Study of the Influence of Photon Energy Cuts on the PET Simulation Results

K. Mitev, A. Kirov, Y. Madzhunkov, G. Gerganov and I. Kawrakow

Abstract—**The objective of this work is to study the influence of photon energy cuts on the results and speed of positron emission tomography (PET) simulations. The investigation is performed with two different MC codes: GATE and egs_pet. These codes were used to simulate the response of GE Discovery LS PET scanner to a point, 511 keV back-to-back, photon source placed at the center of a cubic 30x30x30 cm water phantom. The effect of the photon cuts on the simulation results is studied by making simulations with 32 energy cut values in the interval 0.3-350 keV. The dependence of the number of singles, primary and scattered coincidences on the applied energy cut is evaluated. The effect of the cuts on the simulation speed is also estimated. The results from the two codes are found to agree well within the statistical uncertainties for all the cuts applied. It is found that the simulation of atomic relaxation processes and the propagation of characteristic X rays play important role if an accurate modeling of a scanner system is to be achieved. For this scanner which is made of BGO crystals the usage of cuts below the Kα X-rays of Bi does not lead to statistically significant differences in the number of recorded events. Photon cuts in the interval 80-100 keV lead to less than 1.5% change in the number of singles, and less than 3% difference in the number of true and scattered coincidences. The differences are mainly due to the simulation/no simulation of Bi X_K-rays in the BGO. Energy cuts higher than 170 keV result in a strong increase in the number of detected events due to the increased absorption of Compton scattered photons and are not appropriate for PET simulations. The simulation time does not change dramatically for photon cuts between 0.3 and 100 keV. In the current studies an acceleration of the order of 35% is achieved by changing the photon cut from 1 to 100 keV.**

I. Introduction

Monte Carlo (MC) simulations are a widely used tool in Positron Emission Tomography (PET) research. Different MC codes have been developed for the purpose of PET simulations such as GATE (the Geant 4 Application for Tomographic Emission)[1], SimSet[2] and, more recently, egs_pet [3]. A common feature of these codes is the existence of a cut-off energy value (hereafter referred as energy cut), which represents the minimum kinetic energy of particles of different type and origin, below which the particle is assumed to be absorbed and its simulation is terminated. For example, in SimSet the user is allowed to set an energy cut for photons and the simulation is discontinued when their energy drops below the cut value. In egs_pet the user sets energy cuts for photons, electrons and positrons. These cuts are applied to the primary particles, but they also control the production of secondary particles as they are not generated if their kinetic energy is below the corresponding cut (the energy is absorbed on the spot). The GATE code allows the user to set production cuts for secondary electrons, X-rays and δ-rays, while the cuts for primary particles cannot be altered by the user. Strictly speaking, the energy cuts affect the results from MC simulations in terms of both accuracy and speed. Evidently, high energy cuts will make a simulation faster compared to the same simulation with low cuts, but the high cuts can bias the simulation results due to artificially decreased number of simulated secondary particles (including atomic relaxation particles), increased particle absorption probability etc.

The objective of this work is to study the influence of photon energy cuts on the results and speed of PET MC simulations. The dependence of the number of singles, primary and scattered coincidences on the energy cut is evaluated by means of MC simulations of a particular PET scanner with two MC codes. The dependence of the simulation speed on the cuts is presented and the choice of the photon energy cuts is discussed.

II. Method and Materials

The studies are performed with egs_pet and GATE MC codes. egs_pet is an EGSnrc [4] based PET simulation application which allows precise and efficient modeling of the phantom, scanner system and its digitizer modules [3]. In addition, it can act as a plugin for GATE by performing the simulation of radiation transport in the phantom (this mode of egs_pet operation is described in detail in Ref. [5]). The GATE simulations are performed with a modified version of GATE v3.1.2, where the modifications include some changes in Geant4 and GATE classes in order to introduce the application of energy cuts for all types of particles in the simulation. To facilitate the comparison between the two codes for the modeling of the scanner system and to avoid potential differences coming from the simulation of radiation transport in the phantom, egs_pet is used as a plugin in GATE simulations (hereafter referred as GATE+egs_pet simulations). Thus the differences between the results from the codes can be directly attributed to differences in the simulation of radiation transport in the scanner. The Geant4 [6] low energy module is used in the simulations with GATE+egs_pet.

The system that is modeled in the present studies consists of a 30x30x30 cm^3 water phantom with a 511 keV back-to-back photon point source placed at its center. The phantom

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K. Mitev, Y. Madzhunkov and G. Gerganov are with the Sofia Univeristy ”St. Kl. Ohridski”, Faculty of Physics, Department of Atomic Physics, Sofia 1164, Bulgaria (Tel.: ++ 359 2 8161292, e-mail: kmitev@phys.uni-sofia.bg)

A. Kirov is with the Memorial Sloan-Kettering Cancer Center, New York, NY, USA

I. Kawrakow is with the National Research Council of Canada, Ottawa, Ontario, Canada

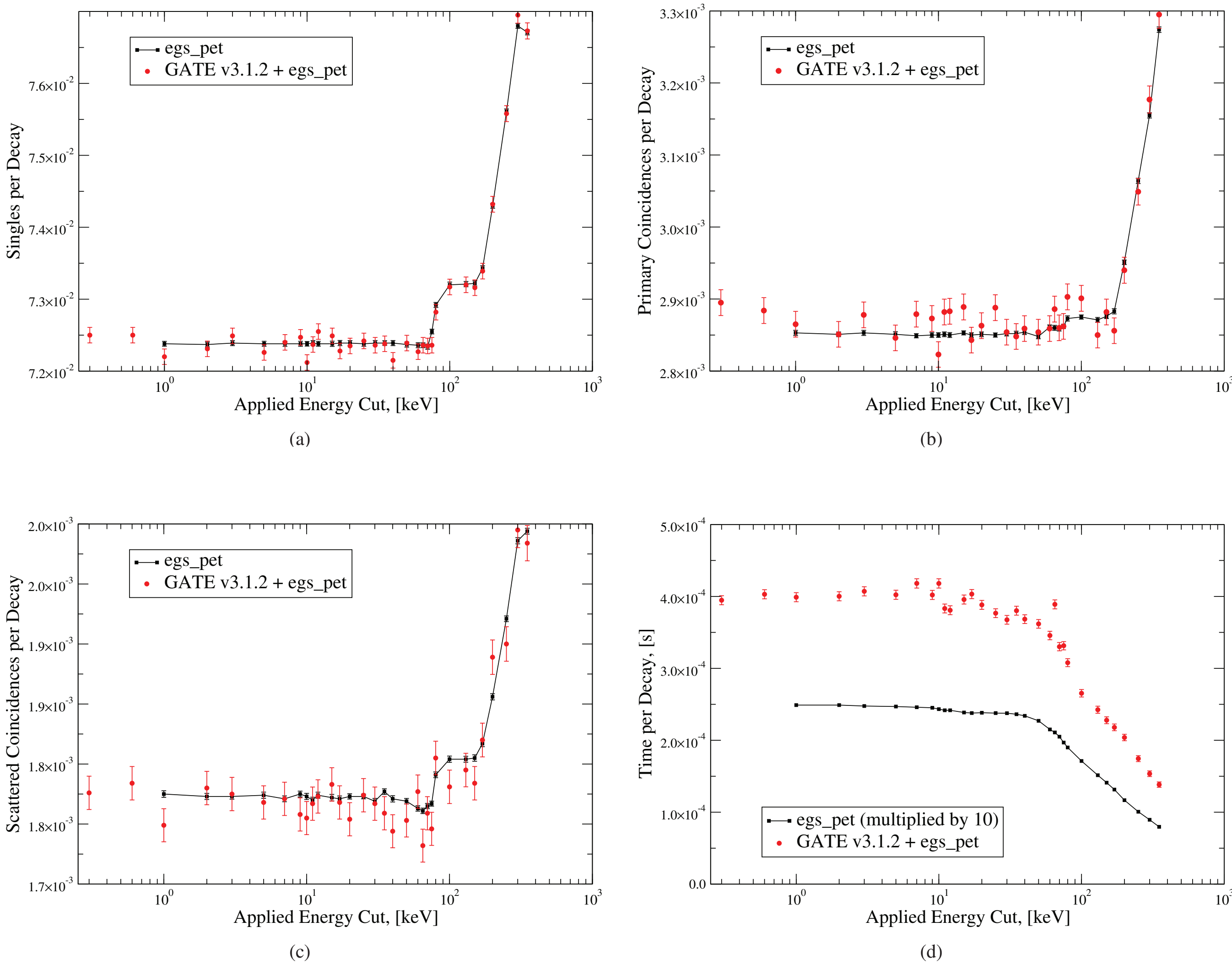

Fig. 1. Dependence of the number of singles (a), primary (b) and scattered (c) coincidences on the energy cut. (d) - Dependence of the simulation speed on the energy cut. In these simulations (scanner and a cubic water phantom with no voxels) egs_pet is approximately 16 times faster than GATEv3.1.2+egs_pet.

and the source are in the center of the scanner and the activity of the source is 10^6 Bq. A well validated model of the GE Discovery LS PET scanner [7] is used in all egs_pet and GATE+egs_pet simulations. The scintillation material of the scanner detectors is Bismuth Germanate (BGO). Figure 2 depicts the cross sections for the various photon interaction processes with the BGO material. Apart from some differences in the Geant 4 low energy and egs_pet physics models (for more details see Ref.[3]), all other simulation parameters such as the phantom and scanner geometries, source activities and digitization chains are set exactly the same in the two codes.

The effect of the photon cuts on the simulation results is studied by making simulations with 32 energy cut values in the interval 0.3-350 keV. For each energy cut value a single simulation of 10^7 decays is performed with GATE+egs_pet. The same procedure is followed in the case of the simulations with egs_pet, except that there are 50 independent simulations of 10^7 decays for each cut. All other inputs are kept the same for all simulations. The choice of cut values is intended to provide good sensitivity for the influence of photo-absorption

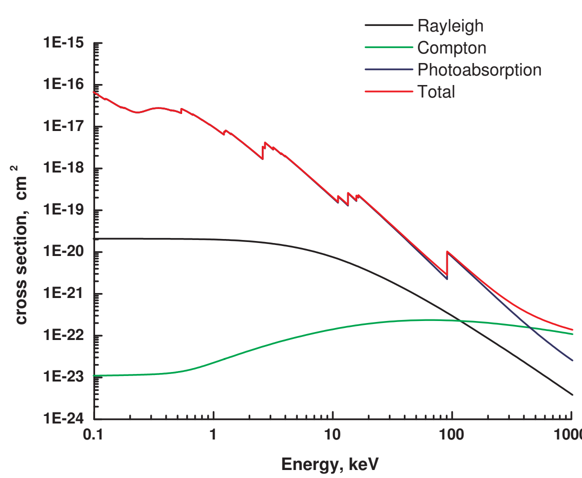

Fig. 2. Photon cross sections for BGO from [8].

edges of the BGO material near 3, 10 and 80 keV (see Fig. 2). It should be emphasized that in all simulations the energy cuts

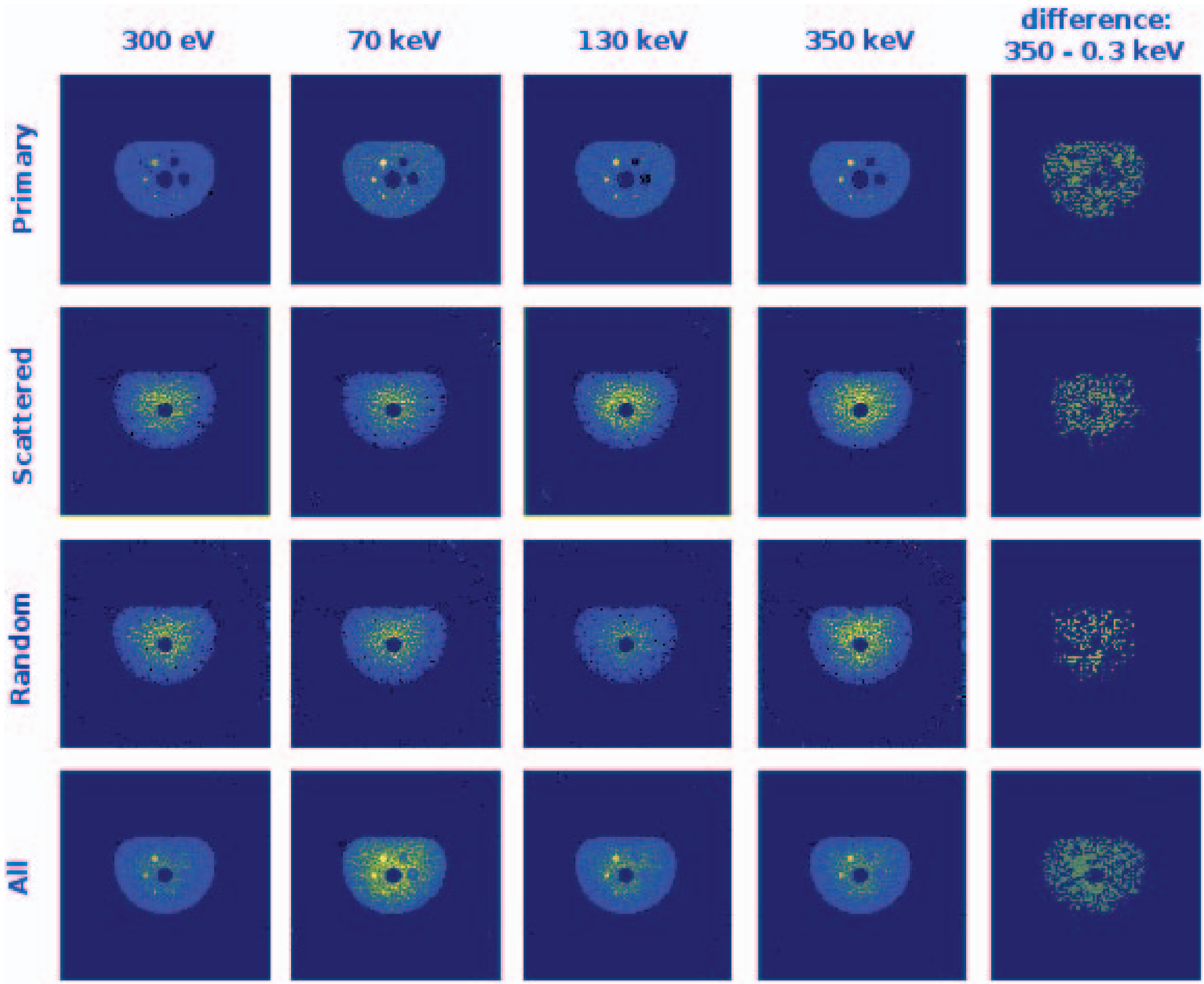

Fig. 3. Reconstructed images of the central slice of the NEMA IQ phantom. The images in each row correspond to a given cut, as indicated. The images in the final row are obtained by subtraction of the images for 0.3 keV cut from those for 350 keV cut. The images in each line are obtained from different types of coincidences as indicated. Each image is normalized to the most intensive pixel in it.

are applied on the primary photons as well as on the photons generated by the atomic relaxation processes. In addition, the cuts are applied in exactly the same way for the photons in the phantom and in the scanner. The transport of charged particles is turned off in all simulations by setting the corresponding cut to a very large value (greater than 1 MeV). Thus, all secondary electrons are absorbed at the place of their origin and their energy is deposited on the spot.

III. Results

Figure 1 shows the dependence of the recorded singles, primary (unscattered) and scattered coincidences on the energy cut applied. The number of singles, primary and scattered coincidences increases with the increase of the cut applied due to the fact that the usage of high photon energy cuts affects directly the production and simulation of characteristic X rays. The results on Fig. 1(a) suggest that there is no statistically significant difference in the number of singles for various photon cuts below 80 keV. The increase of the number of singles for cuts higher than 80 keV is, however, clearly visible and statistically significant. Its origin is in the fact that for 80 keV cut the characteristic K_α X rays (with energies in the interval 76-79 keV, see Fig. 2) of Bi are not simulated, thus possible X-ray escapes from the crystals are ignored. The phenomenon is clearly visible if the singles for 80, 90 and 100 keV cuts are compared. For 90 keV cut, K_α and a part of K_β X rays (with energies around 90 keV) of Bi are not transported, which leads to decreased escape probability and increased number of singles compared to the 80 keV cut results. The same principles should apply for the behavior of singles in the 9-20 keV region, but the effect is not pronounced. This could be explained by the small mean free path for X rays with energy of the order of 10 keV in BGO, which leads to small escape probability from the crystals. For a 100 keV cut, all X rays are stopped at the place of their origin, there are no X-ray escapes from the crystals and therefore the number of singles is further increased. The strong increase in the number of singles for cuts higher than

170 keV is easily explained by the kinematics of the Compton scattering. If we consider a single Compton scattering of a photon with initial energy of 511 keV, its minimal energy after the scattering is 170 keV (backscattering). Thus, the usage of cuts higher than 170 keV will cause increased absorption of a part of the Compton scattered photons. Obviously, the higher the cut, the effect with will be more pronounced. The behavior of primary and scattered coincidences (Figs. 1(b) and 1(c) respectively) can be explained with the same arguments as for the singles. Notice however, that the steep increase of scattered and unscattered coincidences for cuts higher than 170 keV is a purely artificial phenomenon (due to absorption of a part of the Compton scattered photons) and it strongly affects the recorded number of these events. The dependence of the simulation time on the applied cuts is shown in Fig. 1(d). The results for the simulation time from the two codes suggest that setting the cut between 0.1 - 8 keV leads to practically no difference in simulation time. Cuts between 20 and 70 keV lead to approximately 10% gain. Cuts about 100 keV lead to 35 % acceleration. Larger cuts make the simulation faster, but the results are strongly affected and a loss of accuracy with such high values of photon cuts can be anticipated. A similar behaviour of the simulation results can be expected for other PET scanners with BGO crystals. Generally, the same principles should apply for PET scanners with other type of crystals (LSO for example) with the cut off energies adapted for the X-ray energies of the particular scintillation crystal.

In order to investigate the effect of energy cuts on the reconstructed images egs_pet is used to simulate a NEMA IQ phantom at the center of GE Discovery LS PET scanner. Four scenarios were simulated with cuts 0.3, 70, 130 and 350 keV, keeping all other inputs exactly the same. The images were reconstructed with the build-in egs_pet image reconstruction class, which utilizes the Ordered Set Expectation Maximization (OSEM) algorithm. Qualitatively, the reconstructed images look similar (see Fig.3). Work is in progress to quantify the effect of the cuts on the reconstructed images for primary, scattered and random coincidences as well as the total effect on the reconstructed image from all coincidences.

IV. Conclusion

The influence of photon energy cuts on the simulation of a GE Discovery LS PET scanner is studied with two MC codes - egs_pet and GATE+egs_pet. The results from the two codes agree well within the statistical uncertainties. The good agreement indicates that the modifications in GATE and Geant4 classes lead to correct application of the cuts in the simulation with these codes. It is found that the simulation of atomic relaxation processes and the propagation of characteristic X rays play important role if an accurate modeling of a scanner system is to be achieved. For this scanner, which is made of BGO crystals, the usage of cuts below the K_α X rays of Bi does not lead to statistically significant differences in the number of recorded events. Photon cuts in the interval 80-100 keV lead to less than 1.5% change in the number of singles, and less than 3% difference in the number of true and scattered coincidences. The differences are mainly due to the simulation/no simulation of Bi X_K-rays in the BGO. Energy cuts higher than 170 keV result in a strong increase in the number of detected events due to the increased absorption of Compton scattered photons. The simulation time does not change dramatically for photon cuts in the interval from 0.3 to 100 keV. In the current studies an acceleration of the order of 35% is achieved by changing the photon cut from 1 to 100 keV. It can be concluded that for BGO crystals ”safe” values of the photon cuts (i.e. values that do not affect the results of the simulation) are below 8 keV. The same arguments should apply for PET scanners with other type of crystals with the cut off energies adapted for the X-ray energies of the particular scintillation crystal. Qualitatively, the reconstructed images from simulations with different energy cuts look similar. Work is in progress to quantify the effect of the energy cuts on the reconstructed images.

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References

[1] S. Jan *et al.*, Phys. Med. Biol. **49**, 4543-4561 (2004).
[2] T. Lewellen *et al.*, J. Nucl. Med. **29**, 871 (1988)
[3] I. Kawrakow *et al.*, IEEE MIC, Dresden (2008).
[4] I. Kawrakow, Med. Phys. **27**, 485-498 (2000).
[5] I. Kawrakow *et al.*, AAPM Annual Meeting, Houston (2008).
[6] S. Agostinelli *et al.*, Nucl. Inst. Meth. A **506**, 250-303 (2003).
[7] C. R. Schmidtlein *et al.*, Med. Phys. **33**, 198-208 (2006).
[8] F. Salvat *et al.*,PENELOPE-2006: A Code System for Monte Carlo Simulation of Electron and Photon Transport, Workshop Proceedings,4-7 July 2006, Barcelona, Spain, OECD Data Bank,ISBN 92-64-02301-1.