Original article

Optimisation of variance reduction techniques in EGSnrc Monte Carlo for a 6 MV photon beam of an Elekta Synergy linear accelerator

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ABSTRACT

Objective: Monte Carlo (MC) simulations are considered to be the most accurate form of algorithm for dose calculation. However, the main obstacle to using MC, especially in clinical routine, is the simulation time needed to gain results below a desirable level of uncertainty. Variance reduction techniques (VRTs) have been introduced to reduce the simulation time while maintaining the uncertainty at an acceptable level. The aim of this study is to investigate and optimize the VRTs implemented in EGSnrc MC code, BEAMnrc and DOSXYZnrc.
Methodology: The BEAMnrc user code was used to model a 10×10 cm^2 field size of a 6 MV photon beam from an Elekta Synergy linear accelerator. The DOSXYZnrc user code was used to model a water phantom. The effects of different VRTs on the simulation efficiency were investigated either individually or in combination. The directional bremsstrahlung splitting (DBS) technique was investigated further to find the optimum splitting number and splitting field radius. For DOSXYZnrc, the photon splitting was investigated to find the best combination with the VRTs in BEAMnrc and to find the optimum splitting number. Finally, the best combination of VRTs in both BEAMnrc and DOSXYZnrc was compared with the corresponding phase space (PHSP) simulation source.
Results: The DBS technique was found to be the most efficient. The optimum splitting number was found to be 10,000 and 15,000 with and without electron splitting, respectively. For the DBS splitting field radius, overestimating by up to 3 cm would be sufficient without causing a significant loss in efficiency. For both BEAMnrc and DOSXYZnrc, the combination of DBS, bremsstrahlung cross-section enhancement, range rejection with 2 MeV and photon splitting (with optimum splitting number of 35) was the most efficient, and was about 8% less efficient than PHSP simulation.
Conclusion: The VRTs implemented in EGSnrc MC code made it possible to achieve an acceptably small uncertainty within a reasonable simulation time, if optimised properly. The combination of VRTs presented in this study eliminates the need to spare a large amount of disk space, and where parallel computing could allow for MC dose calculation in real-time adaptive treatment planning.

1. Introduction

In radiotherapy, the Monte Carlo (MC) simulation is effectively considered the gold standard approach to benchmarking treatment planning system dose calculation algorithms (Seco and Verhaegen, 2013). In Monte Carlo simulations, any linear accelerator (Linac)

can be modelled accurately if its components are understood in great detail. The MC method is a numerical method based on random sampling to approximate solutions to mathematical equations or integrals and produces a probability distribution for the quantity being estimated, and where the uncertainty can be calculated from this distribution (Rogers and Bielajew, 1990). A reliable average value can be achieved by simulating a large number of events that are associated with a statistical uncertainty.

However, despite the accuracy of MC simulations, they requires powerful central processing units (CPUs) time to achieve a desirable statistical uncertainty. Even with the arrival of modern fast computers, the calculation time is still the main disadvantage when using pure MC simulations for clinical routines (Zeghari et al., 2019).

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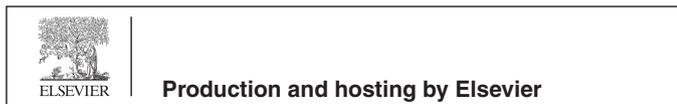
Considerable effort has been devoted to reducing calculation times to clinically acceptable levels, which includes the implementation of variance reduction techniques (VRTs) and the use of distributed computing techniques (Kawrakow et al., 2004; Kawrakow, 2005; Kawrakow and Walters, 2006; French et al., 2016). The aim of a VRT is to minimize either calculation time or the uncertainty without affecting the accuracy of the calculation.

For the EGSnrc MC code, and the BEAMnrc and DOSXYZnrc user codes, there are many VRTs that have been proposed to increase the efficiency of the calculation. Some these VRTs are photon forcing, photon splitting, uniform bremsstrahlung splitting, and directional bremsstrahlung splitting. In addition, the range rejection technique was implemented as an approximate efficiency improvement technique. Various studies have investigated these VRTs for different Linacs with different energies (Almberg et al., 2011; Mohammed et al., 2016; Hoang et al., 2019; Zeghari et al., 2019). The optimal setting of each VRT parameter depends on the energy and the details of the Linac being simulated.

In this study, the VRTs in the EGSnrc MC code are investigated using a MC model of the Elekta synergy Linac with a 6 MV photon beam. Each VRT implemented in BEAMnrc is investigated individually. In addition, the optimum VRT combination is then used to investigate the VRTs implemented in DOSXYZnrc. Finally the combination that gives the most efficient simulation is compared with the corresponding phase space (PHSP) simulation source.

2. Method and materials

2.1. Linear Accelerator

The Elekta Synergy linear accelerator is held at Singleton Hospital, Swansea, UK (version 4.5, Elekta^{TM}, Crawley, West Sussex, UK). It consists of the target, primary collimator, flattening filter, chamber, backscatter plate, multi-leaf collimator (MLC), backup jaws, secondary collimator and Mylar sheet, and was modelled using the BEAMnrc user code using appropriate component modules (CMs) based on manufacturer information (Fig. 1). The validation of the model, however, is beyond the scope of this study.

2.2. BEAMnrc user code

In this study, the most recent version of the EGSnrc MC code was used. The BEAMnrc code was used to simulate a 10×10 cm^2 field size defined at 100 cm using source number 19 (Rogers et al., 2013). The beam intensity and the field size of the beam field were defined using MLC, backup jaws and secondary collimator components.

Most of the simulation parameters used in the BEAMnrc code were left at their recommended (default) values. The energy cutoffs for electrons and photons (ECUT and PCUT) were set to 700 keV and 10 keV, respectively. At first, each VRT was used separately and compared to the analogue method, after which the combination of different BEAMnrc VRTs that provided the most efficient simulation was investigated. Then, the combination that gave the most efficient simulation when combined with particle splitting as implemented in DOSXYZnrc (see Section 2.3.) was compared with the corresponding PHSP simulation source. In the PHSP simulation, the Linac is divided into two phases: the patient-independent and patient-dependent. Thus, it saves time to score a PHSP file just below the patient-independent part and use it as a source to avoid repeating the simulation each time. In this study, the PHSP was placed just above the MLC CM.

In the following subsection, each VRT implemented in BEAMnrc used in this study is briefly described. This includes bremsstrahlung cross-section enhancement, photon forcing, split electron or photon, range rejection and bremsstrahlung splitting, both uniform and directional.

2.2.1. Bremsstrahlung cross-section enhancement (BCSE)

In 2007, the BCSE technique was introduced to improve the efficiency of the production of bremsstrahlung in Linac targets (Ali and Rogers, 2007). The cross-section of the bremsstrahlung in the target is scaled up by a factor defined by the user. In this study, the BSCE was first used alone, where the enhancement constant and the enhancement power were set to 20 and 0, respectively. In this case, the value of enhancement constant became the enhancement factor (Rogers et al., 2013). It was then used in combination with the other VRTs using the same values.

2.2.2. Photon forcing

In specific CM, the probability of interaction of a photon can be improved by forcing photons to interact in that CM (Rogers et al., 2013). When this option is applied, the process is repeated until a number of interactions, defined by the user, have been forced. The photon splitting was performed on the last CM of the Linac, just above the water phantom, and the splitting number (ICM_SPLIT) was 1000. This option was first investigated alone and as compared with other VRTs. It was then used in combination with the other VRTs.

2.2.3. Range rejection

Another technique used to save computing time in the simulation is range rejection. This technique terminates and deposits all of a charged particle's energy locally when it cannot leave a specific CM with an energy greater than the range rejection cutoff energy (ESAVE). Thus, it assumes that any bremsstrahlung photons created by that particle do not leave that region. The ESAVE value is defined by the user for CMs. Below ESAVE, range rejection is turned on. This option was first investigated alone for two different ESAVE values (1 and 2 MeV) and as compared with other VRTs. It was then used in combination with the other VRTs.

2.2.4. Split electrons or photons

When this option is turned on, the photons or electrons are split by a number of times specified by the user as soon as they pass an arbitrary plane at the top of a selected splitting CM, which is also specified by the user (Rogers et al., 2013). This option is mainly designed for photon beams to allow splitting in phantom at the bottom of a Linac, thus improving efficiency of phantom depth-dose calculations. First, this VRT was used alone and then when combined with other VRTs and the splitting photon number (ICM_SPLIT), without electron splitting, was 1000 in the last component of the Linac, just above the water phantom.

2.2.5. Bremsstrahlung photon splitting

The bremsstrahlung splitting technique is introduced in BEAMnrc to increase the statistics of bremsstrahlung photons whilst retaining a reasonable calculation time (Rogers et al., 2013). By applying this technique, the time that would otherwise be required to simulate a large number of electrons is negated. In the most recent version of the BEAMnrc user code, there are only two options, uniform and directional bremsstrahlung splitting.

2.2.6. Uniform Bremsstrahlung Splitting (UBS)

When UBS is applied, each bremsstrahlung event produces a number of photons (NBRSPL). Each of these photons has a weight equal to 1/NBRSPL multiplied by the weight of the electron that underwent the bremsstrahlung event. These split photons create secondary charged particles, and attempting to follow all of them will increases computational time significantly. Using the Russian roulette (RR) technique with these charged particles can reduce
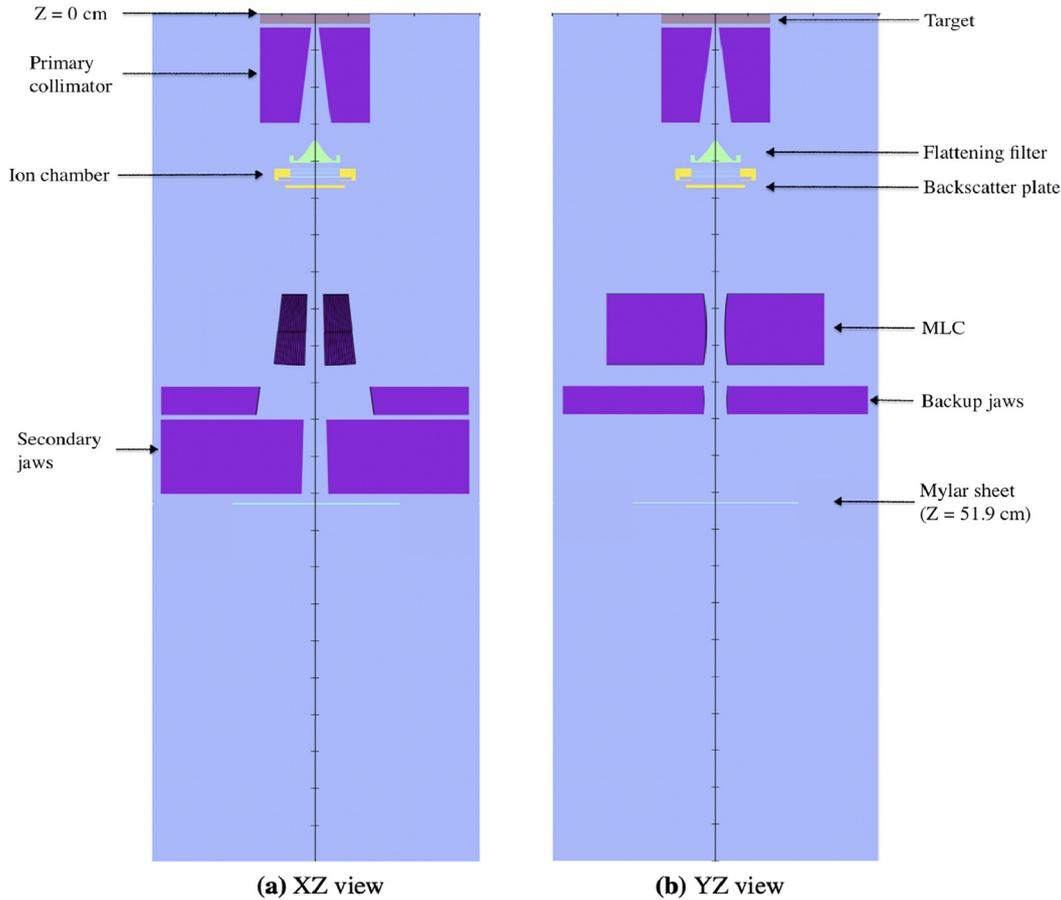
Fig. 1. The MC model components of the Elekta Synergy Linac.

the associated simulation time by determining its survival by comparing a random number to the survival probability (1/NBRSPL). In this study, the UBS technique is investigated with and without use of the RR technique. For both cases, the splitting number was 1000.

2.2.7. Directional Bremsstrahlung Splitting (DBS)

Like UBS, DBS uses a constant value of NBRSPL but only considers photons that fall within a specific field radius defined by the user (Kawrakow et al., 2004; Kawrakow and Walters, 2006). On the other hand, RR is applied to those photons that are not directed into the field of interest to determine their survival by comparing a random number to the survival probability. The photon is kept if the random number is less than the survival probability and its statistical weight multiplied by the NBRSPL, and is considered to be a fat photon. In this study, the DBS parameters were first chosen as follows: the splitting number was 1000, the splitting field radius was 10, and the source to surface distance (SSD) at which the field was defined was 100 cm with no CM for e−/e+ splitting. Then, the DBS technique was investigated further to determine the optimum splitting number, with and without CM for e−/e+ splitting. Finally, after determining the optimum values, the splitting field radius for a 10×10 cm^2 field size in this instance, was investigated further to determine the optimum splitting field radius.

2.3. DOSXYZnrc user code

The DOSXYZnrc code was used to model a water phantom (Walters et al., 2013). At first, all simulations were performed using a $20.25 \times 20.25 \times 30$ cm^3 water phantom, where the voxel size was
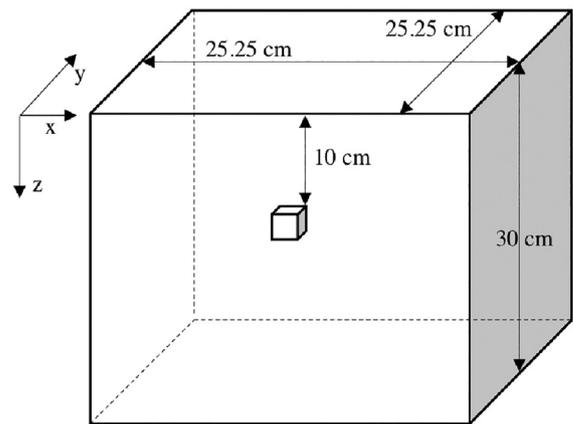
Fig. 2. Voxel water phantom modelled in DOSXYZnrc code.

$0.5 \times 0.5 \times 0.5$ cm^3 as shown in Fig. 2. The SSD was 90 cm. In combination with different BEAMnrc VRTs, the photon splitting number (n_split) implemented in DOSXYZnrc to increase the efficiency of dose calculations was investigated with and without the e−/e+ splitting option (e_split), which is available with source number 9. This technique allows splitting photons as they enter the phantom geometry. Then, after finding the most efficient combination, the photon splitting number was investigated further to find the optimum n_split.

2.4. Efficiency calculation

The efficiency ε of a MC simulation can be defined as per the following equation:

$$\varepsilon = \frac{1}{T.s^2}, \tag{1}$$

where T is the CPU time and s is the uncertainty of the quantity of interest (Kawrakow and Walters, 2006). In this study, the efficiency, ε, was calculated using the uncertainty of the dose in a voxel on the central axis at a 10 cm depth in the water phantom. All simulations were performed on a MacOS 10.15 with a 2.9 GHz Quad-Core Intel Core i7 processor and 16 Gb of RAM.

3. Results and discussion

3.1. Efficiency of BEAMnrc VRTs

First, each VRT implemented in BEAMnrc was investigated individually using the same number of particles, which here was 50×10^6 particles. The effect of increasing the number of particles was not considered in this study as this only reduces the uncertainty, allowing better estimation, without increasing the efficiency.

Table 1 shows the effects of different VRTs on the simulation efficiency. It can be clearly seen that all the VRTs improved the simulation efficiency compared with the analogue simulation. For the range rejection technique with 2 MeV, the efficiency was improved by a factor of about 1.9 compared to the analogue simulation. Compared to the analogue calculation, the simulation was about 3.6 and 32 times more efficient when using the UBS technique without RR and with RR, respectively. The efficiency was improved by a factor of about 51 when photon splitting was applied individually. From Table 1, it appears that the most efficient VRT was the DBS technique, where the efficiency was improved by a factor of 477 compared to the analogue simulation, and 9 times compared to photon splitting. In addition, the DBS technique provided the greatest efficiency gain, with dose efficiencies a factor of up to 131 and 15 greater than for the UBS technique without RR and with RR, respectively.

Mohammed et al. (2016) found that the DBS technique improved the efficiency by a factor of 1130 compared to the analogue case for a Saturne 43 Linac with a 12 MV photon beam. Hoang et al. (2019) investigated te DBS technique with a 6 MV photon beam from a HPD Siemens Primus Linac and found that the efficiency was improved by a factor of 90 compared to the analogue simulation. The differences in results between the previous studies and the current study might be due to the differences in both photon energy and Linac geometry.

Fig. 3. The effects of different DBS splitting numbers on efficiency.

3.2. Optimisation of DBS efficiency

The results reported in the previous section showed that DBS was the most efficient VRT technique, which was therefore investigated further to find the optimum splitting numbers (NBRSPL). Fig. 3 shows the variation of simulation efficiency with DBS splitting number. The efficiency of the simulation increased with increasing splitting number until reaching a maximum at an NBRSPL of 15,000; beyond this, the efficiency decreased gradually; therefore, the optimum value of the NBRSPL was found to be 15,000.

Hoang et al. (2019) investigated the efficiency of DBS with different splitting numbers for dose calculations. Their results showed that the optimal value was 1000. The maximum splitting number used in the study was 1500. It is worth mentioning that, in order to use high NBRSPL, the beamnrc_user_macros.mortran file has to be modified to avoid overflow.

In the DBS technique algorithm, almost all the charged particles are eliminated; few survive with a large weight (fat), thus it is very efficient with regard to photon fluence or dose. If the interest is in the charged particles' contribution to the dose, the e−/e+ splitting option in the DBS technique should be used to recover the charged particles (Rogers et al., 2013). In this study, the DBS with e−/e+ splitting was performed for the flattening filter CM (ICM_DBS). Table 2 shows the effects of DBS splitting number with e−/e+ splitting on the efficiency. Here, the optimum NBRSPL with e−/e+ splitting was found to be 10,000. Rogers et al. (2013) suggested that, in general, a NBRSPL of around 1000 achieves peak efficiency when e−/e+ splitting is used. As mentioned in Section 1, the optimal setting for each VRT parameter depends on the energy and the details of the Linac being simulated.

Fig. 4 shows the efficiency of the DBS splitting number (15,000) with different DBS splitting field radii. It can be clearly seen that as field radius increased the efficiency decreased. This may be due to the fact that, as the field radius increases, the DBS algorithm uses more CPU time as it loops through the split photons, determining

Table 1
Comparison of VRT simulations.

VRT		Time (s)	s	ε (s^{-1})
Analogue		1941483	0.0185	0.001505
BCSE		1931384	0.0185	0.001513
Range rejection	1 MeV	1080649	0.0184	0.002733
	2 MeV	1020836	0.0185	0.002862
Photon forcing		387416	0.0406	0.001565
Photon splitting		19988	0.0256	0.076341
UBS		54962	0.0186	0.005458
	with RR	6013	0.0184	0.047871
DBS		4207	0.0182	0.717480

Table 2
The effects of different DBS splitting numbers with e−/e+ splitting on the efficiency.

DBS splitting number	Time (s)	s	ε (s^{-1})
1000	46020	0.0180	0.067067
5000	44522	0.0180	0.069323
10000	43948	0.0180	0.070229
15000	44346	0.0180	0.065887
20000	44302	0.0184	0.066670
25000	43697	0.0184	0.067590
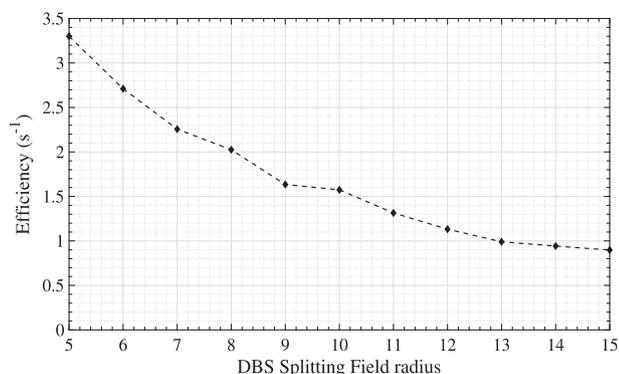
Fig. 4. The effects of different DBS splitting field radii on the simulation efficiency.

whether or not they are directed into the field of interest for each split photon. Thus the larger the radius the more photons are kept and simulated. The smallest field radius, 5 cm, that still provides adequate coverage (not diagonally) was the most efficient radius. Moving from 8 cm to 9 cm, the efficiency dropped sharply. Therefore, if there is a doubt about how far outside the edges of the beam field the splitting field of interest should go, overestimating by up to 3 cm would be sufficient for this purpose without causing a significant loss in efficiency. Moving from a 9 cm to a 10 cm radius, the efficiency decreased slightly. This might be due to the fact that not only increasing the number of histories affects the uncertainty on the efficiency estimate but also variability in the hardware performance, and other activity on the machine will also affect the estimate. However, this finding applies to DBS with e−/e+ splitting.

Zeghari et al. (2019) used BEAMnrc code to model a Saturne 43 Linac with a 12 MV photon beam. The study investigated the influence of using different splitting field radii (7, 10 and 13 cm) on the photon fluence efficiency for a 10×10 cm^2 field size. It was found that the field radius of 7 cm provided the highest efficiency. This is in agreement with the current finding results.

3.3. Efficiency of DBS combined with other BEAMnrc VRTs

Based on the previous results, the DBS technique was further investigated when it was combined with other VRTs. The results of this subsequent investigation are not shown for the sake of brevity but are provided in Appendix, Table A1. The best combination that provides the most efficient simulation was found when BCSE, range rejection with 2 MeV and splitting photons (ICM_SPLIT) were used with the DBS technique (with 15,000 NBRSPL and a 5 cm radius, as previously found). Such a combination was about 352% and 892% more efficient than DBS alone, with and without optimization, respectively, thus maximising the efficiency of the BEAMnrc calculation. This means that this calculation can be done in $\approx$ 1.2 h when using this combination to obtain a 0.5% dose uncertainty.

Zeghari et al. (2019) found that using the DBS technique individually was more efficient than combining it with other VRTs. The reason behind this observation may be due to the fact that the DBS parameters were not optimized. Another possible reason is that the BCSE enhancement constant and enhancement power were set to 20 and 2, respectively. Such a configuration would invoke a different BCSE algorithm than that described in the BEAMnrc manual, and the enhancement constant is no longer straightforward (Rogers et al. 2013). Thus, this might consume more CPU time than when DBS technique is used individually. In this study, the enhancement power was set to 0 and the enhancement constant to 20, which then effectively becomes the enhancement factor.

3.4. Efficiency of DOSXYZnrc photon splitting combined with BEAMnrc VRTs

In DOSXYZnrc, as soon as the particles (photons or electrons/-positrons) enter the geometry, they can be split a number of times. In this part of the study, the photon splitting (n_split) was investigated with different BEAMnrc VRTs to maximize the efficiency of the DOSXYZnrc calculation. The results are not shown for the sake of brevity (see Table A2 in the Appendix). At first, the photon splitting number (n_split) was set to 10 for all simulations in this part of the study.

The results showed that the most efficient simulation was when photon splitting was combined with DBS (with 15,000 NBRSPL and 5 cm radius), BCSE and range rejection with 2 MeV. This combination achieved an efficiency of 14.892 s^{-1}, which was about 109% greater than the best combination of BEAMnrc VRTs (without n_split) mentioned in Section 3.3. Then, for the same combination of VRTs, the efficiency of the simulation was investigated further using different photon splitting numbers, as shown in Fig. 5, for which the optimum n_split was found to be 35 where the efficiency was 20.67 s^{-1}. This is in agreement with what was generally suggested by Walters et al. (2013), which is 32. Therefore, this maximised the efficiency of the DOSXYZnrc calculation. This means that this calculation can be completed in $\approx$ 1.7 h to obtain a less than 0.3% dose uncertainty when using this combination. This increase in the efficiency is due to the efficiency inherent in the technique's algorithm (n_split) as well as the reduction on the number of source particles needed. Therefore, the CPU time required to generate these particles is reduced, consequently avoiding the need to simulate the entire Linac head.

In addition, the charged particle split (e_split) was implemented in DOSXYZnrc in conjunction with photon splitting to prevent higher-weight charged particles from compromising the dose statistics (Rogers et al., 2013). From Section 3.2. and Section 3.3, the DBS with e−/e+ splitting (with 10,000 NBRSPL and a 5 cm radius) combined with BCSE, range rejection with 2 MeV was used to examine the e_split in DOSXYZnrc. As recommended in the DOS-XYZnrc documentation, the e_split should be set equal to n_split to achieve the optimum efficiency (Walters et al., 2013). Fig. 6 shows the comparison of efficiency using different charged particle splittings. The most efficient simulation was achieved when the e_split and n_split were both set to be 55.

3.5. Efficiency of PHSP simulation vs full beam simulation

Based on the results found in Section 3.4, a large (92 Gb) PHSP file source was generated using the same VRT combination that provided the most efficient full beam simulation. As mentioned
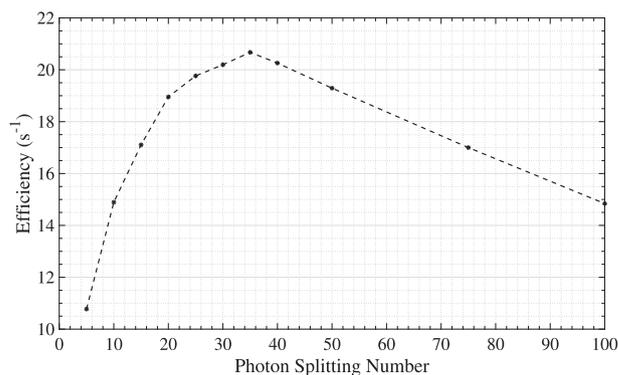
Fig. 5. The effects of photon splitting number on the simulation efficiency.
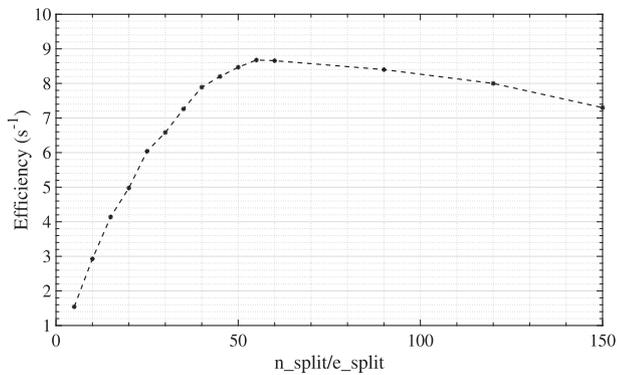
Fig. 6. The effects of different photon and electron/positron splitting numbers on the simulation efficiency.

in Section 2.2., the PHSP file was placed above the MLC CM and the number of particles collected was 1.44×10^9. Then, the PHSP was used as a source for the rest of the Linac CMs. The same number of histories in DOSXYZnrc for the full beam simulation was used. The results showed that even if the time to generate the PHSP file was omitted, the efficiency of the full beam simulation was only 8% lower than the PHSP simulation. Despite the fact that the results are comparable, the PHSP file requires a large amount of disk space, thus making it difficult to retrieve PHSP data over a network, and indeed subject to errors when transferred through networks (Alhakeem and Zavgorodni, 2018).

4. Conclusion

This study investigated the VRTs implemented in the BEAMnrc and DOSXYZnrc user codes, as provided in EGSnrc. The most efficient VRT was found to be the DBS technique and the optimum value of the NBRSPL was found to be 10,000 or 15,000 with and without e−/e+ splitting, respectively. For the DBS splitting field radius, overestimating by up to 3 cm would be sufficient without causing a significant loss in efficiency. The combination of DBS, BCSE, range rejection with 2 MeV and splitting photons was found to maximise the efficiency of the BEAMnrc calculation.

For DOSXYZnrc, the efficiency of the dose calculation can be maximised by combining photon splitting with DBS, BCSE and range rejection with 2 MeV. The optimum photon splitting was 55 and 35 with and without charged particle splitting, respectively. Compared to a full beam simulation using the optimum VRTs combination, the PHSP simulation was only 8% more efficient. Therefore, using the proposed VRTs combination eliminates the need to spare a large amount of disk space, and where parallel computing could allow for MC dose calculation in real-time adaptive treatment planning.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1

Tables A1 and A2.

Table A1
The comparison of efficiency using DBS in combination with other VRTs.

DBS combined with	Time (s)	s	ε (s^{-1})
BCSE	1336	0.0159	2.9607
ESAVE1	1130	0.0159	3.5005
ESAVE2	1096	0.0161	3.5193
Split ph	257.4	0.0299	4.3456
Force	2322	0.0224	0.8583
BCSE, ESAVE1	1261	0.0160	3.0977
BCSE, ESAVE2	1246	0.0159	3.1746
BCSE, Split ph	263.6	0.0233	7.0038
BCSE, Force	2329	0.0220	0.8871
Split ph, ESAVE1	260	0.0289	4.6050
Split ph, ESAVE2	259	0.0291	4.5595
Split ph, Force	1760	0.0411	0.3363
Force, ESAVE1	2246	0.0222	0.9034
Force, ESAVE2	2230	0.0221	0.9181
BCSE, ESAVE1, Split ph	261	0.0233	7.0574
BCSE, ESAVE2, Split ph	261	0.0232	7.1184
BCSE, ESAVE1, Force	2264	0.0222	0.8962
BCSE, ESAVE2, Force	2269	0.0220	0.9105
BCSE, ESAVE1, Split ph, Force	1769	0.0309	0.5920
BCSE, ESAVE2, Split ph, Force	1759	0.0312	0.5840

Abbreviations: BCSE = Bremsstrahlung cross-section enhancement; ESAVE1 = Range rejection with energy 1 MeV; ESAVE2 = Range rejection with energy 2 MeV; Split ph = Splitting photons in BEAMnrc (ICM_SPLIT); Force = Photon forcing.

Table A2
The comparison of efficiency using DBS (with 15000 NBRSPL and 5 cm radius) and photon splitting, n_split, techniques in combination with other VRTs.

DBS & n_split combined with	Time (s)	s	ε (s^{-1})
BCSE	2754	0.0051	13.960
ESAVE1	2464	0.0054	13.918
ESAVE2	2454	0.0054	13.975
Split ph	1487	0.0258	1.0103
Force	3039	0.0074	6.009
BCSE, ESAVE1	2755	0.0050	14.519
BCSE, ESAVE2	2686	0.0050	14.892
BCSE, Split ph	1527	0.0177	2.0903
BCSE, Force	3211	0.0071	6.1779
Split ph, ESAVE1	1493	0.0257	1.0073
Split ph. ESAVE2	1503	0.0255	1.0232
Split ph, Force	2492	0.0357	0.3148
Force, ESAVE1	3046	0.0075	5.8364
Force, ESAVE2	3020	0.0075	5.8867
BCSE, ESAVE1, Split ph	1545	0.0176	2.0895
BCSE, ESAVE2, Split ph	1554	0.0175	2.1012
BCSE, ESAVE1, Force	3217	0.007	6.3438
BCSE, ESAVE2, Force	3246	0.007	6.2872
BCSE, ESAVE1, Split ph, Force	2635	0.0232	0.7387
BCSE, ESAVE2, Split ph, Force	2641	0.0236	0.6798

Abbreviations: BCSE = Bremsstrahlung cross-section enhancement; ESAVE1 = Range rejection with energy 1 MeV; ESAVE2 = Range rejection with energy 2 MeV; Split ph = Splitting photons in BEAMnrc (ICM_SPLIT); Force = Photon forcing.

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