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Journal
Physica Medica, 31(1)

ISSN
1120-1797

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Publication Date
2015-02-01

DOI
10.1016/j.ejmp.2014.09.001

Peer reviewed

Published in final edited form as:

Phys Med. 2015 February ; 31(1): 43–48. doi:10.1016/j.ejmp.2014.09.001.

Towards component-based validation of GATE: aspects of the coincidence processor

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Abstract

GATE is public domain software widely used for Monte Carlo simulation in emission tomography. Validations of GATE have primarily been performed on a whole-system basis, leaving the possibility that errors in one sub-system may be offset by errors in others. We assess the accuracy of the GATE PET coincidence generation sub-system in isolation, focusing on the options most closely modeling the majority of commercially available scanners.

Independent coincidence generators were coded by teams at Toshiba Medical Research Unit (TMRU) and UC Davis. A model similar to the Siemens mCT scanner was created in GATE. Annihilation photons interacting with the detectors were recorded. Coincidences were generated using GATE, TMRU and UC Davis code and results compared to "ground truth" obtained from the history of the photon interactions. GATE was tested twice, once with every qualified single event opening a time window and initiating a coincidence check (the "multiple window method"), and once where a time window is opened and a coincidence check initiated only by the first single event to occur after the end of the prior time window (the "single window method"). True, scattered and random coincidences were compared. Noise equivalent count rates were also computed and compared.

The TMRU and UC Davis coincidence generators agree well with ground truth. With GATE, reasonable accuracy can be obtained if the single window method option is chosen and random coincidences are estimated without use of the delayed coincidence option. However in this GATE version, other parameter combinations can result in significant errors.

Keywords

GATE; nuclear medicine; positron emission tomography; Monte Carlo methods

Introduction

The Geant4 Application for Emission Tomography (GATE) [1] is a suite of programs for generating and processing Monte Carlo simulations of PET and single photon imaging systems. Radiation transport is modeled using, as the name suggests, the well-validated Geant4 engine. GATE contains extensive and flexible tools for creating models of imaging systems, radioactive source distributions and attenuation maps, together with tools for modeling electronic sub-systems and detector characteristics. There is also a tool for tracking optical photons within a scintillation detector. For PET modeling, there is a coincidence sorter which allows pairing of single detection events in a wide variety of ways, including most of those currently used by commercial systems and several others that may be of more interest for research. Data may be output in several formats including some that are compatible with existing or historically available commercial scanners.

GATE has been used for scanner design studies [2–4], investigations into the physics of emission [5, 6] and investigations of the accuracy of coincidence generation policies in PET [7]. It is an extremely valuable tool to the community, with this value being enhanced as it becomes increasingly validated. There are several such validations – e.g. [8–10].

However, most of these validations have been performed on a whole-system basis. Since there are multiple components to the software platform, there is the possibility that errors or approximations in one part of the model may be cancelled out (in specific situations) by errors or approximations in another. For example, the amount of scintillation light produced in a given scintillator may not be completely modeled as a function of the energy deposited by incident radiation. This may lead to an error – say, too many - single events being generated for a given amount of activity in the field of view. If there also approximations in the dead-time model (for example, using simplified model for event loss rather than modeling the actual pulse pile-up and processing on an event-by-event basis), then it is possible that the number of lost events might be, for example, over-estimated. Under certain circumstances one may generate numbers of events that closely match measurements even in the presence of these approximations, since they act in opposite directions. There is therefore substantial value in validating the individual components of the code. This is of course a very large undertaking given the enormous scope and flexibility of the GATE software suite (the source distribution contains more than 1000 files).

In this study we examine the accuracy of the coincidence sorter as implemented in GATE version 5.0.0p.1, with specific reference to options that might be selected when simulating typical whole-body PET systems. We use a simulation of a scanner broadly similar to the Siemens Biograph mCT to generate single events. We then compare the performance of the GATE coincidence sorter set up with these options with two independently coded sorters, and, where possible, with “ground truth” determined by direct examination of the simulated data.

While a comprehensive validation of the entire coincidence option parameter space is desirable, it lies beyond the scope of this work, which is focused on those options that most closely describe the majority of currently available clinical PET systems.

Methods

Coincidence sorting algorithms

In most modern whole-body PET scanners, every qualified single event is checked to see if it is in coincidence with another event (the "multiple window method", explained in detail in [11]). This contrasts with earlier designs which tended to use the "single window method", where a qualified single event is chosen as a reference event opening a single time-window [11]. The multiple window method leads to somewhat greater sensitivity at higher event rates [11]. In addition, most modern PET scanners (at this time, scanners offered by General Electric and Siemens) accept all possible coincidences provided that they fall within certain geometric limits (e.g., maximal ring difference and radial position) [12]. Finally, most modern PET scanners provide options to estimate random coincidences either through a delayed channel or by computation from singles rates. The latter method results in a noise reduction in the corrected data, but may not always be as accurate [13].

In GATE PET simulations, photons interacting with the detectors create single events, which are then positioned and processed using modules configured by the user. The GATE coincidence sorter searches through the resulting list to create pairs of coincident singles. Whenever two or more singles are found within a user-defined span of time (the "coincidence window"), these singles are grouped to form one or more coincidence events. Coincidence time windows may be created using the multiple window method, or by the single window method. There are nine different policies for the treatment of multiple coincidences occurring within a time window implemented in GATE, ranging from "killAll", where all multiple coincidences are rejected, to "takeAllGoods", where all possible coincidences (within geometric constraints) are accepted – that is, coincidences between more than two events result in the maximum possible number of coincidence pairs. There is also an option to model delayed channel coincidence pairing in order to provide an estimate of the number of random coincidences using the same pairing method. A simplified diagram showing the data processing chain is shown in Figure 1; full details may be found in the GATE user manual [14].

Theoretically, the design choices currently implemented by GE and Siemens in their whole body PET scanners (the multiple window method and accepting all possible coincidence pairs) are best modeled in GATE by choosing the "takeAllGoods" coincidence policy, and selecting the "allPulseOpenCoincGate" option. We subsequently refer to this as the "GATEMW" option, signifying the modeling of the multiple window method. An alternative is to de-select the "allPulseOpenCoincGate" option [15, 16], which we will refer to as the "GATESW" configuration. This models the single window method, and theoretically should be in close agreement with the multiple window approach at low rates, with discrepancies increasing at high rates. The GATESW approach has been recommended by members of the GATE consortium for modeling modern PET scanners [17], and we test it for comparison, even though it does not model the actual pairing algorithm used.

Random coincidences may be estimated for either method using GATE's delayed window option. An alternative approach is to examine the labels ("eventIDs") of coincidences found in the prompt data. A random occurs when coincidences do not arise from the same annihilation. Prior to GATE version 2.1.0, this was the only way to obtain estimates of randoms [16].

GATE implementation

GATE version 5.0.0p1 was downloaded and compiled to run on CentOS 5.4 ×86-64 using AMD x64 quad-core processors. Geant4 version 9.2 p03 and CLHEP 2.0.4.2 was used to run GATE. Data processing was performed using ROOT 5.24/00 [18].

Alternate coincidence processors

Two independent coincidence sorters were coded, one at UC Davis (UCD) and one at Toshiba Medical Research Unit (TMRU). No discussions regarding implementation were undertaken, and no sight of the other's code stream was had during development. Both the UCD and TMRU coincidence sorter algorithms independently implement the "take-all-goods" coincidence policy. Detected singles from the detector elements are collected over a period of time and passed to both coincidence processors. Each single acts as the reference pulse (the multiple window method) and is paired with other singles ahead in time within a coincidence time window τ, which was set to 2.05 ns (for the mCT, $2\tau = 4.1$ns). A coincidence pair is considered a valid prompt if it meets the transaxial FOV and maximum accepted ring difference criteria of the scanner. Examples of coincidence pairing schemes are shown in figure 2. Both the TMRU and the UCD algorithms implemented the policy shown in the left-most column.

Scanner and phantom model

We developed a PET scanner model in GATE loosely based on the Siemens mCT tomograph, with 192 LSO crystal blocks of 13×13 crystals arranged in 4 adjacent rings with opposing detectors separated by a distance of 849 mm [19]. The crystal size was $4.0\times4.0\times20.0$ mm^3. Blocks were arranged in 48 modules per ring. An energy blurring of 11.7% at 511 keV and an acceptance window of 435.0 keV to 650.0 keV was applied. A paralyzable deadtime of 120.0 ns was applied at the block level, and a non-paralyzable deadtime of 80.0 ns was applied to each module of 4 blocks. No time blurring was applied. The front of each block was covered by a 1.0 mm thick aluminum sheet. Data were stored as lists of single events. The NEMA NU-2 2007 scatter phantom was modeled and placed in the center of the simulated scanner field of view. This phantom is a cylinder, diameter of 203 mm and 700 mm length, made of polyethylene with a 6.4 mm cylinder hole parallel to the central axis, at a radial distance of 45 mm [20]. The source is a cylinder shell, of internal diameter of 3.2 mm and 700 mm length, filled with an ^{18}F source type.

Coincidence testing

Data generated from the scanner and phantom model described above were processed to estimate true, scattered and random coincidences. 32 different time and activity acquisitions were simulated with the scatter phantom, ranging from 0.0 to 1.0334 GBq (47 kBq/mL) and time from 30 to 0.75 seconds, respectively. The minimum number of counts obtained for any acquisition was 2.9 million.

All the results were processed in the GEANT 4 “root” environment code. Based on the NEMA NU-2 2007 protocol, only coincidences in the central +/− 12 cm of the transaxial field of view were processed [20]. For delayed coincidences, a delay of 500 ns was applied.

i) Validation of the UCD coincidence sorter—The accuracy of the UCD and TMRU coincidence processors for true and scattered coincidences were determined by comparing them to each other and to ground truth, which was obtained by searching through the stored singles data for pairs of events with the same “eventID”, indicating that the events originated from the same annihilation.

Ground truth cannot easily be determined for random coincidences since these are essentially an artifact of coincidence processing. We compared delayed channel randoms estimates from the UCD and TMRU coincidence processors with each other. Since the code streams were independent, agreement between the two would provide a strong plausibility argument for accuracy, although not definitive proof. In other work, the UCD coincidence processor has been tested very successfully against measured data [12], but again, since the referenced test was performed at a whole-model and not a component level, it provides additional plausibility for but not definitive proof of accuracy. We also estimated randoms by searching through the prompt coincidence list and discarding those coincidences arising from singles sharing the same eventID – this allows determination of consistency between randoms in the prompt and delayed channels for a particular coincidence sorter. We name this approach “randoms from labels”.

ii) Validation of the GATEMW coincidence sorter; testing of GATESW as a surrogate for MW with take-all-goods—True, scattered and delayed channel randoms were estimated using GATESW and GATEMW; randoms from labels were also determined. Results were compared with those from the UCD sorter.

iii) NEC—For each of the coincidence processors investigated, noise-equivalent counts for both noise-free randoms estimates (NEC1R) and Poisson-distributed randoms estimates (NEC2R) were computed according to equations 1 and 2 respectively [21]:

$$NEC1R=\frac{T^2}{T+S+R}, \quad (1)$$

$$NEC2R=\frac{T^2}{T+S+2R}, \quad (2)$$

where T is the true rate, S, the scattered rate and R, the randoms rate.

Results

Validation of the UCD coincidence sorter

True coincidence rates for TMRU and UCD show a very high degree of agreement, differing by less than 0.01%. Both methods underestimated ground truth by 0.6% or less. These data are shown in Figure 3. Similar levels of agreement were found for scattered coincidences. Delayed channel randoms obtained from TMRU and UCD coincidence processors also are in excellent agreement and follow closely the results obtained by counting randoms from labels (errors no greater than 1.4%).

Validation of the GATEMW coincidence sorter; testing of GATESW as a surrogate for MW with take-all-goods

True coincidences estimated from GATESW agree well with ground truth, but the GATEMW generator shows a rate-dependent error that increases from 0.7% at 8.7 MBq (0.40 kBq/mL) in the phantom to 28.3% at 1.0334 GBq (47 kBq/mL) in the phantom (figure 4). Essentially identical results were found with scatter.

There are somewhat fewer randoms in the GATESW prompt channel than in the reference data (UCD randoms from labels) - the difference is ~8% at 47 kBq/ml. This is not necessarily an inconsistent result, as the single window method would be expected to be slightly less sensitive than the multiple window method (see figure 2). However, there are substantially more randoms in the GATEMW prompt channel than there are in the reference data, which is not consistent since theoretically, these methods should be the same. The difference is ~22% at 47kBq/ml. The UCD and GATEMW delayed channel data are in excellent agreement, both with each other and with the reference data (UCD randoms from labels). However, the GATESW delayed channel data show a rate-dependent difference that increases from 1.21% at 8.7 MBq (0.40 kBq/mL) in the phantom to 31.0% at 1.0334 GBq (47 kBq/mL) in the phantom. These data are summarized on Figure 5, which shows random coincidence rates from labels generated from GATESW and GATEMW coincidence sorters as random coincidences estimated by the delayed window by GATESW and GATEMW, with the UCD randoms from labels shown as reference.

Unsurprisingly, NEC curves are affected by these differences. Figures 6a and 6b show NEC curves from the various coincidence sorters for a “1R” (noise free randoms estimate) and a “2R” (Poisson distributed randoms estimate) formulation respectively. The smallest difference between UCD NEC and GATE NEC is found for the GATESW sorter with randoms estimated from labels – this difference is 6.6% at 47 kBq/mL for the 1R case and 7.9% at 47 kBq/mL for the 2R case. This suggests that the impact of the differences in sensitivity between the single window method and the multiple window method on NEC are quite small for this fairly typical scanner configuration and can probably be ignored in most cases.

However, there are substantial errors in the other configurations, with the worst case being GATEMW sorter with randoms estimated from delays. Here the error reaches 52.0 % at 47 kBq/mL for the 1R case and 56.5% at 47 kBq/mL for the 2R case. These errors and differences are summarized in Tables 1 and 2.

Discussion and Conclusions

Examination of the labels of the coincidences generated by the GATEMW code shows that some coincidences have duplicate eventIDs, a phenomenon that increases with activity in the field of view, ranging from zero at 8.7 MBq (0.40 kBq/mL) to as many as 6 times at 1.0334 GBq (47 kBq/mL). Further testing of the code in collaboration with the GATE software team indicated that this fault is only present when the "allPulseOpenCoincGate" flag is set true. The source of the error in the GATESW delayed channel estimator is not yet known to the authors. The randoms obtained by delayed channel on GATEMW configuration are in agreement with the expected results.

We conclude that when simulating whole-body PET scanners that accept all possible coincidences that fall within appropriate geometric limits (i.e., most current PET scanners manufactured by Siemens or GE), reasonably accurate estimates of true and scattered coincidences may be obtained from GATE when the flag "allPulseOpenCoincGate" flag is set false and the "takeAllGoods" coincidence policy is chosen – that is, if the coincidence policy is approximated by using the single window method and by accepting all possible coincidences within the geometric limits set by the scanner. Accurate estimates of random coincidence rates may also be obtained if they are determined by discarding pairs of events in the prompt channel that share an eventID. Other combinations of options, however, may potentially result in substantial errors and are not recommended for use until this part of the GATE code is revised. This conclusion is particularly important because the GATE options that most closely match the architecture of these scanners do not currently appear to generate accurate results and could lead to problems for researchers using them for modeling purposes.

It should be noted that the magnitude of the errors found in this work will be dependent on the source and scanner geometry.

It should also be noted that the randoms distribution obtained from the prompt channel is an exact result and does not accurately model the variance in an actual randoms estimate computed either from a delayed channel approach or from single event rates.

The GATE CoincidenceSorter code is a historic class that dates back to at least GATE version 4. We would therefore expect to see similar results in simulations using GATE version 4 and 5. We also performed a superficial test of GATE 6.2.0 by sorting approximately 2 million coincidences with the "takeAllGoods" coincidence policy and the "allPulseOpenCoincGate" flag set true, and we found that about 35% of the counts had duplicate eventIDs. This strongly suggests that the problem remains active in all GATE versions between 4 and 6.2.0.

Acknowledgments

This work was supported in part by the following sources of funding: Toshiba Medical Research Institute, NIH-NCI R01 CA129561, NIH-NCI R01 170874 and the National Council for Scientific and Technological Development of Brazil (CNPq), 201050/2009-9.

We are very grateful to Irene Buvat, Sebastien Jan and Didier Benoit from the GATE collaboration and to Sara St James for useful discussions.

References

1. Jan S, Santin G, Strul D, Staelens S, Ass K, Autret K, et al. GATE: a simulation toolkit for PET and SPECT. Phys Med Biol. 2004; 49(19):4543–61. [PubMed: 15552416]
2. Yang CC, Yu J, Lee JJS, Tsui BMW. Monte Carlo simulation of a GE eXplore VISTA system for quantitative smalll animal PET imaging. Nucl Med Commun. 2010; 31:32–8. [PubMed: 19972634]
3. Rechka S, Fontaine R, Rafecas M, Lecomte R. Development and Validation of a GATE Simulation Model for the LabPET Scanner. IEEE Trans Nucl Sci. 2009; 56(6):3672–9.
4. Delso G, Martinez MJ, Torres I, Ladebeck R, Michel C, Nekolla S, Ziegler SI. Monte Carlo simulations of the Count Rate Performance of a Clinical Whole-Body MR/PET Scanner. Med Phys. 2009; 36(9):4126–35. [PubMed: 19810486]
5. Hasegawa T, Yoshida E, Kobayashi A, Shibuya K, Nishikido F, Kobayashi T, et al. Evaluation of static physics performance of the jPET-D4 by Monte Carlo simulations. Phys Med Biol. 2007; 52(1):213–30. [PubMed: 17183137]
6. Goertzen AL. Coincidences originating from a single photon: An unrecognized and potentially significant source of scatter in small animal PET? IEEE Nucl Sci Symp Conf. 2009; M05-352:2888–91.
7. Zhang Y, Li H, Liu S, An S, Wang C, Baghaei H, et al. The systematic errors in the random coincidence estimation using a delayed window. IEEE Nucl Sci Symp Conf. 2009; M13-339:3897–99.
8. Lamare F, Turzo A, Bizais Y, Le Rest CC, Visvikis D. Validation of a Monte Carlo simulation of the Philips Allegro/GEMINI PET systems using GATE. Phys Med Biol. 2006; 51(4):943–62. [PubMed: 16467589]
9. McIntosh B, Stout DB, Goertzen AL. Validation of a GATE Model of (176)Lu Intrinsic Radioactivity in LSO PET Systems. IEEE Trans Nucl Sci. 2011; 58(3):682–6.
10. Buvat I, Lazaro D. Monte Carlo simulations in emission tomography and GATE: An overview. Nucl Instr Meth A. 2006; 569(2):323–9.
11. Oliver JF, Torres-Espallardo I, Fontaine R, Ziegler SI, Rafecas M. Comparison of Coincidence Identification Techniques for High Resolution PET. IEEE Nucl Sci Symp Conf. 2008; M10-102:4732–5.
12. Poon JK, Dahlbom ML, Moses WW, Balakrishnan K, Wang W, Cherry SR, Badawi RD. Optimal whole-body PET scanner configurations for different volumes of LSO scintillator: a simulation study. Phys Med Biol. 2012; 57(13):4077–94. [PubMed: 22678106]
13. Badawi RD, Miller MP, Bailey DL, Marsden PK. Randoms variance reduction in 3D PET. Phys Med Biol. 1999; 44(4):941–54. [PubMed: 10232807]
14. GATE. Opengate Collaboration: GATE user guide [Online]. Nov 12. 2012 Available from: http://wiki.opengatecollaboration.org/index.php/Users_Guide_V6.2
15. Oliver JF, Rafecas M. Improving the Singles Rate Method for Modeling Accidental Coincidences in High-Resolution PET. Phys Med Biol. 2010; 55(22):6951–71. [PubMed: 21048288]
16. Guez A, Bataille F, Comtat C, Honoré PF, Jan S, Kerhoas S. Counting Rates Modeling for PET Scanners With GATE. IEEE Trans Nucl Sci. 2008; 55(1):516–23.
17. Buvat, I. Private communication. 2011.
18. Brun R, Rademakers F. ROOT – An object oriented data analysis framework. Nucl Instr Meth A. 1997; 389(1):81–6.
19. Jakoby BW, Bercier Y, Conti M, Casey ME, Bendriem B, Townsend DW. Physical and clinical performance of the mCT time-of-flight PET/CT scanner. Phys Med Biol. 2011; 56(8):2375–89. [PubMed: 21427485]
20. NEMA. NEMA Standards Publication NU 2-2007 Performance Measurements of Positron Emission Tomographs. 2007.
21. Strother SC, Casey ME, Hoffman EJ. Measuring PET Scanner Sensitivity Relating Countrates to Image Signal-to-Noise Ratios using Noise Equivalent Counts. IEEE Trans Nuc Sci. 1990; 32(2):783–8.

Bullet points for the highlights

1. The GATE Simulation tool kit has been used extensively by the PET community
2. We tested two GATE Simulation tool kit coincidence policies
3. The policy most similar to that commonly used in clinical PET scanners results in significant errors
4. An alternative policy generates results that are reasonably accurate

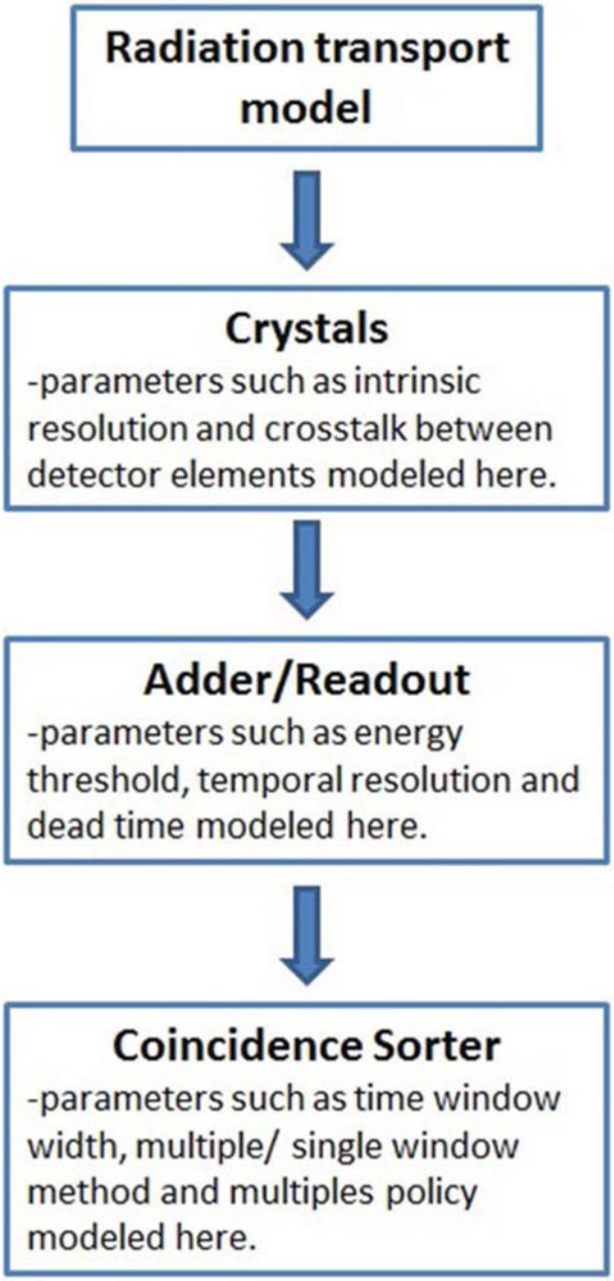
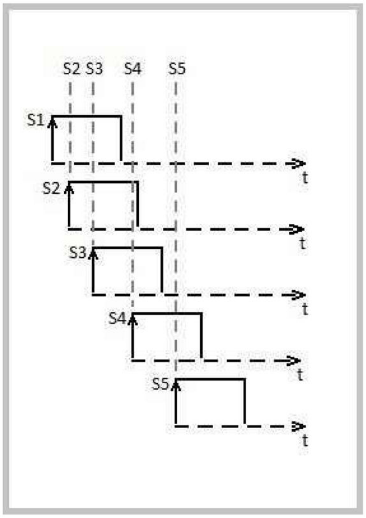


Figure 1.

Simplified block diagram showing the data processing chain for events in a GATE PET simulation. For testing, the coincidence sorter was replaced by custom code.



MW, takeAllGoods	SW, takeAllGoods	SW, killAll
s1s2, s1s3	s1s2, s1s3	-
s2s3, s2s4	-	-
s3s4	-	-
s4s5	s4s5	s4s5

Figure 2.

A sequence of single events and the coincidence pairs that would be generated using the multiple-window (MW) take-all-goods policy, the single-window (SW) take-all-goods policy, and for comparison, the single-window kill-all policy. The latter rejects all multiple coincidences. A valid prompt is counted if the coincidence pair meets the transaxial FOV and maximum accepted ring difference criteria of the scanner. If all coincidences listed meet these criteria, then the five single events shown will give rise to 6 prompts under the MW take-all-goods policy, but only 3 under the SW take-all-goods policy.

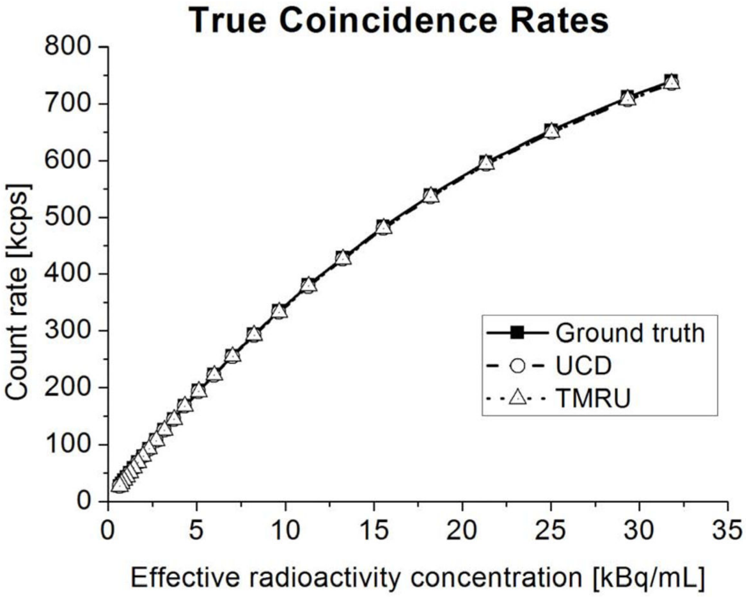


Figure 3.

True coincidence rates from the UCD and TMRU prompt coincidence sorters, compared to ground truth derived from eventIDs of single events.

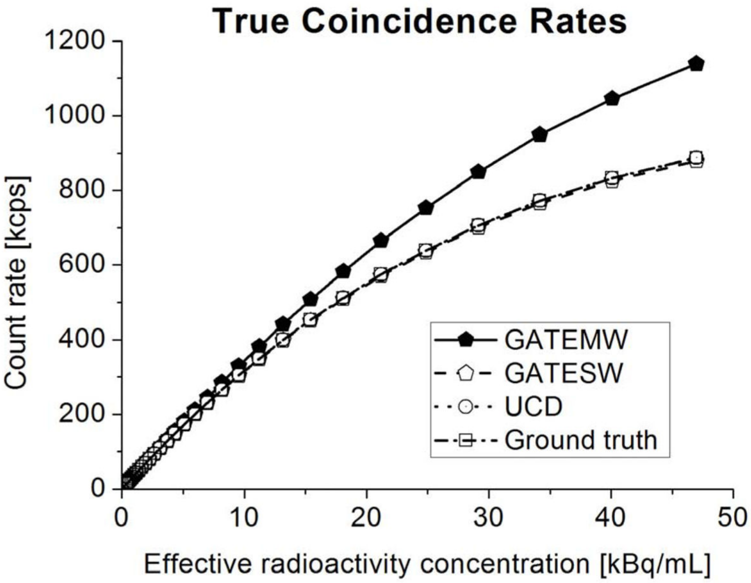


Figure 4.

True coincidence rates from GATESW, GATEMW and UCD coincidence sorters, together with ground truth derived directly from the single events.

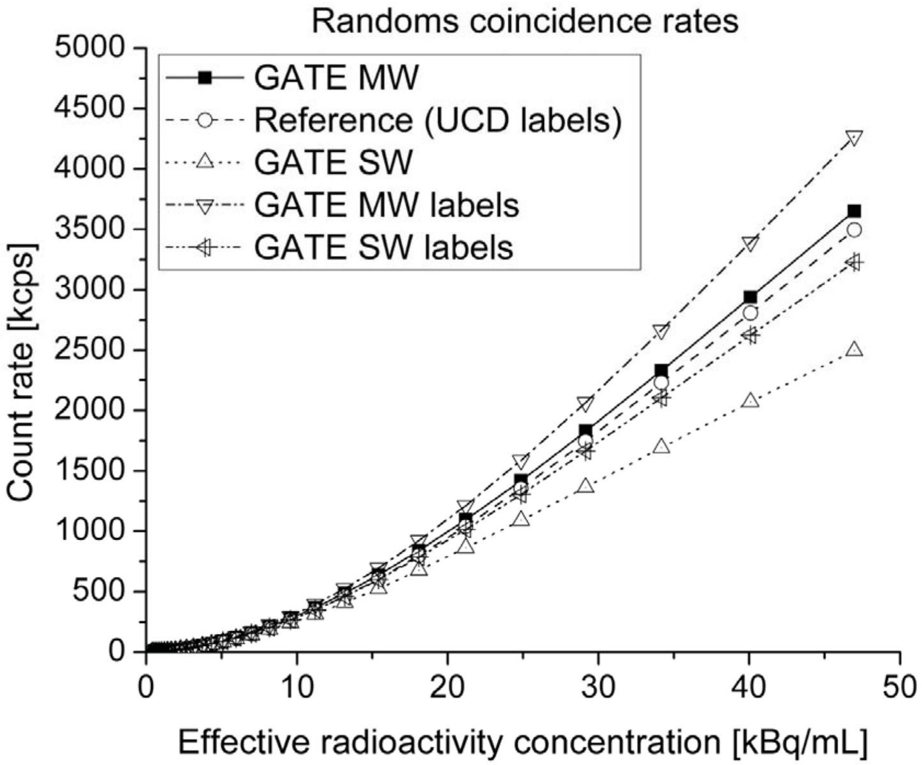


Figure 5.

"Randoms from labels" for GATESW, GATEMW prompt coincidence generators and Random coincidence rates estimated using the delayed channel approach for GATESW and GATEMW with the UCD data by label plotted as reference.

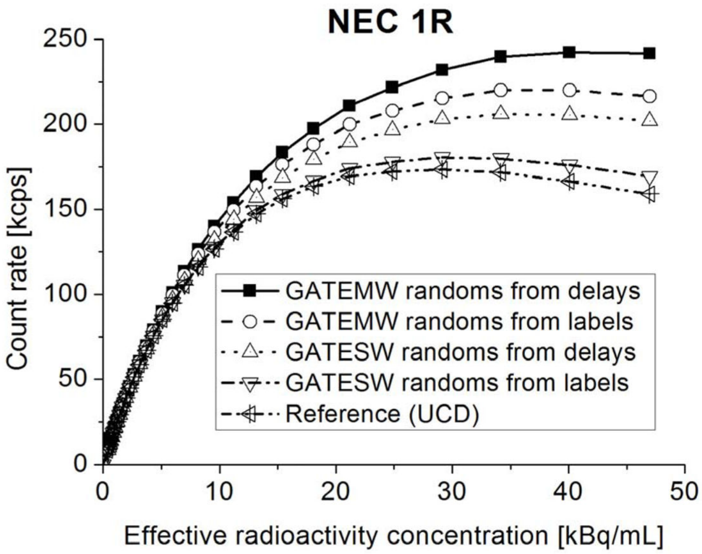


Figure 6a

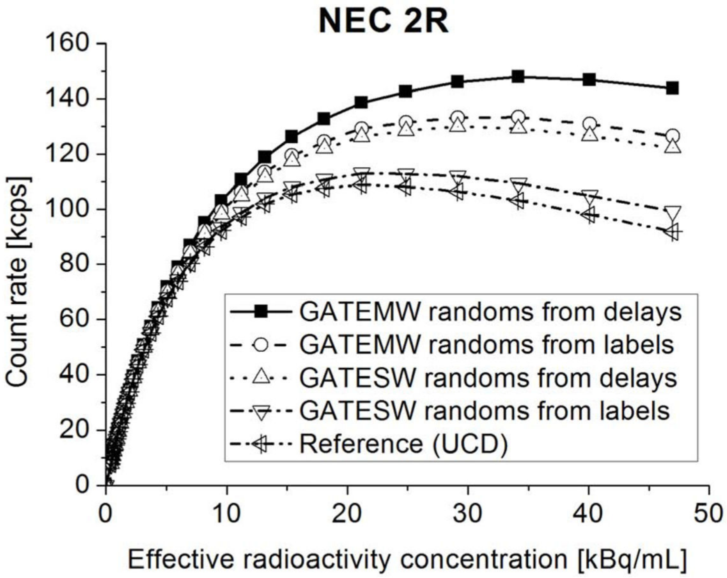


Figure 6b

Figure 6.

Figure 6a. Noise-equivalent count rates, calculated assuming a low-variance estimator for randoms, for GATESW, GATEMW, with either delayed randoms or randoms from labels, compared with data derived from the UCD coincidence processor.

Figure 6b. Noise-equivalent count rates, calculated assuming a Poisson-distributed estimator for randoms, for GATESW, GATEMW, with either delayed randoms or randoms from labels, compared with data derived from the UCD coincidence processor

Table 1

Peak noise equivalent count rates for the coincidence sorters used.

		UCD Ref.	SW labels	SW delays	MW labels	MW delays
NEC1R	Peak (kcps)	173.42	180.50	205.95	220.05	242.20
	Activity (kBq/mL)	29.15	29.15	34.18	46.97	46.97
NEC2R	Peak (kcps)	108.87	113.02	129.82	133.27	147.90
	Activity (kBq/mL)	21.19	21.19	29.15	34.18	34.18

Table 2

Summary of percent errors on Trues and Randoms from GATE MW and GATE SW compared to the UCD coincidence processor. Activity selected maximizes NEC for the UCD coincidence processor.

	GATE MW			**GATE SW**		
	Trues	**Randoms: label**	**Randoms delayed**	**Trues**	**Randoms label**	**Randoms delayed**
@ 29.15 kBq/mL	+ 20.20%	+18.39%	+4.71%	−0.75%	−4.59 %	−21.85%
@ 21.19 kBq/mL	+15.66 %	+16,27%	+5,18	−0,63%	−2,67%	−17.19%