1 shows that the isodose distribution was significantly improved by using the new method without losing the dose accuracy. The dose statistical uncertainties in the air cavities were reduced from about 39% to the same level of the surrounding human tissues, which was about 2%.
The dose profiles shown in figure 2 also indicate that the dose statistical uncertainties in the air cavities were significantly reduced and the dose in the target region was kept unchanged. The simulation time with the new method was increased by about 2% but the simulation efficiency was not reduced because the dose uncertainty was also reduced slightly in the high dose region of human tissue by using the new method.

Figure 1. Isodose comparison for a head & neck patient before (left) and after (right) the new method was applied. A 0.7MeV ECUT was used for both calculations.

Figure 2. Comparison of dose profiles along the line depicted in figure 1. The darker (black) line is the result without the new method showing large error bars in the air cavities. The lighter (red) line is the result with the new method.
4. Conclusion

High electron cutoff energy reduces the simulation time but increases the statistical uncertainty, especially in low-density regions such as air cavities. A non-stop electron transport method was developed to reduce the dose statistical uncertainty caused by high ECUT and thus improve the Monte Carlo dose calculation efficiency. A significantly reduced uncertainty and an improved dose distribution can be achieved by using the new method for patient with air cavities in the treatment region without losing simulation efficiency and dose accuracy. The method described in this paper can also be implemented in other Monte Carlo codes.

Acknowledgments

We acknowledge the support from the NIH (CA78331).

References

[1] Keall P J, Siebers J, Jeraj R and Mohan R 2000 The effect of dose calculation uncertainty on the evaluation of radiotherapy plans Med. Phys. 27 478
[2] Kawrakow I 2004 The effect of Monte carlo statistical uncertainties on the evaluation of dose distributions in radiation treatment planning Phys. Med. Biol. 49 1549
[3] Jiang S B, Pawlicki T and Ma C-M 2000 Removing the effect of statistical uncertainty on dose-volume histograms from Monte Carlo dose calculations Phys. Med. Biol. 45 2151
[4] Ma C-M, Li J S, Jiang S B, Pawlicki T, Xiong W, Qin L H and Yang J 2005 Effect of statistical uncertainties on Monte Carlo treatment planning Phys. Med. Biol. 50 891
[5] El Naqa I, Kawrakow I, Fippel M, Siebers J V, Lindsay P E, Wickerhauser M V, Vicic M, Zakarian K, Kauffmann N and Deasy J O 2005 A comparison of Monte Carlo dose calculation denoising techniques Phys. Med. Biol. 50 909
[6] De Smedt B, Fippel M, Reynaert N, Thierens H 2006 Denoising of Monte Carlo dose calculations: smoothing capabilities versus introduction of systematic bias Med. Phys. 33 1678
[7] Ma C-M, Li J S, Pawlicki T, Jiang S B, Deng J, Lee M C, Koumrian T, Luxton M and Brain S 2002 A Monte Carlo dose calculation tool for radiotherapy treatment planning Phys. Med. Biol. 47 1671-89
[8] Nelson R, Hirayama H and Rogers D W O 1985 The EGS4 Code System Stanford Linear Accelerator Center report SLAC-265 (Stanford, CA: SLAC)
[9] Kawrakow I and Fippel M 2000 Investigation of variance reduction techniques for Monte Carlo photon dose calculation using XVMC Phys. Med. Biol. 45 2163-83
[10] ICRU 1984 Radiation Dosimetry: Electron beams with energies between 1 and 50MeV, ICRU report 35 (Bethesda, MD: ICRU)
[11] Ma C-M et al 2004 MCSIM: a Monte Carlo dose calculation tool for radiation therapy, Proc. 14th Int. Conf. on the Use of Computer in Radiation Therapy (ICCR) ed BY Yi, SD Ahn, EK Choi and SW Ha (Seoul: Jeong Publishing) p 515
[12] Bielajew A and Rogers D W O 1987 PRESTA-the parameter reduced electron step algorithm for electron Monte Carlo transport Nucl. Instrum. Methods B 18 165