Scatter and Attenuation Corrections for a PEM Detector Using List-Mode OSEM

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Introduction

The ClearPEM detector is a Positron Emission Mammography (PEM) imaging system, developed by the Crystal Clear Collaboration. This functional imaging scanner has been specially designed and refined to achieve both high resolution and sensitivity standards, essential for detection of early stage breast cancer lesions. ClearPEM is a dual-head, LYSO:Ce crystal based, planar scanner. It presents depth-of-interaction (DOI) measurements with a resolution of 2.8 mm (FWHM) [1], provided by its double read-out APD based scheme. Energy and time resolution are 15.9% (FWHM) at 511 keV and 5.2 ns (FWHM) [2], respectively. Image spatial resolution was evaluated in 1.3 mm [3].

A breast exam performed with the ClearPEM scanner is typically a low count acquisition (approximately 1 million counts in total). However, this system presents more than 37 million possible lines-of-response (LOR), since DOI discretization is possible. A 3D-OSEM List-Mode reconstruction was thus implemented [4] to obtain time efficient and accurate reconstructions. For an accurate diagnosis, quantification cannot be disregarded and data corrections are of special importance for proper correlation between image counts and true tissue activity. Random events correction method and results were previously reported [5]. Scatter and attenuation corrections developed for this non-standard system will be now presented.

Methods

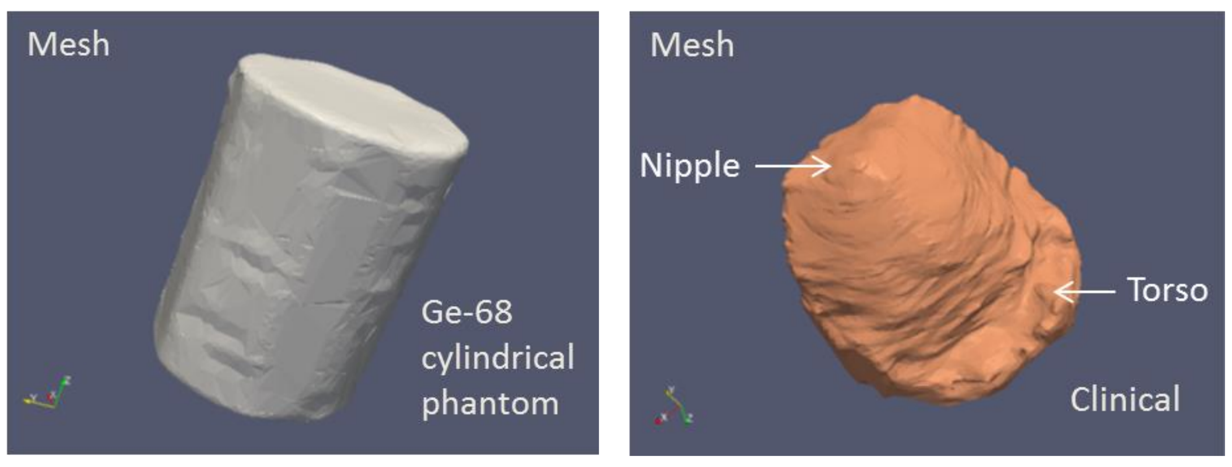
Attenuation correction method

The attenuation correction approach developed for the ClearPEM scanner uses the reconstructed emission image to obtain a contour of the object. This is a suitable choice when no transmission information is available. Since the breast is composed of soft tissue, an uniform attenuation coefficient is assumed and the correction proceeds as follows:

1. Emission image smoothing for noise reduction;
2. Segmentation of the object;
3. Mesh creation from the segmented image (Figure 1);
4. Calculation of the intersections of each acquired LOR with the mesh obtained in the previous step;
5. Calculation of the attenuation correction factor (ACF) per LOR, considering the distance x traveled inside the object and Beer-Lambert law:

$$\frac{I}{I_0} = e^{-\mu.x} \Rightarrow ACF = e^{\mu.x}$$

where μ is the linear attenuation coefficient, which for 511 keV photons in breast tissue is approximately 0.0958 cm^{-1}. The speed of the method is strongly dependent on the number of LORs to be processed.



Mesh structures obtained for a cylindrical phantom (left) and a clinical case (right).

Scatter correction method

A Monte Carlo (MC) based method was used for correction of Compton scattered events (Sc). This PET imaging correction approach is accurate although time consuming. To overcome this problem, we implemented a dedicated simulation tool for the ClearPEM scanner, which is parallelized to run in multiple processors. Our scatter estimate is obtained in just a few minutes.

The segmented image volume obtained from the emission image is given as input to the MC simulation, defining the boundaries that limit the traveling and interactions of randomly generated 511 keV photon pairs inside the object. Photon transport and interactions in the media are followed until detection. The recorded Sc events are weighted considering the total number of events acquired during the real acquisition.

Emission image segmentation → **MC simulation** → **Scaled Sc estimate** → **Smoothed Sc estimate image** → **3D LM-OSEM**

The low statistics nature of PEM acquisitions may lead to a severe bias when removing the weighted Sc estimate from the real data. To avoid it, instead of direct subtraction, a smoothed image of the Sc distribution was used. This method was previously used for random events removal for the ClearPEM data using LM reconstruction [5]. This correction image (δ) is then introduced in the LM-OSEM algorithm according to [5]:

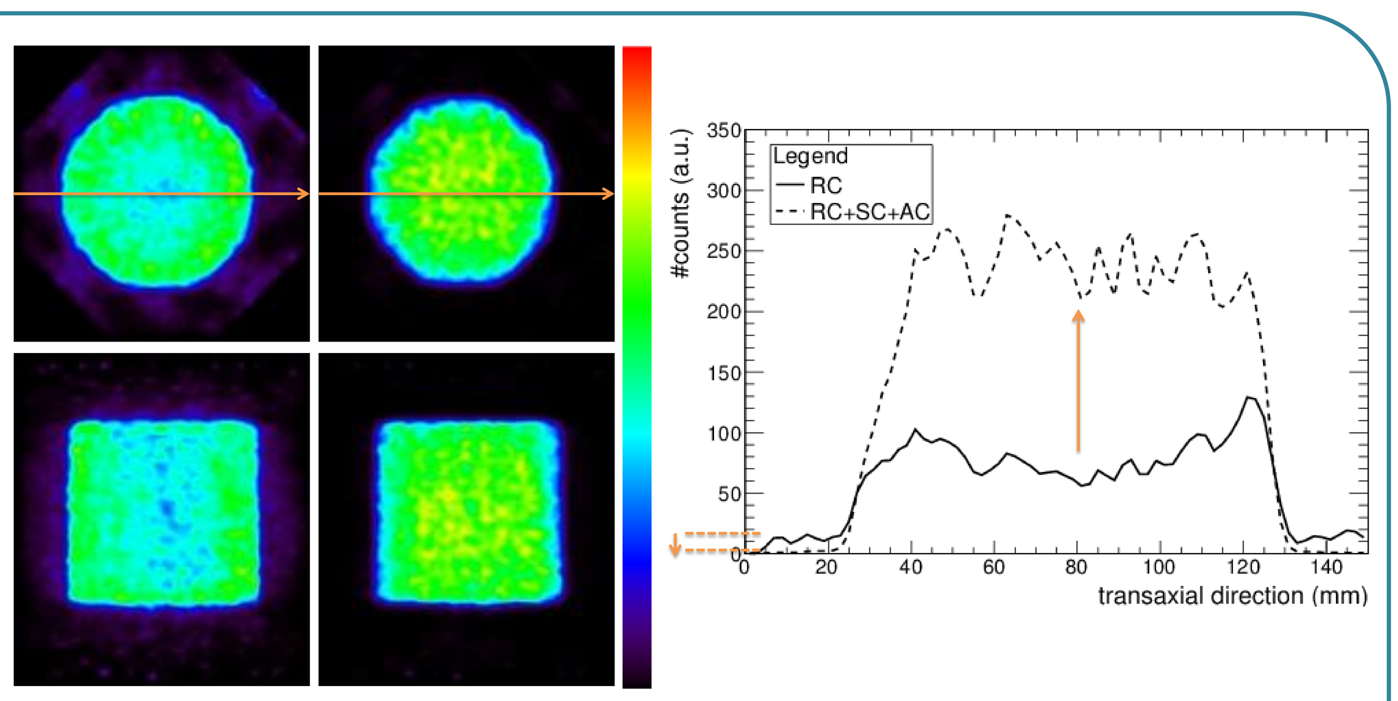
$$x_k^{(n+1)} = x_k^{(n)} \frac{1}{\varepsilon_k} \sum_{i=1}^{N} \frac{(1-S_{n_i}{}^{(n)}) c_{n_i k}}{\sum_{k'=1}^{K} c_{n_i k'} x_{k'}{}^{(n)}} \quad ; \quad S_j{}^{(n)} = \frac{\sum_{k=1}^{K} c_{jk} \delta_k}{\sum_{k=1}^{K} c_{jk} (x_k{}^{(n)} + \delta_k}$$

where for the i^{th} event detected in detector bin $n \in N$, x_k is the value of the k^{th} voxel of the image with K total voxels, ε_k denotes the efficiency correction weight for voxel k and c_{jk} is the system matrix that defines the probability that an event from voxel k is detected in bin j. S_j is the mean scattered coincidence rate.

Results

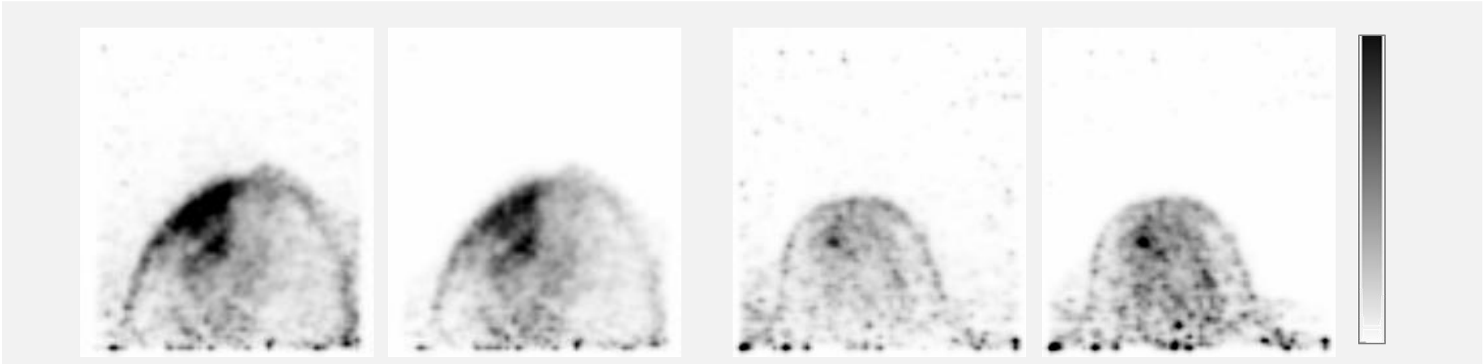
Correction methods were tested on a uniformly filled water+FDG cylindrical phantom (diameter = 10 cm; height = 10 cm), scanned with the ClearPEM detector assembled in Coimbra, Portugal. Approximately 10 million prompts were recorded. Activity decay correction was always considered. LM-OSEM was used with 7 iterations and a inter-iteration Gaussian filter with FWHM=1 mm. Image voxel size was 2 mm.

Axial (top row) and sagittal (bottom row) slices corrected for random events (on the left) and corrected for random and scattered events and attenuation (on the right).



A reduction of 77% in the mean counts of the cylinder's background was obtained. The recovery of counts in the cylinder was approximately 61%.

Attenuation and scatter correction methods were also used on a high statistics clinical study with an injected dose of 9.3 mCi of ^{18}F-FDG. After a tracer distribution waiting period of 1h25m and a 20 min exam, approximately 2.5 million prompt events were recorded for the right breast and 500 thousand prompt events for the left breast. Image reconstruction used 7 iterations of LM-OSEM with an inter-iteration Gaussian filter with FWHM=1 mm. Image voxel size used was 2 mm. Decay correction was considered.



Coronal slices, (a) and (b), of the right breast of the patient showing a malignant lesion and sagittal slices, (c) and (d), of the left breast with a possible initial lesion.
(a) and (c): random events corrected; (b) and (d) random, scatter and attenuation corrected.

Conclusions

PEM is a quantitative imaging technique and is characterized by typically low counts acquisitions. To obtain reconstructed images in a short period of time, a 3D-LM-OSEM reconstruction algorithm is thus used. Correction methods for Compton scattered events and attenuation were implemented for use with ClearPEM data and this reconstruction algorithm.
Image segmentation of the emission image is used as input for both attenuation and MC based scatter corrections, since anatomical information provided by other imaging modalities is not available. The scattered events estimate for scatter correction is introduced during reconstruction via a smoothed image of this distribution.
Both corrections resulted in image improvements in terms of mispositioned scattered events removal and recovery of counts lost due to photon attenuation. These improvements were observed with real data, both phantoms and clinical cases, using the most common radiotracer for cancer studies, ^{18}F-FDG.

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