Sensitivity Enhancement Using Triple-Coincidence Events in the AXPET Demonstrator.

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I. INTRODUCTION

The general goal of developments in detection systems for Positron Emission Tomography (PET) is the enhancement of image quality, generally without change to object activity. However, in an attempt to improve a particular detection parameter novel systems may measure new, information-bearing, data types that are often discarded or used only approximately in the process of image generation. One such example is the generation of increased levels of Inter-Crystal Scattering (ICS) that occurs in PET when detection resolution is enhanced [1]. ICS are potentially useful events that may be measured in a PET system yet are difficult to process and may introduce resolution degradation. In this investigation different methods of data treatment are explored with the Maximum Likelihood Expectation Maximization (ML-EM) reconstruction algorithm to investigate the inclusion of ICS events directly into the system matrix. A novel approach [2] is compared to more standard methods of addressing triple-coincidence data. The AXPET prototype [3] was employed to acquire experimental data from a NEMA-like phantom [4] and standard figures of merit were calculated.

The AXPET demonstrator uses a rotating-phantom geometry and suffers from long scan times and saturation effects at higher activities. While with great care the time-profile for each acquisition could be balanced, in this investigation we developed a method that could be used to approximate acquisition contributions from each phantom position to correct sensitivity estimation and hence enhance quantitative accuracy. Using experimental data from the AXPET and the more accurate sensitivity matrix, the method of ICS inclusion proposed in [2] is compared to standard approaches [5], [6] that only approximately model the transition probabilities of ICS in the system matrix. Finally, images of small animals, acquired using the AXPET demonstrator are used to illustrate ICS inclusion using biological systems.

II. TREATMENT OF INTER CRYSTAL SCATTER

In this investigation, only ICS events containing triple-coincidence measurements were considered. It was assumed that each of the two annihilation photons could be distinguished using spectral discrimination (a single energy-deposition and the energy sum of the two other interactions lie within a photo-peak gate centered at 511 keV), resulting in a two-fold ambiguity in the Line of Response (LoR). Generally, it is presumed that the remaining task is that of determining which LoR of the pair is correct (i.e. which of the ICS pair is associated with the initial photon interaction). However, in this investigation it was assumed that no information was available to distinguish the two ICS events such that each has a 50% probability of being the initial interaction. Because there is no ability to distinguish the primary LoR, the standard method of incorporation of such events into the image reconstruction algorithm would be to weight the contribution to the data-set, such that each measurement \( y_i \) is incremented by 0.5 in a measurement histogram. The list-mode MLEM algorithm is given as:

\[
I_{j+1}^k = \frac{n_j^k}{\sum_{i=0}^{J} a_{ij} n_j^k}, \quad j = 0, ..., J
\]

where \( n_j^k \) is the value of an image pixel \( j \) at iteration \( k \), the sum is over the list of measurements \( i \) and \( a_{ij} \) are the elements of the system matrix. In the list-mode formulation the separation and weighting of events results in an alteration of the inner sum for each ICS measurement \( i' \) to:

\[
I_{j+1}^{i'} = 0.5 a_{i'j} n_j^k + 0.5 a_{i'j} n_j^k, \quad j = 0, ..., J
\]

However, this approach is both incorrect and (for list-mode using on-the-fly calculation) computationally inefficient. The relationship between each possible LoR is broken, and each ICS measurement requires twice the computational effort during image reconstruction. The computational problem may be addressed by making a random selection from the two LoRs at each iteration:

\[
I_{j+1}^{i'} = \frac{a_{i'j}}{\sum_{j=0}^{J} a_{i'j} n_j^k} = \frac{a_{i'j}}{\sum_{j=0}^{J} a_{i'j} n_j^k}, \quad j = 0, ..., J
\]

Where \( t = 1, 2 \). However, again, the relationship between the two LoRs is broken and at each iteration the ICS data contribute 50% incorrect LoRs. Instead the LoR relationship should be retained such that the inner sum of the algorithm is unchanged, but new system matrix elements are calculated:

\[
I_{j+1}^{i'} = \frac{a_{i'j}}{\sum_{j=0}^{J} a_{i'j} n_j^k}, \quad a_{i'j} = 0.5 a_{i'j} + 0.5 a_{i'j}
\]

While this approach does require twice the computational effort for ICS measurements as for standard coincidence when calculating transition probabilities on-the-fly, it retains the full detection response (here termed a V-projection after [7]) and should hence produce optimal results. Here no calculations are applied to determine LoR probabilities, yet extra information might improve the calculation of the relative weight of each LoR which could be included in each of the methods proposed - such an extension was not considered in this investigation. During image reconstruction standard coincidence events, here termed Golden events were combined with ICS measurements using each of the three approaches outlined.

III. EXPERIMENTAL APPARATUS

The AXPET prototype [3] was used to acquire data of a NEMA-like phantom [4] in which the air-filled void was replaced with a hot region of activity three times the uniform region. The data were reconstructed using the three approaches outlined: separation (2), randomized selection (3) and V-projections (4). Approximate corrections were applied to the calculation of the sensitivity normalization matrix that included estimates of phantom activity decay and detector saturation in order to minimize non-uniformities in the reconstructed image. The results were analyzed using the standard NEMA protocols - here we assess the Recovery Coefficient (RC), Spill Over Ratio (SOR) for the cold, water-filled, void and the Signal to Noise Ratio (SNR) of the uniform-region. For qualitative demonstration using realistic
Fig. 1. (a) Slices from reconstructed images using Golden and ICS events at iteration 50. Slices through the NEMA-like phantom are shown illustrating the rod-features, uniform region and void-region. All images are normalized to the maximum of the slice.(b) The standard deviation in the RC is shown against the RC value for the 2 mm and 5 mm rod features of the NEMA phantom. Each 5th iteration between 0 and 100 are shown and iteration proceeds from the left to the right.

IV. RESULTS AND ANALYSIS

In Fig. 1(a) slices through the reconstructed NEMA-like phantom for which ICS events have been incorporated are shown at the 50th iteration. The uniform region, while not perfect, shows reasonable uniformity such that quantification is expected to be accurate. In Fig. 1(b), the Recovery Coefficient (RC) and its corresponding error are plotted for each method of ICS incorporation as well as for Golden-only events. An RC of one is achieved for all rod features of sizes greater than 3 mm using both Golden events and with the V-projection method for ICS. Both separation and randomized selection reduce the RC in comparison to Golden-only reconstruction - indicating that while statistics are improved these events reduce the accuracy of the reconstructed image when utilized. Of importance is the background, or noise, that is introduced using these extra ICS events. The SOR (measured in the cold void) can be used to quantify the level of activity reconstructed into an otherwise empty region. The SNR of the uniform region of the phantom can also be used to estimate the impact of extra statistics. These values are summarized, for each approach, in Tab. I. The SOR of the cold void and the SNR of the uniform region shows that while all methods of ICS incorporation show an SNR enhancement, only the method of V-projection inclusion provided both SNR increase and SOR reduction - indicating a noise enhancement in all phantom regions.

Finally, images reconstructed using Golden events only, as well as inclusion of ICS events using V-projections are displayed in Fig. 2. Differences are observed between the two reconstructed images for both animals, and while direct improvement is unclear, the NEMA results would indicate that statistical enhancement was achieved leading to improved image quality for images incorporating ICS using V-projections.

V. CONCLUSIONS AND FUTURE WORK

Three methods of ICS inclusion were proposed and implemented using experimental data from the AXPET prototype. It was shown that the extra statistics represented by ICS could be used to enhance image quality using the NEMA small animal phantom without loss to resolution based on the recovery coefficient of the rod-features of the phantom. However, approximate methods of ICS incorporation were shown to be inferior to inclusion of the full V-projection calculation during image reconstruction.

While not presented here, the data-sets were also divided into subsets to investigate the enhancement as a function of statistical quantity. As data-set size is reduced visible enhancement is expected due to the constant relative percentage of ICS events. Because the calculation of ICS events may increase computational load (in comparison to Golden events) the investigation will also discuss the extra computational burden represented by ICS as well as propose and assess means for reduction of this burden.

REFERENCES