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A combined approach of variance-reduction techniques for the efficient Monte Carlo simulation of linacs

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Abstract

A method based on a combination of the variance-reduction techniques of particle splitting and Russian roulette is presented. This method improves the efficiency of radiation transport through linear accelerator geometries simulated with the Monte Carlo method. The method named as 'splitting-roulette' was implemented on the Monte Carlo code PENELOPE and tested on an Elekta linac, although it is general enough to be implemented on any other general-purpose Monte Carlo radiation transport code and linac geometry. Splitting-roulette uses any of the following two modes of splitting: simple splitting and 'selective splitting'. Selective splitting is a new splitting mode based on the angular distribution of bremsstrahlung photons implemented in the Monte Carlo code PENELOPE. Splitting-roulette improves the simulation efficiency of an Elekta SL25 linac by a factor of 45.

1. Introduction

Monte Carlo (MC) simulation of radiation transport through linear accelerators (linacs) for the estimation of dose distributions and other quantities of interest has become widespread in medical physics. The possibility of accurately describing the beams produced by treatment machines has been invaluable in research, with important consequences in the clinical practice. In the last decades, codes with MC modules have been developed for radiotherapy treatment planning or plan verification (Neuenschwander *et al* 1995, Keall and Hoban 1996, Wang *et al* 1998, Fippel 1999, Sempau *et al* 2000, Hartmann Siantar *et al* 2001, Kawrakow 2001, Ma *et al* 2002, Reynaert *et al* 2004, van der Zee *et al* 2005).

The MC simulation of radiation transport in linac targets is particularly inefficient. In these structures, electrons are transported through high atomic numbered materials in order to produce bremsstrahlung photons. Furthermore, photons are emitted in all directions and only a fraction of them are directed at the bottom of the accelerator and are useful for dose

calculations; the rest are absorbed in the linac head components or exit the geometry. Thus, the use of variance-reduction (VR) techniques has been mandatory to reduce the simulation times to clinically acceptable values.

Recently, Brualla and co-workers (2009) proposed a VR technique based on defining layers of variable thickness in parts of the linac geometry (movable skins). Collimating structures are constructed with those skins in the surfaces that are directly exposed to the beam. In skin regions, all the particles are simulated normally, whereas in non-skin regions charged particles are locally absorbed. This technique can save a substantial amount of simulation time otherwise dedicated to transport particles that will not contribute to tallied quantities. These authors also showed that an additional improvement of efficiency can be obtained when the movable-skin technique is combined with rotational splitting (Brualla and Sauerwein 2010) of photons in a plane situated above the jaws.

Kawrakow *et al* have provided the code BEAMnrc (Rogers 1995) with a powerful VR method called directional bremsstrahlung splitting (DBS) which is applied to most components of the linac head, including the target (Kawrakow *et al* 2004). The method offers an important improvement in simulation efficiency associated with the computation of the dose (of about 6 times for a 6 MV beam in a realistic geometry of an Elekta SL25 linac) over other splitting methods previously implemented in BEAMnrc. The simulation efficiency relative to an analogue simulation (obtained for the same beam and geometry) is presented as a function of radius and depth in the phantom and varies between 100 and 180 inside the radiation field. DBS relies on calculating the probability of a photon entering a user-defined field by integrating the angular distributions of bremsstrahlung and Compton-scattered photons over the solid angle formed by the field as seen from the point of emission or scattering. Photon sampling subroutines implemented in EGSnrc (Kawrakow and Rogers 2001) are superseded by subroutines that use this probability of determining the number of bremsstrahlung photons or Compton interactions to be sampled.

In this paper, we propose a method to improve the simulation efficiency of photon beams produced by linacs. The method, called splitting-roulette, is based on a combination of the Russian roulette technique, applied to electrons, and particle splitting applied to their descendant photons. It has been implemented on the MC code PENELOPE (Salvat *et al* 2009, Sempau *et al* 1997, Baró *et al* 1995). All simulations have been done using the PENELOPE's associated steering main program PENEASY (Sempau *et al* 2011). This main program offers some advantages to users, such as the possibility of adding new functionalities without altering the overall structure of the code or the implementation of the transport algorithm.

2. Classification of photons

The criterion used here to classify photons according to whether or not they are directed at the bottom part of the linac is similar to the one proposed by Kawrakow and co-workers (2004) and it is based on establishing a region-of-interest representative of the radiation field at the bottom of the accelerator. Our geometric model is detailed in figure 1. The z-axis is the central axis of the photon target, i.e. the beam central axis of the linac. To represent the useful radiation field, a circular region of interest (CROI) of radius R has been defined at a distance d from the origin of coordinates located at the center of the upstream surface of the target. In our MC simulations, primary electrons start moving from the origin and travel toward the positive direction of the z-axis. Let us consider a photon moving from the point (x_0, y_0, z_0) in a direction, determined by its direction cosines (u, v, w), such that it crosses the CROI plane at a point (x_1, y_1, z_1). The photon is considered as pointing to the radiation field at the bottom

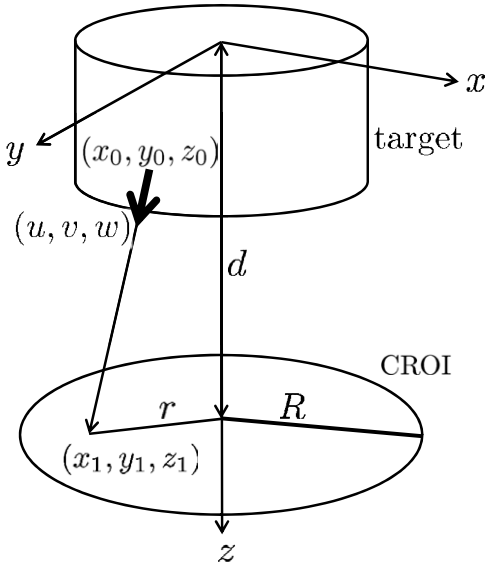

Figure 1. The geometry used for classifying photons produced in the target.

Table 1. Results of the classification of photons produced in an Elekta target by electrons with initial energy of 6.5 and 18.0 MeV.

Initial energy of electrons (MeV)	Site of classification	IN-photons per initial electron	OUT-photons per initial electron	Total photons per initial electron	IN-photons Total photons (%)
6.5	Emission point	0.249	0.687	0.936	26.63
	Target border	0.222	0.714	0.936	23.76
18.0	Emission point	1.340	1.342	2.682	49.97
	Target border	1.193	1.490	2.682	44.46

of the linac if its radial distance r is less than R (see figure 1). These photons will be referred to as IN-photons. Photons not crossing the CROI ($r > R$) will be referred to as OUT-photons.

We have classified all photons produced in the target of an Elekta linac according to their position and direction of flight in two different instants of their simulation, namely immediately after they are produced and when they cross any of the external surfaces of the target. The values of d and R have been selected in such a way that the CROI is located at the plane of the upper surface of the primary collimator of an Elekta linac and its diameter is 1 cm wider than the aperture of the collimator at that plane. Note that the primary collimator was not included in the geometry. The classification was done for beams with initial energies of 6.5 and 18.0 MeV. A total of 5×10^8 primary electrons were simulated in both cases. We have added a new module to penEasy which classifies photons in the target and saves that information in a phase-space file.

Results of the photon classification are shown in table 1. It is notable that most of the photons produced in the target (73.4%) by electrons with an initial energy of 6.5 MeV are not aimed at the CROI. When photons are reclassified as they exit the target, this percentage becomes still higher (76.2%). Thus, interactions in the target reduce even more the already

scarce population of photons aimed at the CROI. In contrast, electrons with an initial energy of 18.0 MeV nearly produce as many IN as OUT photons. This is because higher energy electrons produce more bremsstrahlung photons in the forward direction.

3. Splitting-roulette

Simulation efficiency can be improved if all the electrons with a polar angle above a selected cut-off are subjected to Russian roulette and their descendant photons are split. The polar angle is the angle of the direction vector of the particle with respect to the positive z-axis. When Russian roulette is played on a particle, it continues to be simulated only if a uniformly distributed random number between zero and unity is smaller than a given survival probability SP. The statistical weight of the surviving particle is multiplied by a factor SP^{-1}. Russian roulette is frequently combined with particle splitting. In splitting, a particle is replicated NSPL times and the statistical weight of all resulting particles is multiplied by a factor NSPL^{-1}.

Russian roulette increases the particle's weight, whereas splitting decreases it. A proper combination of the two methods should ensure that the distribution of statistical weights of the particles arriving at the CROI has a relatively small dispersion, thus avoiding a degradation in efficiency. Dispersion in particle weight degrades the efficiency and, therefore, a technique focused on reducing the variance should avoid producing such particles. What follows is a comprehensive description of the algorithm implemented.

As an electron starts to be simulated or after it undergoes an interaction, the algorithm proceeds as follows.

If the statistical weight of the electron is less or equal to unity and its polar angle is larger than the cut-off, then Russian roulette is applied with a survival probability SP. If the electron does not survive, it is discontinued from simulation. Otherwise, its statistical weight is increased by a factor of SP^{-1}.

As a photon starts to be simulated, the algorithm proceeds as follows.

If the photon is IN, then it splits NSPL times and its statistical weight and that of its replicas are multiplied by a factor of NSPL^{-1}. All the split photons are simulated. If the photon is OUT it is simulated without splitting.

After a photon undergoes an interaction, the algorithm proceeds as follows.

If the photon weight is greater or equal to unity and its direction points to the CROI, then it splits NSPL times and its statistical weight and that of its replicas are multiplied by a factor of NSPL^{-1}. Otherwise, the photon is simulated without splitting. Note that photons have to be reclassified after undergoing an interaction due to the possible change of their direction of flight.

The splitting-roulette technique was implemented in the program penEasy. A new Fortran module was written and linked to the program. The input file was extended to include a new block that allows us to enable/disable the method and to set values for the radius and distance of the CROI, the cut-off angle, the electron survival probability and the photon splitting number.

4. Performance of the method

4.1. Simulation geometry

In order to assess the effect on efficiency of the splitting-roulette technique, we have performed simulations in a simplified model of an Elekta linac and a water phantom. The geometry includes the target, the primary collimator and the 6 MV flattening filter. A water cylinder with 40 cm radius is situated at 70 cm from the target. There is no air in the geometry, so particles

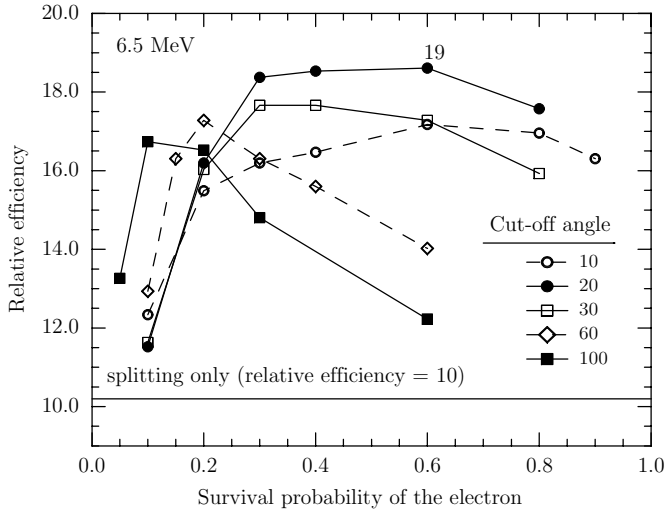

Figure 2. Variation of the efficiency for a range of survival probabilities and cut-off angles. The values were normalized to the efficiency with no VR. The splitting number was of 40 in all cases. Maximum efficiency is obtained for a cut-off angle of 20° and a survival probability of 0.6. The initial energy of electrons was 6.5 MeV.

exiting one component are ray-traced until they reach the surface of another component or abandon the geometry. The primary electron source is assumed to be a monoenergetic 6.5 MeV point-like pencil beam with zero divergence. Dose distribution in water is estimated at radial intervals of 0.5 cm from $r = 0$ to 25 cm, and depth intervals of 0.5 cm from $z = 0$ to 10 cm. The efficiency of the simulation is evaluated as

$$\epsilon = \frac{1}{t\overline{\Delta}^2}. \tag{1}$$

In this definition, t is the total simulation time and $\overline{\Delta}$ is the relative uncertainty of the dose averaged for all bins with a dose value higher than half the maximum dose. The cylindrical symmetry of the simulated geometry allows estimating the efficiency with a low statistical uncertainty in a reasonable simulation time. This cylindrical geometry is used for testing the method and for calculating the set of parameters that better improve the efficiency.

4.2. Selection of the cut-off angle and the survival probability

We have evaluated a range of cut-off angles and survival probabilities in order to determine what combination produces the highest efficiency. For this purpose, the CROI was located at the surface of the water phantom ($d = 70$ cm) with a radius R of 35 cm. A splitting number of 40 was chosen. As will be seen in section 4.4, this is a reasonable value. The splitting-roulette technique was applied only to the photon target. Efficiency values were normalized to the efficiency obtained with no VR. Simulations were run until a relative uncertainty of 2.0% (2 s.d.) was reached.

The results are presented in figure 2. When the cut-off angle was set to 180°, i.e. no electrons were subjected to Russian roulette, the gain in efficiency was a factor of 10. This value is represented as a baseline in figure 2. As can be seen in this figure, the combination of Russian roulette and splitting enhances the efficiency up to a factor of 1.9 over the one obtained with splitting only. Results also show that the efficiency increases with combinations of low-to-mid cut-off angles (10–30°) and mid-to-high (0.3–0.8) survival probabilities. The

combination of low survival probabilities and low cut-off angles impoverishes the efficiency because many electrons are early discontinued from simulation and the photons created by those electrons that survived Russian-roulette have a high statistical weight. For high cut-off angles the efficiency gain is poor, due to the considerable time that is employed in simulating the electron before it is subjected to Russian roulette. In all cases, as the cut-off angle increases, the maximum relative efficiency is obtained at a lower survival probability of the electron. The overall maximum of 19 is obtained for a cut-off angle of 20° and a survival probability of 0.6. For that cut-off angle, the variation of the efficiency with the survival probability is small in the range of 0.3–0.6.

4.3. Extension of the method to various linac components

The splitting-roulette technique proposed here is not only suitable to be used in the photon target, but also in other components of the linac. The procedure for the classification of particles employed in the photon target applies irrespective of the place where the particle is created or scattered. The only condition to satisfy is that the CROI plane must be located downstream of all active structures. That could be at the bottom of the linac. When the method is applied to the target, the primary collimator and the flattening filter, it is convenient to locate the CROI in a plane above the jaws. The radius of the CROI should be set slightly larger than the aperture of the jaws in order to reproduce the penumbras.

Furthermore, one inherent and undesirable characteristic exhibited by the splitting-roulette technique when it is not used in all the components of the linac geometry is that high-weight particles interact in the scoring zone. That is, a high-weight OUT-photon can undergo scattering in a component where the method is disabled. If as a consequence of changing its direction of flight that initially OUT-photon becomes IN, then it will not be split. So, it is aimed at the scoring zone where it could interact and introduce a very large contribution to the uncertainty. Particles descending from a high-weight OUT photon could also reach the scoring zone.

Figure 3(a) shows a surface plot of the inverse of the relative efficiency for the whole range of radii and depths in the water phantom used for tallying the dose distribution obtained in a simulation in which the method was applied only to the photon target. The presence of prominent peaks corresponding to low values of the relative efficiency can be seen in the surface graph. These peaks are produced by particles with high statistical weight that interact in the water phantom.

A simple solution to this difficulty is to forcefully split high-weight particles as they traverse the plane of the CROI. In practice, all particles with weight greater or equal to unity are split at the CROI with a splitting number calculated as NSPL times the weight of the particle. This is to ensure a uniform weight of NSPL^{-1} for all particles reaching the tally.

Figure 3(b) shows the surface plot of the inverse of the relative efficiency for the same simulation used to produce figure 3(a), but in this case, high-weight particles were split at the CROI plane that was located just above the water phantom. It can be seen that the low efficiency peaks have disappeared.

When high-weight particles are split at the CROI plane, the efficiency improvement of 19 determined in the previous section by using the best values of the cut-off angle and the survival probability (i.e. 20° and 0.6, respectively) and a NSPL of 40, augments to 21, which is 1.1 times better.

We also performed a simulation in which the splitting-roulette method was applied to the photon target, the primary collimator and the flattening filter, i.e. all the linac components included in the simplified geometry. The splitting number was set to 40. Other simulation settings remained the same as in the previous section. Under these conditions, the efficiency

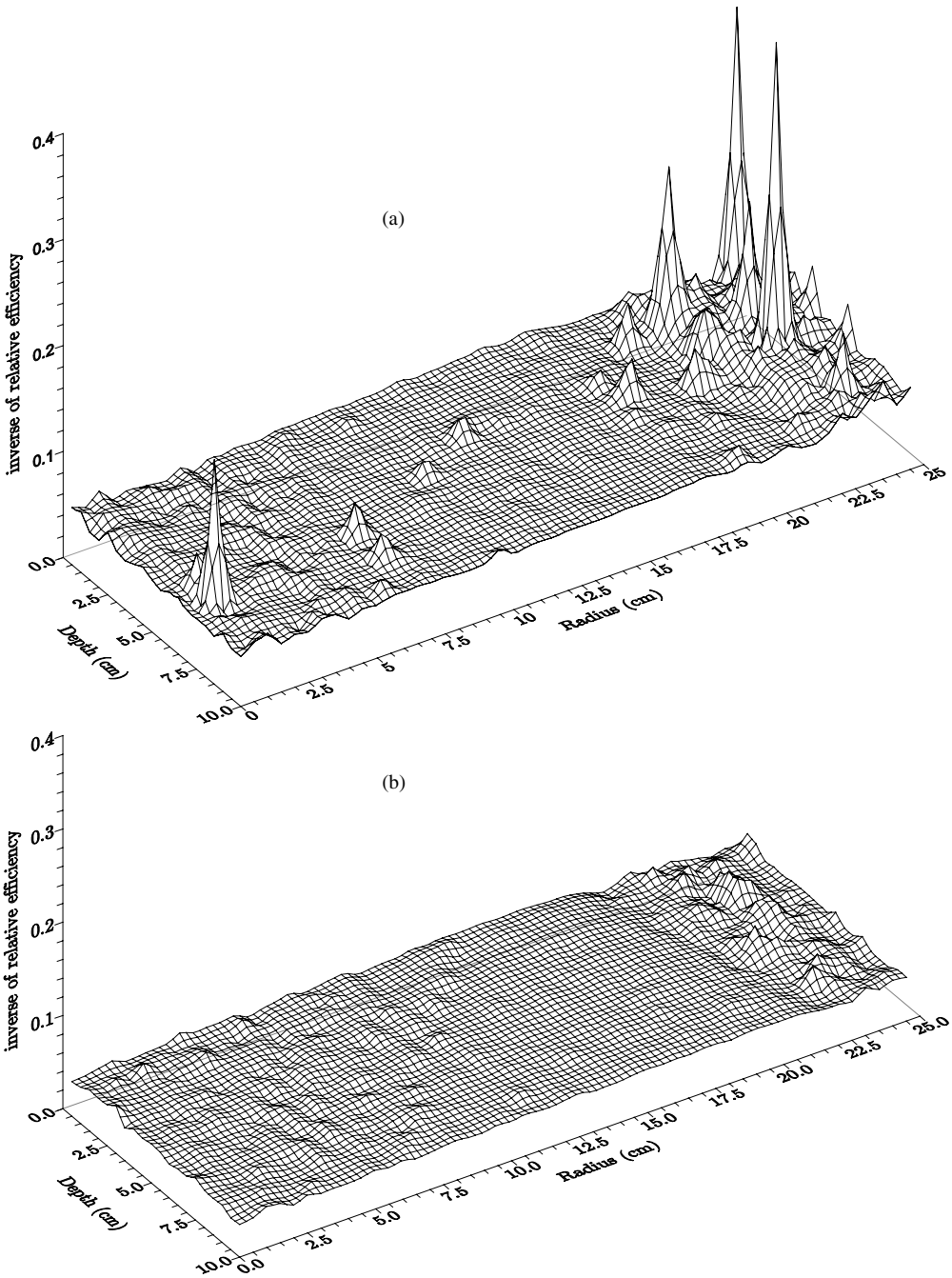

Figure 3. Surface plots of the inverse of the relative efficiency calculated for a simulation in which the splitting-roulette was applied only to the target. (a) The peaks represent the effect of particles with high statistical weight that hit the scoring zone after being scattered in linac components in which the method is off. (b) The high variance peaks are eliminated by forcing splitting of high weighted particles at crossing the CROI plane.

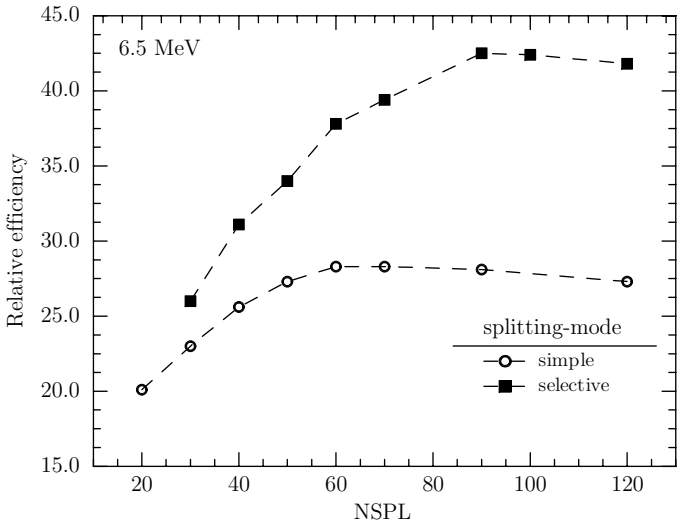

Figure 4. Variation of the relative efficiency with the splitting number and mode. The method was applied to the target, the primary collimator and the flattening filter.

is improved by a factor of 1.2 with respect to a simulation in which the splitting-roulette technique was applied only to the target and 26 with respect to a simulation in which VR was not applied at all. So, extending the use of the method to various linac components proved to be advantageous.

4.4. Splitting number and mode

A new particle splitting technique for bremsstrahlung photons has been implemented. The method, which will be referred to as selective splitting, consists in creating replicas of a bremsstrahlung photon in such a way that each photon is emitted with a direction of flight, respective to that of the emitting electron, sampled independently from the direction assigned to the other replicas. Photons flying in the direction of the CROI are stored in a particle stack and simulated sequentially after the simulation of the primary electron has been completed. Photons not aiming at the CROI are subjected to Russian roulette and, if they survive, stored in the stack.

The direction cosines for each replica are obtained by calling the PENELOPE subroutines that sample the photon direction. In PENELOPE, the angular distribution of bremsstrahlung photons produced by electrons with kinetic energies below 500 keV is modeled with a parameterization of the partial-wave shape functions of Kissel *et al* (1983). For electrons with kinetic energies larger than 500 keV, the shape function is approximated by the classical dipole distribution. The random sampling of the photon direction is implemented in a simple and fast algorithm (Salvat *et al* 2009). For annihilation and Compton scattered photons, the algorithm proceeds as described in section 3.

We have evaluated the variation of the efficiency with the splitting number and mode. In this case, we have applied the algorithm to the target, the primary collimator and the flattening filter. For a given simulation, the same splitting number was used in the three structures. The best combination of the cut-off angle and survival probability was used in all cases.

Figure 4 shows the variation of the efficiency against the splitting number normalized to the efficiency with no VR. It is clear that selective splitting is considerably more efficient

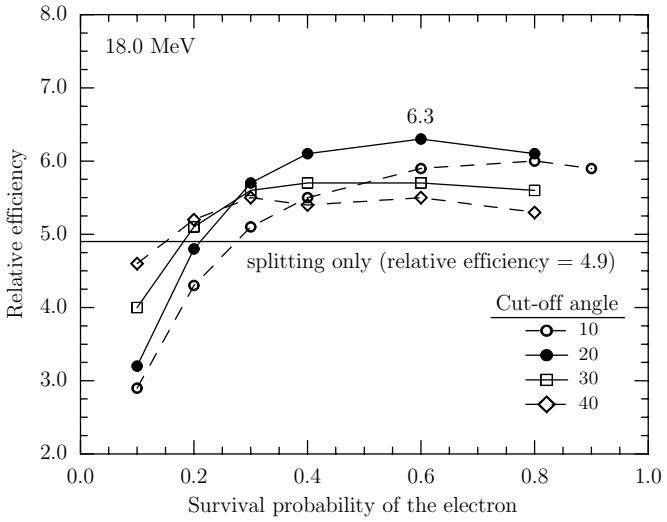

Figure 5. Variation of the efficiency for a range of cut-off angles and survival probabilities for simulations with initial energy of electrons of 18.0 MeV. The values were normalized to the efficiency with no VR. The splitting number was of 40 in all cases.

than simple splitting. The maximum relative efficiency of simple splitting is 28 at NSPL = 60, whereas for selective splitting it is 43 at NSPL = 90, which is 1.5 times better.

4.5. Performance at high energy

We tested the performance of the method for electrons with an initial energy of 18 MeV. In this case, the simplified geometry described above was modified to remove the 6 MV flattening filter and to include the low-energy 4 MV filter and the 4/18 MV difference filter. The rest of the geometry characteristics were maintained.

The results obtained for the classification of photons in the target demonstrated that due to the more peaked forward angular distribution of bremsstrahlung photons at high energies, the fraction of IN-photons per initial electron increases considerably at 18 MeV. As a consequence, the simulation efficiency associated with the dose estimation with no VR obtained for the 18.0 MeV beam is a factor of 3.7 higher than the one obtained for the 6.5 MeV beam. This has a repercussion on the performance of the method. It can be seen from the curves of efficiency against the cut-off angle and survival probability, represented in figure 5, that the best values of those parameters are the same found for the 6.5 MeV beam (i.e. 20° and 0.6). However, for the 18 MeV case, the maximum efficiency improvement factor is only 6.3. The same effect is seen in the curves of efficiency against the splitting number shown in figure 6. Again, the best results are obtained for the selective splitting mode, but the maximum efficiency gain is merely a factor of 10. Also, the maximum improvement is obtained at a lower splitting number (40) than in the 6.5 MeV case (90). However, the absolute value of the maximum efficiency obtained for both energies is similar.

4.6. Performance in a realistic linac geometry

The performance of the method in the calculation of the dose produced by a 6.5 MV photon beam of an Elekta SL25 linac has been investigated. We have coded the geometry of the linac

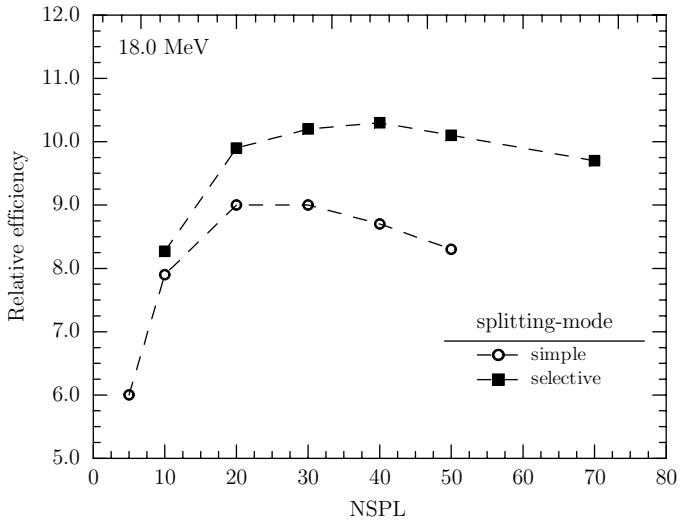

Figure 6. Variation of the relative efficiency with the splitting number and mode for simulations with an initial energy of electrons of 18.0 MeV. The method was applied to the target, the primary collimator and the flattening filters.

provided by the manufacturer. The jaws were positioned to define a 10×10 cm^2 field at the surface of a water phantom that was situated at 100 cm from the source. For dose estimation, we used a cubic phantom gridded in bins of $0.6 \times 0.6 \times 0.6$ cm^3 size. Two simulations were performed, one in which no VR of any kind was used and another in which the splitting-roulette method was applied to the target, the primary collimator and the 6 MV flattening filter. The best parameters found above for the cut-off polar angle (20°), the survival probability of the electron (0.6), the splitting type (selective splitting) and the splitting number (90) were used in those components. A CROI with $R = 4.5$ cm was situated above the jaws at a distance of 25.8 cm from the source. Both simulations were run for a total of 2×10^9 initial electrons.

The value found for the relative efficiency was 45. This value is similar to the one obtained for the simulation using the best parameters in a simplified geometry (43) proving the suitability of that geometry for the evaluation of the method.

In all simulations presented in this paper, the values of survival probability, cut-off polar angle and splitting number that produced the highest efficiency have been found by varying only one of those parameters while keeping the others fixed. Hence, it is not guaranteed that the set of parameters found is optimal for each simulation and the relative efficiencies found might be further increased.

5. Conclusions

We have shown that the use of the splitting-roulette technique can significantly improve the efficiency of MC simulations of photon beams produced by linacs. Splitting-roulette is based on a combination of standard VR techniques. We have found a set of parameters that improves the dose calculation efficiency in a simplified geometry of an Elekta linac and a water phantom. Using those parameters, a gain by a factor of 45 times in the dose calculation efficiency is obtained in a realistic geometry of an Elekta SL25 linac and in a water phantom with bins sized in the range relevant for treatment planning purposes.

It is worth pointing out that the use of the DBS method of Kawrakow and collaborators (Kawrakow *et al* 2004) improves the simulation efficiency with respect to a simulation without VR by a factor that is 3.5 higher than the corresponding factor obtained with the method presented in this work. However, the implementation of DBS in a MC code is a non-trivial task. It requires adapting the algorithm that generates bremsstrahlung radiation to ensure that all the created photons aim at the field. In contradistinction, our VR technique can be implemented at the main program level without altering the inner workings of the physics routines. Thus, it can be used by other general-purpose MC codes with a relatively low coding effort.

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References

Baró J, Sempau J, Fernández-Varea J M and Salvat F 1995 PENELOPE: an algorithm for Monte Carlo simulation of the penetration and energy loss of electrons and positrons in matter *Nucl. Instrum. Methods* B **100** 31–46

Brualla L, Salvat F and Palanco-Zamora R 2009 Efficient Monte Carlo simulation of multileaf collimators using geometry-related variance-reduction techniques *Phys. Med. Biol.* **54** 4131–49

Brualla L and Sauerwein W 2010 On the efficiency of azimuthal and rotational splitting for Monte Carlo simulation of clinical linear accelerators *Radiat. Phys. Chem.* **79** 929–32

Fippel M 1999 Fast Monte Carlo dose calculation for photon beams based on the VMC electron algorithm *Med. Phys.* **26** 1466–75

Hartmann Siantar C L *et al* 2001 Description and dosimetric verification of the PEREGRINE Monte Carlo dose calculation system for photon beams incident on a water phantom *Med. Phys.* **28** 1322–37

Kawrakow I 2001 VMC++, electron and photon Monte Carlo calculations optimized for Radiation Treatment Planning *Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications: Proc. of the Monte Carlo 2000 Meeting Lisbon* ed A Kling, F Barao, M Nakagawa, L Távora and P Paz (Berlin: Springer) pp 229–36

Kawrakow I and Rogers D W O 2001 The EGSnrc code system: Monte Carlo simulation of electron and photon transport *Report* PIRS-701 (Ottawa: National Research Council of Canada)

Kawrakow I, Rogers D W O and Walters B 2004 Large efficiency improvements in BEAMnrc using directional bremsstrahlung splitting *Med. Phys.* **31** 2883–98

Keall P J and Hoban P W 1996 Super-Monte Carlo: A 3-D electron beam dose calculation algorithm *Med. Phys.* **23** 2023–34

Kissel L, Quarles C A and Pratt R H 1983 Shape functions for atomic-field bremsstrahlung from electrons of kinetic energy 1–500 keV on selected neutral atoms $1 \leqslant Z \leqslant 92$ *At Data Nucl. Data Tables* 381–460

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

Neuenschwander H, Mackie T R and Reckwerdt P J 1995 MMC—a high-performance Monte Carlo code for electron beam treatment planning *Phys. Med. Biol.* **40** 543–74

Reynaert N, De Smedt B, Coghe M, Paelinck L, Van Duyse B, De Gersem W, De Wagter C, De Neve W and Thierens H 2004 MCDE: a new Monte Carlo dose engine for IMRT *Phys. Med. Biol.* **49** N235–41

Rogers D W O 1995 BEAM: a Monte Carlo code to simulate radiotherapy treatment units *Med. Phys.* **22** 503–24

Salvat F, Fernández-Varea J M and Sempau J 2009 PENELOPE-2008: A code system for Monte Carlo simulation of electron and photon transport *OECD/NEA* No 6416 (Issy-les-Moulineaux, France)

Sempau J, Acosta E, Baró J, Fernández-Varea J M and Salvat F 1997 An algorithm for Monte Carlo simulation of coupled electron–photon transport *Nucl. Instrum. Methods* B **132** 377–90

Sempau J, Badal A and Brualla L 2011 PENELOPE-based system for the automated Monte Carlo simulation of clinacs and voxelized geometries—application to far from-axis fields *Med. Phys.* at press doi:10.1118/1.3643029

Sempau J, Wilderman S and Bielajew A 2000 DPM, a fast, accurate Monte Carlo code optimized for photon and electron radiotherapy treatment planning dose calculations *Phys. Med. Biol.* **45** 2263–91

van der Zee W, Hogenbirk A and van der Marck S C 2005 ORANGE: a Monte Carlo dose engine for radiotherapy *Phys. Med. Biol.* **50** 625–41

Wang L, Chui C S and Lovelock M 1998 A patient-specific Monte Carlo dose-calculation method for photon beams *Med. Phys.* **25** 867–78