Simulation Studies for PET Imaging With Non-Pure Positron Emitters

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I. INTRODUCTION

In a typical PET measurement pure short-lived positron emitters as ^{18}F are common. Non-pure positron emitters as ^{124}I or ^{86}Y have been utilised for certain applications, for example in the study of slow biochemical processes where a long half-life time is needed, or for dosimetry with PET where a positron emitting analogue of a therapeutic nuclide can be applied (e.g. ^{86}Y for ^{90}Y [1]). Imaging with non-pure emitters is complicated by a low ß$^{+}$-abundance and additional γ-radiation, in particular by γ-radiation that appears in cascade with the positron. In these cases the image quality is deteriorated by additional false coincidences, and standard correction procedures (dead-time, randoms and scatter) are less adequate. The development and validation of optimized correction procedures is therefore essential for quantitative imaging with non-pure ß$^{+}$-emitters. A mandatory first step is a detailed understanding of the imaging system and its response to the input signal. This can be obtained by a complete simulation of all stages of image formation.

II. METHODS

To gain insight into the factors influencing imaging of non-pure ß$^{+}$-emitters a simulation program has been developed based on GATE/GEANT4 [2][3]. The modelled PET scanner is an ECAT EXACT HR+. The simulation comprises all physical processes from the ß-decay to the photon interaction within tissue or phantom and the detector crystals, as well as a description of electronic components and the standard output data formats. The simulated sinograms can be processed with the same tools for correction and reconstruction as real sinograms.

First tests with the original simulation code showed that the amount of CPU time would be huge. The expected time to simulate a realistic 10 minute PET scan was about 45 years on a P4 with 2.6 GHz. A detailed profiling of the time consumption revealed that the radioactive decay module of GEANT4 was wasting an enormous amount of time by simulating the β-decay. This problem could be solved by designing a new algorithm for the β-decay which meanwhile became part of GEANT4 with version 4.7. The new algorithm gives a speed-up factor of 27. Further improvement was achieved by a parallelization of the GATE simulation platform, which will be reported elsewhere [4]. For the results presented in this paper 9 CPUs contained in a Linux cluster had been used in parallel.

Eventually, to allow for the simulation of the billions of β-decays which contribute to even a short PET measurement, Further work was necessary to improve the stability of the original GEANT4 β-decay code.

III. RESULTS

The simulation system has been validated in different respects. The exact modelling of the HR+ scanner was demonstrated elsewhere [5]. We could show a good agreement between the γ- and β^{+}-spectra of several nuclides and the corresponding experimental data.

The simulation enables us to observe γ-spectra at different stages of the image formation. For the example of ^{124}I the three plots in Fig. 1 show which parts of the primordial γ-spectrum (Decay) survive the energy window (Singles) and the coincidence electronics (Coincidences). Besides the annihilation photons at 511 keV a strong line due to electron capture is visible at 603 keV. This γ-energy also appears in cascade with the positron. In addition several lines at higher energies contribute to the spectrum. While the number of singles caused by γ-radiation from electron capture is strongly suppressed by the coincidence electronics, the part of γ-radiation emitted in cascade with the positron is not reduced. This can be seen in the lower plot of Fig. 1.

Another example is shown in Fig. 2 where the same analysis is presented for the case of ^{86}Y. The simulation gives a much larger number of lines at different energies due to a higher Q-value and a more complex decay scheme for this nuclide.

The γ-energy registered by the PET scanner can be reduced by different processes, for example by Compton scattering in the phantom or if only a fraction of the total energy is deposited in the detector crystal. Thus, even at energies much larger then the upper energy threshold a signal can be created that contributes to the system dead time at this processing level. The energy window in our examples accepts signals from 350 keV to 650 keV but there is still a clear contribution to the number of singles from photons with energies even larger than 2.5 MeV, as can be seen in Fig. 1 and Fig. 2 (middle plots).

The above results have been obtained from samples of 37 million simulated decays. In order to collect enough data for a 3D image a 400 times larger simulation run (2 months real time with 9 parallel processes) had been performed. The results from a simulated 6 minutes 3D scan with 37 MBq ^{124}I in a water filled 3 rod phantom are presented in Fig. 3. The 3 cold rods are made of air, water and Teflon. An iterative reconstruction algorithm [6] has been used. The resulting image is compared with a phantom measurement. To allow for a direct comparison neither the measured nor the simulated image data is corrected for attenuation. A more quantitative presentation of the intensity distribution is obtained by defining

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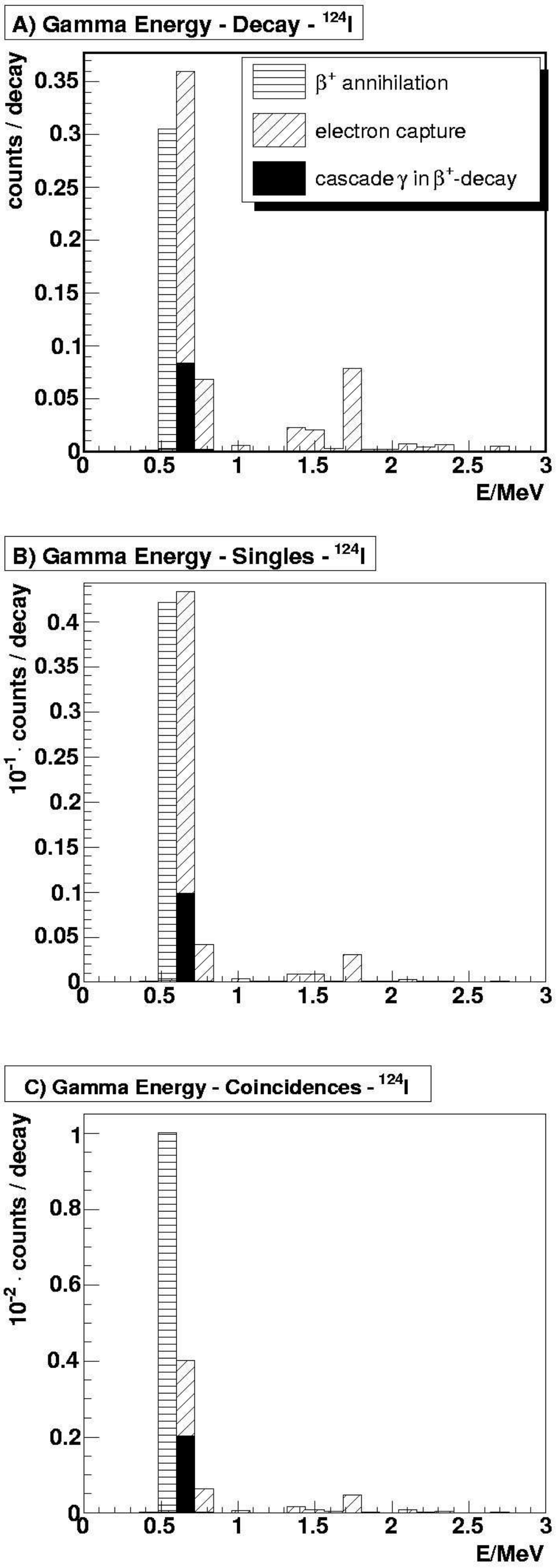


Fig. 1. Relative contribution of the different classes of γ-radiation at different stages of image formation process for ^{124}I: A) primordial γ-radiation, either emitted by the daughter nucleus or due to β$^+$ annihilation, B) γ-radiation that contributes to the number of singles, C) γ-radiation that contributes to the number of coincidences.

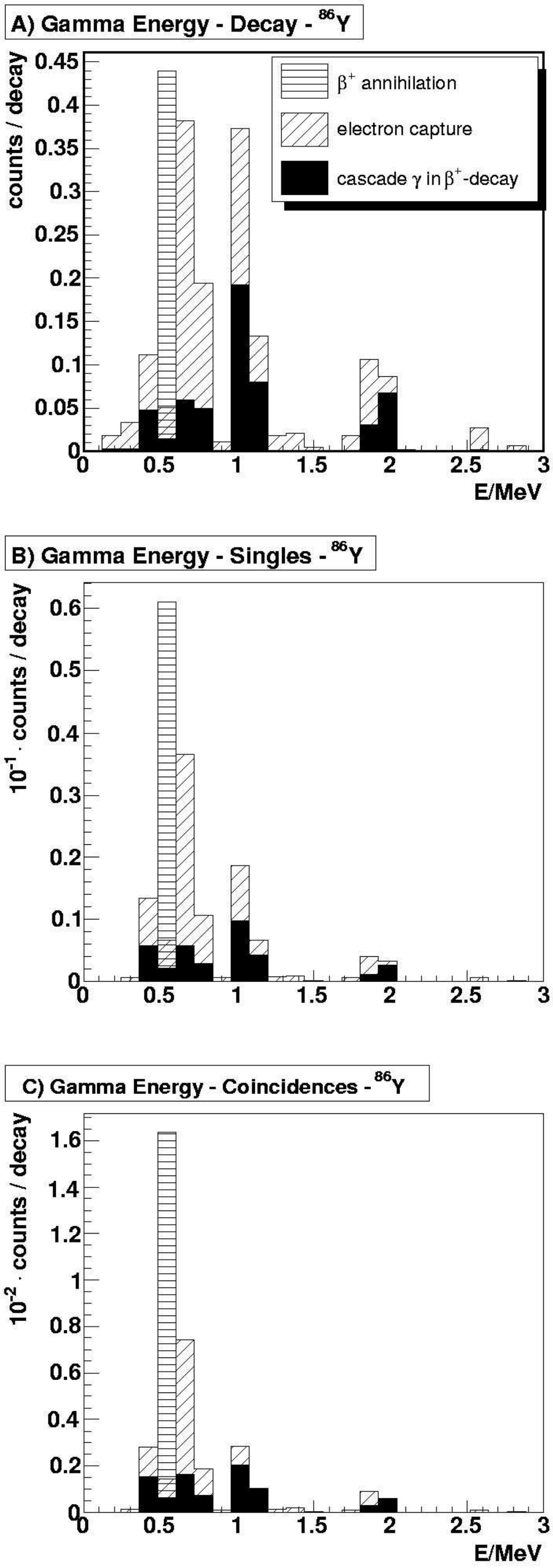
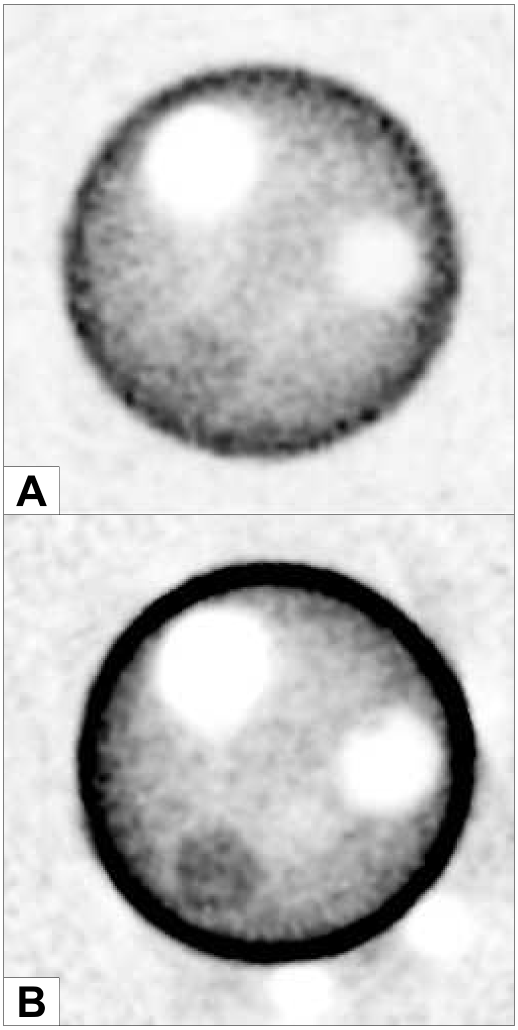


Fig. 2. Relative contribution of the different classes of γ-radiation at different stages of image formation process for ^{86}Y – see Fig. 1.



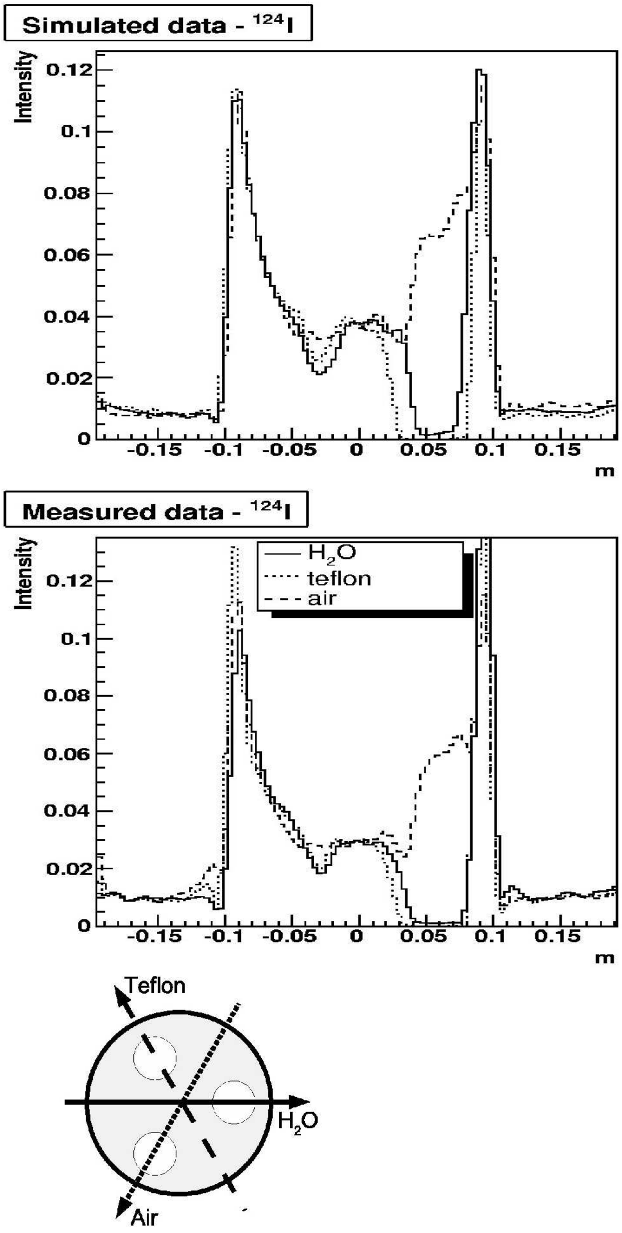


Fig. 2. Left side: Simulated (A) and measured (B) 3D PET images from a water filled 3 rod phantom with ^{124}I. The three cold rods are air (lower left circle), water (right circle) and Teflon (upper left circle). The images are not corrected for attenuation. The plots on the right side show profiles of the intensity distribution as depicted by the diagram on the right.

slices through the phantom centre and one of the cold rods. This is seen on the right side of Fig. 2.

All image details are well reproduced by the simulation. The real data image shows a larger dynamic range which is probably related to the 2 times higher statistics. The images are not corrected for attenuation. Therefore, the intensity decreases towards the centre of the phantom.

IV.CONCLUSION

This paper demonstrates the abilities of our PET simulation platform for non-pure positron emitters. A speed-up of about 250 could be accomplished. Further work is planned to reduce the still demanding time consumption. Presently a full simulation of all decays within the phantom is performed but only a small fraction contributes to the final image. A more efficient approach is expected to reduce the simulation time by another factor of 10. Already in its present form the program allows for detailed studies of image formation and background contributions, All simulations reported here are in good agreement with real measurements.

V.REFERENCES

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