A prompt-gamma correction method for non-standard PET radionuclides based on the detection of triple coincidences

J. L. Herraiz, S. C. Moore, V. Parot, S.R. Dave, M. Park, S. Yoo, W. Lee, H. Kim, E. Lage

I. Introduction

When PET radiotracers are labeled with non-standard β^+ emitter radionuclides such as ^{124}I, ^{76}Br or ^{86}Y, the prompt gamma rays emitted in cascade with positrons can be detected in coincidence with each other or with annihilation photons, thereby creating spurious double coincidences. These coincidences cause a significant additional background in resulting PET images which reduces their contrast and quantitative accuracy [1]. Corrections such as the subtraction of a uniform [2] or a linear [3] background fitted to the sinogram data outside the object have been suggested. However, although this subtraction gives a good first approximation, depending on the size of the imaged object, the assumption that the background caused by spurious coincidences is uniform or linear may be wrong [1]. A convolution-subtraction algorithm described by Beattie et al. [4] does take patient-specific variations into account; however, so far, this has only been described for 2-D acquisitions. Overall, methods implemented in current clinical PET scanners are generalizations of scatter-correction methods. For example, some Philips scanners use a geometric correction, integrated in the single-scatter simulation (SSS) scatter correction [5], which is based on calculating the contribution of prompt-gamma coincidences from several source points to each line-of-response (LOR) [6]. On the other hand, Siemens has reported a correction method based on the subtraction of a scaled randoms sinogram that is also incorporated into the SSS scatter correction [7].

In general, these estimation procedures require significant additional computational time for obtaining accurate results, and they can introduce bias into the images, so incorporating this into the scatter correction may not be the best choice [4]. Furthermore, as with most standard scatter correction methods, they require measurements in some regions of the sinogram, where it is known that no signal should be present, to scale the estimates to fit the measured data. In some cases, for instance with obese patients that fill the whole field-of-view of the scanner, these measurements are not possible [8]. For all of these reasons, it would be desirable to have a direct measurement of the background caused by the prompt gammas, instead of relying on estimates based on simulations or approximations.

In this work, we propose to overcome this problem by means of registering in the PET scanner $\beta^+\gamma$ triple coincidences caused by the detection of prompt gammas in coincidence with annihilation photons (Fig. 1). These coincidences, when properly reconstructed, do not have spurious contributions and therefore, when combined with the standard double-coincidences, can provide reconstructed images with good image quality and proper contrast. This is a natural approach, considering the multiple gamma emissions occurring in these acquisitions.

II. Materials and Methods

1) *Data Acquisition*

To validate our methodology we used the Argus small-animal PET/CT scanner (Sedecal S.A. Madrid, Spain) which was formerly distributed by General Electric under the name eXplore Vista/CT [9]. The acquisition software of this scanner was rewritten to provide list-mode data files with all the single events detected within a coarse coincidence window (± 10 ns) and a 100 to 900 keV Energy window. Each single event in the file contains energy and position information and coarse plus fine time-stamps. In order to process these list-mode files we created software which allows sorting the data into double, triple, or higher-order coincidences using user-specified energy and timing windows.

2) *Methodology*

A $\beta^+\gamma$ triple coincidence defines 3 possible LORs along which the decay may have occurred; however, only one of them is the correct one and the others correspond to the same type of spurious background present in the double coincidences. In most cases, 1 of the 3 possible LORs of a triple coincidence lies outside the FOV (e.g., the line connecting points 2-3 in Fig. 1) and can be discarded (>95 % of the time in the Argus scanner). Therefore, each triple coincidence can be represented as a v-shaped LOR or vLOR (Fig 1) which contains the remaining two possible LORs. In sinogram space, a vLOR is composed of a pair of bins: one of them is the correct one (along which the annihilation occurred), while the other leads to spurious background. The idea of the method is to iteratively separate the LORs defined by $\beta^+\gamma$ triple coincidences into two different datasets, one corresponding to the signal (normal coincidences) and the other corresponding to spurious background.

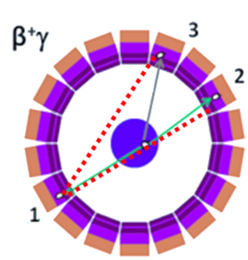

Fig. 1 – Concept of vLOR ≈ 2 joined LORs. In $\beta^+\gamma$ triple coincidences, usually one of the lines can be directly discarded (2-3 in the example). The two remaining lines (red dotted lines) define the vLOR or v-shaped LOR.

In a first step, we process the list-mode file to extract double and triple coincidences and record them in separate files. The vLORs are stored as a list of pairs of sinogram bins

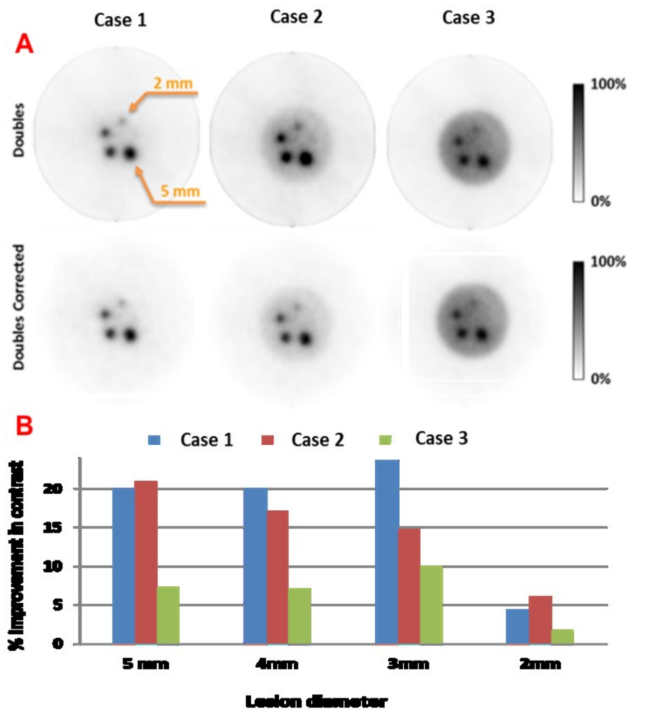

Figure 2. Images of a contrast phantom, showing the effect of the proposed spurious background compensation. The phantom was filled with different ^{124}I relative activity concentration values in the cylinder, with respect to the rods (CASE 1 = 0%, CASE 2 = 40%, and CASE 3 = 60%), and was scanned in our µPET scanner. (B) The effect of the proposed compensation on lesion visibility was evaluated by comparing the % improvement in contrast of hot lesions resulting from the method. A gain in ^{124}I image contrast of up to 23% was obtained by properly including the prompt gamma events. Percent reduction in noise after correction was of 3.23%, 6.8% and 5.4% for cases 1 to 3, respectively.

corresponding to the two LORs of the vLOR, while double coincidences are stored in a standard sinogram. We first process the triples dataset by assigning weights between 0 and 1 to each LOR of each vLOR. Those weights (w_{ij}) represent the probability that each LOR is the correct one and initially, if no other information is available, are set to ½ for all the possible LORs. In the next step, we use these weights to histogram the counts into a triples sinogram. Then, the weights w_{ij} are iteratively updated until convergence, based on the relative number of counts in each LOR, with respect to the total number of counts in the vLOR. For that purpose we use the following expression:

$$w_{ij} = \frac{N_{ij}}{N_{i1} + N_{i2}} , \qquad i = 1..N_{Triples}$$

where N_{ij} represents the occurrence rate of the LOR_{ij} in the triples sinogram. The index i represents the index of the vLOR and j is the index of each LOR of the VLOR. In each iteration, the sinogram obtained using the final weights (w_{ij}) represents the signal, while the sinogram constructed using the complementary weights ($1-w_{ij}$) represents the background.

The iterative method is fast and can be computed in less than 1 minute before the actual image reconstruction. It is important to note that this method requires that the size of the sinogram bins should be large enough to ensure a good overlap of the vLORs in the sinogram space (in this work we used axial rebinned sinograms (SSRB) with 45x32 bins each). As the background to be corrected is very smooth, this does not have a significant impact on the results. The final sinogram containing the signal information is free of the background caused by the prompt-gammas. We use this sinogram in combination with the conventional double-coincidence dataset within an iterative reconstruction algorithm, to provide images with reduced spurious background and improved contrast. Note that the signal extracted from the triple coincidences is also used to increase the sensitivity of the acquisition.

III. Experimental Results

We have evaluated the performance of this methodology in phantoms using our preclinical scanner. The effect of the compensation method on lesion visibility was studied in an experiment with a contrast phantom containing rods of different diameters (5, 4, 3, and 2 mm), surrounded by a fillable cylindrical compartment (Fig. 2). The phantom was filled with different ^{124}I relative activity concentrations values in the cylindrical compartment with respect to the rods. We compared the contrast of the rods (hot lesions) in images with and without thiscompensation. A gain in ^{124}I image contrast of up to 23% and a reduction in image noise of up to 6.8% were obtained after correction for prompt gamma coincidences with this methodology.

IV. Discussion and Conclusions

This work demonstrates the feasibility of a new approach for spurious prompt-gamma coincidences correction in PET for non-pure positron emitters. It is based on the measurement of the triple coincidences created by these radionuclides. Since this methodology does not rely on estimation procedures based on measurements in regions of the sinogram where it is known that no signal should be present, its performance may be less sensitive to inaccuracies for large patients, which is a general limitation of most existing methods [8].

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Non-standard PET radionuclides like ^{124}I, ^{76}Br, or ^{86}Y, emit prompt gamma rays together with the positrons which can be detected in coincidence with annihilation photons, creating spurious double coincidences. This causes a background in the PET images that reduces contrast and hampers quantitative accuracy. Existing correction methods are computationally intensive and since they depend on the size of the subject and on the accuracy of a number of complicated estimates, they may be valid for large source distributions only up to a certain size. To overcome these challenges, we have implemented a novel correction which is based on the measurement of $\beta^{+}\gamma$ triple coincidences. In such events, only one of the possible lines-of-response (LOR) defined by the triple interaction is the correct one, while the others correspond to the same type of spurious background present in the double coincidences. We use triple coincidences to iteratively separate those LORs into two different datasets, one corresponding to the 'signal' and the other corresponding to the 'spurious background'. These datasets are then combined with the standard double-coincidences within an iterative reconstruction algorithm to generate background-corrected images with improved contrast. We evaluated the proposed methodology in a preclinical PET/CT scanner, modified to enable the acquisition of triple coincidences, using a contrast phantom filled with ^{124}I. Our methodology provides a significant improvement in image contrast (up to 23%) in hot lesions and an extra gain in sensitivity due to the inclusion of recovered triple coincidences which leads to images with up to 6.8% less noise.