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A method for measuring the energy spectrum of coincidence events in positron emission tomography

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Abstract

Positron emission tomography (PET) system energy response is typically characterized in singles detection mode, yet there are situations in which the energy spectrum of coincidence events might be different than the spectrum measured in singles mode. Examples include imaging with isotopes that emit a prompt gamma in coincidence with a positron emission, imaging with low activity in a LSO/LYSO-based cameras, in which the intrinsic activity is significant, and in high scatter situations where the two 511 keV photons have different scattering probabilities (i.e. off-center line source). The ability to accurately measure the energy spectrum of coincidence events could be used for validating simulation models, optimizing energy discriminator levels and examining scatter models and corrections. For many PET systems operating in coincidence mode, the only method available for estimating the energy spectrum is to step the lower and upper level discriminators (LLD and ULD). Simple measurement techniques such as using a narrow sliding energy window or stepping only the LLD will not yield a spectrum of coincidence events that is accurate for cases where there are different energy components contributing to the spectrum. In this work we propose a new method of measuring the energy spectrum of coincidence events in PET based on a linear combination of two sets of coincident count measurements: one made by stepping the LLD and one made by stepping the ULD. The method was tested using both Monte Carlo simulations of a Siemens microPET R4 camera and measured data acquired on a Siemens Inveon PET camera. The results show that our energy spectrum calculation method accurately measures the coincident energy spectra for cases including the beta/gamma spectrum of the ¹⁷⁶Lu intrinsic activity present in the LSO scintillator crystals, a ⁶⁸Ge source and an ¹²⁴I source (in which there are prompt γ -rays emitted together with the positron).

1. Introduction

The energy response of a positron emission tomography (PET) system is normally characterized and measured with the system operating in singles mode. Singles mode acquisition of energy spectra is sufficient, and indeed essential, for uses such as characterizing the energy resolution of a PET system and setting up energy discriminator levels. In general, the architecture of PET system electronics is such that when the camera is operating in coincidence detection mode, energy information about each detected event is

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not explicitly included in the data stream. Thus, the only energy information available for the two singles that created a coincidence event is whether each was above some lower level discriminator (LLD) and below some upper level discriminator (ULD) value. For many reasons, the energy spectrum of coincidence events can be different from the energy spectrum of singles events. One example of this is when low amounts of activity are imaged in a lutetium oxyorthosilicate (LSO)- or lutetium–yttrium oxyorthosilicate (LYSO)-based PET system, which has intrinsic radioactivity in the detector scintillation crystals (Goertzen *et al* 2007, Yamamoto *et al* 2005). The decay scheme of ^{176}Lu involves a β^- emission (mean energy 420 keV) followed by a prompt gamma cascade with energies of 307 keV (94%), 202 keV (78%) and 88 keV (15%) (Browne and Junde 1998). This decay scheme leads to the creation of a number of true coincidence events originating from the detection of the β^- in the crystal in which the ^{176}Lu decay occurred and one of the prompt γ -rays in another detector crystal. We have previously shown that when very low amounts of radioactivity are in the PET system field of view (FOV), the coincident count rate is dominated by the detection of these intrinsic true events (Goertzen *et al* 2007).

The energy spectrum of these intrinsic coincidence events cannot be measured using the traditional method of a singles-mode acquisition because the spectrum that will be measured will be dominated by the β^- emission spectrum due to the high probability of detection. In addition, the method of using a compact scattering source, as suggest by Watson (1997), does not apply because the activity is originating from within the scintillation crystals. Another commonly used option for measuring the coincidence energy spectrum is to set a high value for the ULD and step the LLD, recording the difference in counts between two successive LLD settings. This method will not accurately describe the higher energy β^- particle contribution to the coincident energy spectrum because once the LLD is set high enough to exclude the γ -rays at 202 keV and 307 keV, the coincidence count rate will effectively drop to zero. In addition, stepping the LLD will distort the shape and position of the γ -ray photopeaks, since the coincidence spectrum in practice involves two photons rather than just one. The case can be made that current methods are inadequate for evaluating the energy spectrum of coincidence events for any imaging situation in which a coincidence pair is created by two singles that are drawn from different energy spectra. Examples other than the intrinsic radioactivity of LSO could include so-called dirty positron emitters, such as ^{124}I or ^{76}Br , which emit one or more prompt photons in coincidence with a positron, or asymmetrical scatter situations, where an offset source causes one detector to see minimal scatter and another detector to see large amounts of scatter. Finally, the energy spectrum of detected coincident events will always be different from that of the single events when a limited transaxial field of view is imposed when histogramming the coincident events.

In this paper we present a new simple method for estimating the energy spectrum of coincidence events in a PET system. The method uses a combination of two complementary measurements, one acquired by stepping the LLD and the other by stepping the ULD. The spectrum calculation method is derived theoretically and evaluated using both Monte Carlo simulation methods and measured data.

2. Methods

2.1. Derivation of spectrum calculation method

We assume that coincidence events are generated by two events with different energy spectra $S_1(E)$ and $S_2(E)$. For coincidence events we should know the average of $S_1(E)$ and $S_2(E)$, $S_{\text{avg}}(E)$, where

$$S_{\text{avg}}(E) = \frac{S_1(E) + S_2(E)}{2}. \quad (1)$$

We normalize $S_1(E)$ and $S_2(E)$ as

$$\int_0^\infty S_1(E) dE = \int_0^\infty S_2(E) dE = 1 \quad (2)$$

and define the probability $P_1(E_1, E_2)$ that an event in spectrum 1 has an energy between E_1 and E_2 as (with a similar definition for spectrum 2)

$$P_1(E_1, E_2) = \int_{E_1}^{E_2} S_1(E) dE. \quad (3)$$

For a defined energy window of $E_1 = \text{LLD}$ to $E_2 = \text{ULD}$, the probability of two events from spectra 1 and 2 being within the window, $P_C(\text{LLD}, \text{ULD})$ is the product of $P_1(\text{LLD}, \text{ULD})$ and $P_2(\text{LLD}, \text{ULD})$:

$$P_C(\text{LLD}, \text{ULD}) = P_1(\text{LLD}, \text{ULD}) \cdot P_2(\text{LLD}, \text{ULD}). \quad (4)$$

When we step the LLD up from a level E to $E + \Delta E$ with a very high ULD setting, the difference in counts for the two energy windows, ΔC_{LLD} , is

$$\begin{aligned} \Delta C_{\text{LLD}}(E, E + \Delta E) &= P_C(E, \infty) - P_C(E + \Delta E, \infty) \\ &= P_1(E, \infty) \cdot P_2(E, \infty) - P_1(E + \Delta E, \infty) \cdot P_2(E + \Delta E, \infty). \end{aligned} \quad (5)$$

When we step the ULD down from a level of $E + \Delta E$ to E with a very low LLD setting, the difference in counts for the two energy windows, ΔC_{ULD} , is

$$\begin{aligned} \Delta C_{\text{ULD}}(E, E + \Delta E) &= P_C(0, E + \Delta E) - P_C(0, E) \\ &= P_1(0, E + \Delta E) \cdot P_2(0, E + \Delta E) - P_1(0, E) \cdot P_2(0, E). \end{aligned} \quad (6)$$

If we add ΔC_{LLD} and ΔC_{ULD} for a similar step $(E, E + \Delta E)$ we get

$$\Delta C_{\text{LLD}} + \Delta C_{\text{ULD}} = P_1(E, \infty) \cdot P_2(E, \infty) - P_1(E + \Delta E, \infty) \cdot P_2(E + \Delta E, \infty) + P_1(0, E + \Delta E) \cdot P_2(0, E + \Delta E) - P_1(0, E) \cdot P_2(0, E). \quad (7)$$

It can be shown that the rearrangement of equation (7) will give

$$\begin{aligned} \Delta C_{\text{LLD}} + \Delta C_{\text{ULD}} &= P_1(E, E + \Delta E) \cdot \{P_2(0, E) + P_2(E, \infty)\} + P_2(E, E + \Delta E) \cdot \{P_1(0, E) + P_1(E, \infty)\} \\ &= P_1(E, E + \Delta E) \cdot P_2(0, \infty) + P_2(E, E + \Delta E) \cdot P_1(0, \infty) \\ &= P_1(E, E + \Delta E) + P_2(E, E + \Delta E). \end{aligned} \quad (8)$$

But from equation (3), as ΔE becomes small we can make the approximation that

$$P_1(E, E+\Delta E) \cong S_1 \left(E + \frac{\Delta E}{2} \right) \cdot \Delta E \quad (9)$$

with a similar approximation for $P_2(E, E + \Delta E)$ so that

$$\begin{aligned} \Delta C_{\text{LLD}} + \Delta C_{\text{ULD}} &= P_1(E, E+\Delta E) + P_2(E, E+\Delta E) \\ &\cong \left\{ S_1 \left(E + \frac{\Delta E}{2} \right) + S_2 \left(E + \frac{\Delta E}{2} \right) \right\} \cdot \Delta E \\ &= \left\{ S_{\text{avg}} \left(E + \frac{\Delta E}{2} \right) \right\} \cdot 2\Delta E. \end{aligned} \quad (10)$$

Then the average spectrum of the coincidence events, $S_{\text{avg}}(E)$, is simply given by

$$S_{\text{avg}} \left(E + \frac{\Delta E}{2} \right) = \frac{\Delta C_{\text{LLD}} + \Delta C_{\text{ULD}}}{2\Delta E}. \quad (11)$$

In this way, the average energy spectrum of the two events forming the coincidence pair can be measured through a simple linear combination of two measurements, the first acquired by stepping the LLD with a fixed ULD (ULD_{max}) and the second acquired by stepping the ULD with a fixed LLD (LLD_{min}).

2.2. Simulated PET data

PET data were simulated using GATE, the Geant4 application for emission tomography (Jan *et al* 2004). The geometry simulated was that of the Siemens microPET R4 (Knoess *et al* 2003) (Siemens Preclinical Solutions, Knoxville, TN). Briefly, this system has 96 detector blocks arranged in four rings with a 14.8 cm ring diameter, providing an axial FOV of 7.8 cm and a transaxial FOV of 10.0 cm. Each detector block consists of an 8×8 array of $2.1 \times 2.1 \times 10 \text{ mm}^3$ LSO scintillator crystals with a center-to-center spacing of 2.4 mm. Only coincidence events within the 10 cm transaxial FOV were accepted. Simulated activity levels were kept sufficiently low so that neither the effects of system dead time nor random coincidences were considered. A system energy resolution of 15% was used in all simulations. Simulated data were histogrammed into Concorde microPET format sinograms using custom-built histogramming software. Single slice rebinning (SSRB) (Daube-Witherspoon and Muehllehner 1987) was used with a ring difference of 31. Four source distributions were simulated.

1. *Intrinsic activity from ^{176}Lu .* The intrinsic radioactivity in the LSO was modeled using the ion source function in GATE with an activity of 250 Bq cc^{-1} , amounting to a total ^{176}Lu activity of 67 kBq distributed uniformly in the 270 cc total volume of LSO scintillator material in the microPET R4.
2. *^{68}Ge line source in air.* An 8 cm long ^{68}Ge line source of activity 50 kBq was simulated as a back-to-back photon source in GATE centered in the FOV of the PET camera with the long axis along the axial direction of the camera.
3. *Intrinsic ^{176}Lu activity + ^{68}Ge line source.* The two sources described for source distributions (1) and (2) were simulated at the same time.

4. *^{124}I line source in water.* An 8 cm long ^{124}I line source of activity 50 kBq was simulated as being centered in the FOV of the PET camera with the long axis along the axial direction of the camera. The ^{124}I was modeled as an ion source in GATE, which simulates the complete decay scheme of ^{124}I including the prompt γ -rays that accompany many of the positron emission events. Due to the large positron emission energies of ^{124}I , and hence substantial positron range, the ^{124}I line source was simulated as being within a 20 mm diameter, 100 mm long water cylinder in order to ensure that most emitted positrons would annihilate within the camera FOV.

For each of the source distributions, two coincidence mode data acquisition runs were simulated. In the first, the ULD was fixed at 850 keV and the LLD was stepped from 50 to 840 keV in 10 keV steps. For each of the first three source distributions, 400 s of data acquisition was simulated per energy window. For the ^{124}I source, 1800 s of data acquisition was simulated per energy window. These times were chosen because it gave a total of approximately 10^6 coincidence counts for each source distribution (^{176}Lu , ^{68}Ge and ^{124}I) when the energy window was 50–850 keV. For the second simulated data acquisition, the LLD was fixed at 50 keV and the ULD was stepped from 60 to 850 keV in 10 keV steps. Again, for the first three source distributions, 400 s of data acquisition was simulated for each ULD setting and 1800 s was simulated for the ^{124}I source. All simulations were run using the GATE multiples policy of ‘KillAll’, in which no multiple coincidence events (i.e. three or more valid single events in coincidence) are accepted as a valid coincidence. In addition to the coincidence mode simulations, a singles mode acquisition was simulated for each source distribution with the energy window set at 50–850 keV.

2.3. Analysis of simulated data

For each simulated source distribution, five energy spectra were calculated. After calculation all simulated spectra results were normalized to have 10^6 total counts. The spectra calculated are as follows.

1. *Singles spectrum.* The singles events recorded in the singles mode simulation were histogrammed into an energy spectrum. This energy spectrum is comparable to the singles mode spectrum that is normally obtained when calibrating the energy window of a PET system.
2. *Coincidence spectrum.* The coincidence events obtained from the 50 to 850 keV energy window simulation were histogrammed into an energy spectrum using the energy of the event recorded in the list-mode simulation output file. For subsequent analysis, this spectrum is considered as the ‘true value’ of the energy spectrum $S_{\text{avg}}(E)$ as described in equation (1) because it represents the actual energy distribution of the coincidence events.
3. $\Delta C_{\text{LLD}}(E, E + \Delta E)$. The difference in counts measured with two successive LLD settings is plotted at the midpoint of the two LLD settings (i.e. at $E + \Delta E/2$). The measurement of $\Delta C_{\text{LLD}}(E, E + \Delta E)$ corresponds to equation (5) and is just the spectrum typically measured with a simple stepping of the LLD. The values were obtained by extracting the number of histogrammed trues (i.e. trues plus scatter) from the sinogram header files.
4. $\Delta C_{\text{ULD}}(E, E + \Delta E)$. The difference in counts measured with two successive ULD settings is plotted at the midpoint of the two ULD settings (i.e. at $E + \Delta E/2$). The measurement of $\Delta C_{\text{ULD}}(E, E + \Delta E)$ corresponds to equation (6) and is just the spectrum typically measured with a simple stepping of the ULD. The values were obtained by extracting the number of histogrammed trues (i.e. trues plus scatter) from the sinogram header files.

5. $S_{avg}(E + \Delta E/2)$. $S_{avg}(E + \Delta E/2)$ is calculated according to equation (11) as a linear combination of $\Delta C_{LLD}(E, E + \Delta E)$ and $\Delta C_{ULD}(E, E + \Delta E)$, the measurements represented by the spectra calculated in items (3) and (4) above. Dividing by $2\Delta E$ could be used to convert the value into counts per second (cps) per keV. This was not done due to the subsequent normalizing of the total number of counts in the spectrum to 10^6 .

For each of the spectra that have a ^{68}Ge source, the position and full width at half maximum (FWHM) energy resolution of the 511 keV photopeak were calculated.

2.4. Measured data for energy spectra measurements

Data were collected on a Siemens Inveon dedicated PET system (Bao *et al* 2009, Visser *et al* 2009, Kemp *et al* 2009) (Siemens Preclinical Solutions, Knoxville, TN) located at the UCLA Crump Institute for Molecular Imaging. Briefly, this system has 64 detector blocks arranged in four rings with a 16.1 cm ring diameter, providing an axial FOV of 12.7 cm and a transaxial FOV of 10.0 cm. Each detector block consists of a 20×20 array of $1.51 \times 1.51 \times 10 \text{ mm}^3$ LSO scintillator crystals with a center-to-center spacing of 1.59 mm. The geometry of the Inveon system is very similar to that of the microPET R4 model used in the Monte Carlo simulation work, with the key differences being the extended axial FOV and larger detector block size present in the Inveon. An Inveon system was used to acquire the measured data instead of a microPET R4 because the data acquisition software for the Inveon allowed the use of imaging protocols with multiple acquisition steps that could be acquired without user intervention. This is in contrast to the older microPET R4 software, which would have required the user to manually start each of the 150 acquisitions needed for a spectrum measurement. The Monte Carlo simulations were performed using the microPET R4 geometry, as we had previous experience with simulating this system and had the existing custom-built software to histogram the simulation output into sinograms for the microPET R4.

Coincidence mode data were acquired in which the LLD_{min} was set at 50 keV and the ULD_{max} was set at 800 keV. A discriminator step size (ΔE) of 10 keV was used for all acquisitions. With the ~14% energy resolution of the Inveon, this would allow approximately seven measurements across the 511 keV photopeak in the energy spectra. With these values for the LLD_{min} , ULD_{max} and ΔE , each spectrum measurement consisted of 150 acquisition steps, 75 of which were acquired with the LLD being stepped from 50 to 800 keV in steps of 10 keV with a fixed ULD_{max} and then a subsequent 75 measurements acquired with the ULD being stepped from 800 to 50 keV in steps of 10 keV with a fixed LLD_{min} . Acquisition of the measured data was done by setting up an 'acquisition workflow' in the Inveon acquisition software so that the entire data acquisition could be performed without manual intervention. On average, between each acquisition step the Inveon system required 15.6 s to change the energy window and setup for the next acquisition so that the total acquisition time required for all 150 measurements was 39 min plus the actual measurement time. Data were histogrammed using the manufacturer's histogramming software into sinograms with 128 bins $\times$ 160 angles $\times$ 159 planes using SSRB with a ring difference of 39. A number of histogrammed trues were extracted from the header of each sinogram and used to calculate $\Delta C_{LLD}(E, E + \Delta E)$ and $\Delta C_{ULD}(E, E + \Delta E)$.

Five data sets were acquired using the method described above for the Siemens Inveon. The sources and acquisition details for the five measurements were as follows.

1. *Background measurement of the intrinsic ^{176}Lu activity only (i.e. no external source in the camera field of view).* The measurement time for each window was 540 s, so that the entire data run of 150 acquisitions required 23.5 h.

2. *35 kBq ^{68}Ge source centered in the camera field of view.* The source geometry was a 0.75 mL Type T gamma tube standard from Isotope Products Laboratory (Eckert & Ziegler Isotope Products, Valencia, CA). This acquisition time per energy window was 360 s.
3. *7.7 MBq ^{68}Ge source centered in the camera field of view.* The source geometry was a 0.75 mL Type T gamma tube standard from Isotope Products Laboratory. The measurement time for each energy window was set at 15 s for this data run so that the entire data run of 150 acquisitions required a total of 90 min to acquire.
4. *7.7 MBq ^{68}Ge source plus a 6.8 MBq ^{133}Ba source.* The ^{68}Ge source was the source described in step (3) above. The ^{133}Ba source was a type RV vial dose calibrator reference standard from Isotope Products Laboratory. The measurement time per energy window was also 15 s for this data run.
5. *4.1 MBq ^{68}Ge cylinder source with a diameter of 10 cm, centered in the camera field of view.* The ^{68}Ge source was the 10 cm diameter animal PET normalization cylinder from Isotope Products Laboratory. The measurement time per energy window was 180 s.

In addition to the coincidence mode energy spectra measurements, singles mode data were acquired in energy spectrum measurement mode for the first four sources used for the coincidence energy measurements. The singles-mode energy spectrum for each source was extracted for one of the detector modules in the system for comparison with the coincidence energy spectra. Variations in the energy response of each crystal was normalized by using the location of the 511 keV photopeak from the spectra acquired with the 7.7 MBq ^{68}Ge source to scale the energy spectrum for each crystal. The scaled spectra from the 400 crystals were then combined into one summed spectrum for the entire block detector, referred to as the singles-mode energy spectrum.

3. Results

3.1. Simulation spectra results

Figures 1–3 show the five energy spectra for the cases of the ^{176}Lu activity only, ^{68}Ge only and ^{176}Lu plus ^{68}Ge activity, respectively. In all three cases, the S_{avg} spectra calculated using equation (11) most accurately recovers the true spectrum shape represented by the coincidence spectrum line. It is believed that discrepancies observed between S_{avg} and the coincidence spectrum plot at lower energies are due to cases where a single γ -ray creates a coincidence event by scattering in one detector and then being detected in a second detector. These types of events are enhanced in the simulations due to the small bore geometry of the microPET R4 that is simulated and the fact that no shielding materials are simulated to attenuate these photons. Further, the multiples policy of ‘KillAll’ has the effect of actually increasing the number of valid coincidences within a given energy window relative to what would be expected from the 50 to 850 keV window because as the LLD is raised, some of the low energy scatter events will be excluded from the singles, thus reducing the number of multiples coincidences and increasing the number of valid coincidences.

For cases containing the intrinsic ^{176}Lu activity, the singles spectrum has a much larger β^- emission spectrum component as compared to the coincidence spectrum. This result is expected since the true coincident events can only occur for a detection of a β^- plus γ -ray emission in coincidence. In the spectra with ^{176}Lu activity it can be seen that measurements made by simply stepping the LLD completely miss the presence of the higher energy β^- events. Similarly, measurements made by stepping the ULD underestimate the γ -ray components of the spectra.

Table 1 gives the location and FWHM resolution of the 511 keV photopeak for the simulations that include a ^{68}Ge source. As expected, for the simulation with only a ^{68}Ge source, the 511 keV photopeak location and the 15% FWHM energy resolution were accurately recovered with the singles spectrum. It can be seen that the 511 keV photopeak location is underestimated when only the ΔC_{LLD} method of stepping the LLD is used to create the energy spectrum and the location is correspondingly overestimated for the ΔC_{ULD} method of stepping only the ULD. In addition, the FWHM energy resolution was underestimated for both cases. In both source distributions that have a ^{68}Ge source, the spectrum given by the calculation of S_{avg} according to equation (11) gives the accurate 511 keV photopeak location and FWHM energy resolutions.

Figure 4 shows the five energy spectra for the ^{124}I source. In the decay of ^{124}I , approximately 50% of positron emissions are accompanied by a 603 keV γ ray emission, and overall, the number of emissions of this γ -ray energy is very similar to the number of 511 keV annihilation photons created. This is reflected in the singles emission spectrum, in which the 511 keV and 603 keV photopeaks are of comparable magnitude. The coincidence energy spectrum is distinctly different from the singles spectrum, with a far larger amount of counts in the 511 keV as compared to the 603 keV photopeak. Again for this case the S_{avg} energy spectrum accurately recovers the true coincidence energy spectrum. As described above for the other coincidence spectra, there are some discrepancies at lower energies, which we attribute to back-scattered photons creating multiple coincidence events.

3.2. Measured singles mode energy spectra

Figure 5 shows the singles mode energy spectra for the 7.7 MBq ^{68}Ge source with and without the 6.8 MBq ^{133}Ba source present. As is expected, the energy spectrum for the two sources clearly shows the contributions of the multiple prominent γ -ray emission lines 161, 276, 302, 356 and 384 keV of the ^{133}Cs daughter of the ^{133}Ba decay (Rab 1995). Figure 6 shows the energy spectra for the ^{176}Lu activity present in the LSO scintillator crystals with and without a 35 kBq ^{68}Ge source. The contribution of the ^{68}Ge source to the spectrum is very subtle compared to the large contribution of the background scintillator activity. The ^{176}Lu spectrum clearly shows a summing peak above 600 keV due to the sum of β^- emission plus γ -ray detection in the same scintillator crystal.

3.3. Measured coincidence mode energy spectra

Figure 7 shows the coincidence mode energy spectra for the ^{68}Ge source with and without the ^{133}Ba source present in the camera. It can clearly be seen that the two spectra have nearly perfect agreement, indicating that the ^{133}Ba photons are not contributing to the coincidence counts in the camera. It should be pointed out that no scaling was applied to the two spectra to normalize for total counts. The agreement between the measurements with and without the ^{133}Ba source being present is distinctly different from the situation of the singles spectra in figure 4 in which the emissions from the ^{133}Cs decay product are clearly seen between 200 and 400 keV. Figure 8 shows the coincidence mode energy spectra for the ^{176}Lu intrinsic activity with and without the 35 kBq ^{68}Ge source present in the camera. Again, no scaling for total counts was applied to the spectra. Differences in acquisition time were accounted for by dividing the total counts in the sinogram by the acquisition time. The β^- plus γ -ray nature of the intrinsic coincidence events can be clearly seen in the spectra and the summing peak about 600 keV that is present in the singles spectra in figure 5 is not seen in the coincidence spectra. The 511 keV peak from the ^{68}Ge source is clearly seen in the spectrum with the ^{68}Ge source and is much more prominent than in the singles spectrum. In every coincidence mode energy spectrum measured with the Inveon system, the measured location of the photopeak was between 2 and 5% lower than the nominal γ -ray energy for that photopeak. In discussions with Siemens, we believe that this discrepancy is most likely

explained by variations in gantry temperature, which cause the signal energy to decrease approximately $1.5\% \text{ }^{\circ}\text{C}^{-1}$ rise in temperature. These effects were not seen in the singles mode spectra, as the 511 keV energy was defined for each detector by the location of the 511 keV photopeak in the ^{68}Ge spectrum measurements.

Figure 9 shows the energy spectra for the low scatter compact ^{68}Ge source and the high scatter 10 cm diameter ^{68}Ge cylinder source. The two spectra have been scaled to have the same number of total counts for clarity. It can be clearly seen that for the cylinder source, there are considerably more counts in the energy region below the photopeak due to the increased scatter.

4. Discussion and summary

In this work we propose a simple method to allow the calculation of the energy spectrum of coincidence events in a PET system using a linear combination of two measurements, one acquired by stepping the LLD and the other acquired by stepping the ULD. This proposed method is tested using Monte Carlo simulation techniques, which showed that the energy spectrum of the coincidence events could be accurately recovered even when the two singles events creating the coincidence event had different emission spectra as is the case of the ^{176}Lu intrinsic activity. For the ^{176}Lu coincidence events, the method we propose accurately shows the β^{-} emission spectrum at energies above the 511 keV photopeak normally seen in PET from β^{+} annihilation photons. For simulations that included a β^{+} emitter in the FOV, the 511 keV photopeak location and FWHM energy resolution were both accurately described with this spectrum calculation method. Finally, this method accurately measures the energy spectrum of coincidence events for ^{124}I , which emits prompt γ -rays in coincidence with the positron emission.

In all of the simulation cases, the new coincidence energy spectrum calculation method most accurately matched the energy spectrum of coincidence events calculated directly from the list-mode simulation data. Simple methods of stepping the LLD and ULD incorrectly identified the photopeak location, energy resolutions and general shape of the coincidence energy spectra.

The energy spectrum measurement method was performed on a Siemens Inveon camera for source configurations that ranged from the intrinsic ^{176}Lu only to a combination of strong ^{68}Ge and ^{133}Ba sources. In the measurements of the ^{176}Lu intrinsic activity and ^{68}Ge sources, the coincidence energy spectra closely match the shape of the simulated results. For the case of a mix of β^{+} emitter (^{68}Ge) together with a single photon emitter (^{133}Ba), the measured coincidence energy spectrum demonstrates that only the ^{68}Ge β^{+} emissions are significantly contributing to coincidence events despite the singles mode energy spectrum showing that approximately 50% of detected photons are from ^{133}Ba emissions. For a reasonable source strength, the measured acquisitions could be acquired in as little as 90 min using 15 s acquisition frames. This relatively short acquisition protocol means that ^{18}F could possibly be used for the measurements, provided a correction was employed for the decay of the source throughout the measurement.

We believe that there are many applications that can make use of this simple technique for measuring the energy spectrum of coincidence events, especially given the ease with which this measurement could be acquired on an actual PET system. An obvious example, as shown in our simulation work, is for imaging studies that make use of so-called dirty positron emitters such as ^{124}I , which emit prompt γ -rays in coincidence with the β^{+} emission. Image reconstruction methods for these isotopes must account for the contamination in the sinograms from the prompt γ -rays. Our energy spectrum measurement

technique allows a simple and rapid way to measure the energy spectrum of coincidence events from these dirty positron emitters that will simplify the benchmarking of simulations and reconstruction algorithms as well as the optimization of energy windows. Another potential application of this technique is in validating the modeling of scatter in the PET system. If the imaging case contains an asymmetric activity distribution and scattering environment, it is very likely that detectors on opposite sides of the detector ring will be exposed to different input energy spectra, containing both scattered and unscattered photons. Our technique could easily be extended to evaluate the coincidence energy spectrum on a per detector basis by evaluating only certain regions on the sinogram, thus allowing the validation of energy spectrum models of scatter on all sides of an object being imaged. Finally, for imaging situations where a LSO-based camera is used to image weak emission sources, an estimate of the extent of the contribution of the intrinsic radioactivity to the counts in the sinogram can be made by measuring the energy spectrum of the coincident events.

One limitation of our method is that it cannot provide real-time information about the energy spectrum of the coincidence events. This means that it cannot easily be used for energy-dependent techniques for scatter estimation and image reconstruction such as those proposed by Popescu *et al* (2006). These techniques depend on real-time acquisition of complete energy information, which our method is not capable of, and require a PET system that includes information about the energy of each event in the list-mode data. PET systems that are capable of acquiring energy information about events in the list-mode coincidence can directly measure the energy spectrum of the coincidence events and thus do not have use of our new method. For these reasons, our approach is useful only for PET systems that are not capable of acquiring coincidence data with energy information included.

In summary, a new method for evaluating the energy spectrum of coincidence events in PET is proposed and evaluated with both Monte Carlo simulation and measured results. The new method accurately calculates the energy spectra of the coincidence events using a combination of stepping the LLD and ULD independently. The Monte Carlo simulation results demonstrate that this new method accurately recovers the energy spectrum of coincidence events even for the case of coincidence events being generated from two single events with different emission energy spectra, such as is the case for the intrinsic radioactivity present in lutetium-based scintillators due to the presence of ^{176}Lu or for dirty positron emitters such as ^{124}I . The measurement method was successfully performed on a Siemens Inveon camera, allowing measurements of the coincidence energy spectrum to be acquired in as little as 90 min with a 15 s per acquisition time frame.

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Figure 1. Simulated energy spectra for the ^{176}Lu activity only. Both the lower energy γ -ray spectrum and the higher energy β^- spectrum are most accurately recovered by the S_{avg} spectrum calculation method proposed by equation (11). Note how the singles spectrum is dominated by the β^- events. All spectra are scaled to contain 10^6 events.

Figure 2.

Energy spectra for the ^{68}Ge source only. The S_{avg} spectrum calculated according to equation (11) accurately recovers the 511 keV photopeak location and shape. All spectra are scaled to contain 10^6 events.

Figure 3.

Energy spectra for the ^{176}Lu intrinsic activity plus the ^{68}Ge source. The S_{avg} spectrum most accurately recovers the shape of the true coincidence event energy spectrum. All spectra are scaled to contain 10^6 events.

Figure 4.

Energy spectra for the ^{124}I source. The S_{avg} spectrum most accurately recovers the shape of the true coincidence event energy spectrum. Note how the 511 keV photopeak and the 603 keV photopeak are of similar magnitude in the singles spectrum, while in the coincidence spectra the 511 keV peak is much more prominent. All spectra are scaled to contain 10^6 events.

Figure 5.

Singles mode energy spectra of a strong ^{68}Ge source with and without a ^{133}Ba source present in the camera field of view. The contribution of the ^{176}Lu background is not seen in these spectra due to the high count rate from the other sources.

Figure 6. Singles mode energy spectra of the intrinsic ^{176}Lu activity with and without a weak ^{68}Ge source present in the camera field of view. Note how the 511 keV photons from the weak ^{68}Ge source are only minimally seen about the ^{176}Lu background.

Figure 7.

Coincidence mode energy spectra for the 7.7 MBq ⁶⁸Ge source with and without a 6.8 MBq ¹³³Ba source present in the camera field of view. Note that the two spectra have nearly identical shapes, indicating that the emissions from ¹³³Ba are not at all contributing to the coincidence counts from the ⁶⁸Ge source.

Figure 8. Coincidence mode energy spectra ^{176}Lu intrinsic activity with and without a weak ^{68}Ge source in the camera field of view. Note how the 511 keV peak from the ^{68}Ge source is much more prominent than in the singles mode spectrum of figure 2.

Figure 9.

Coincidence mode energy spectra of a compact ^{68}Ge source subject to little scatter and a 10 cm diameter ^{68}Ge cylinder subject to a large amount of scatter. The spectra have been scaled to contain the same number of counts. Note the lower fraction of events in the photopeak region for the cylinder source.

Table 1

511 keV photopeak location and FWHM energy resolution.

	⁶⁸ Ge source only		¹⁷⁶ Lu + ⁶⁸ Ge sources	
	511 keV photopeak location (keV)	FWHM energy resolution	511 keV photopeak location (keV)	FWHM energy resolution
Singles	509.9	15.2%	508.3	13.9%
Coincidence	510.2	15.2%	510.1	15.3%
$\Delta C_{LLD}(E, E + \Delta E)$	493.1	13.0%	493.1	13.0%
$\Delta C_{ULD}(E, E + \Delta E)$	523.0	13.3%	522.9	13.6%
$S_{avg}(E + \Delta E/2)$	510.6	15.3%	510.4	15.3%