STUDY ON LISTMODE OSEM RECONSTRUCTION INCLUDING IMAGE-SPACE RESOLUTION RECOVERY TECHNIQUES FOR COMPTON CAMERA

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ABSTRACT

Although Compton camera may has a great potential as next generation imaging modality comparing to SPECT and PET, its fully three-dimensional image reconstruction requires the considerable computational burden and the spatial resolution is suffered from the various physical phenomena arising during detection process. In this study, we investigated the accelerated statistical image reconstruction in which system matrix included a resolution recovery (RR) technique. We considered 3D Gaussian resolution model for the integrated angular and geometric uncertainties. The angular uncertainty is closely related to the limited energy resolution of the Compton camera and Doppler broadening and the geometric uncertainty is due to the segmented detectors. For RR, the 3D Gaussian resolution model is incorporated into listmode OSEM (LMOSEM) using image-space convolution operation. We investigated two different RR approaches: one (denoted by LMOSEM-RR F) is when the convolution is only performed in forward projection step, and the other (denoted by LMOSEM-RR FB) is when it is performed in both forward and backward projection steps. The simulation results showed that both RR approaches gave an improvement on spatial resolution for the resolution-degraded data due to both angular and geometric uncertainties. Although LMOSEM-RR F provided better resolution than LMOSEM-RR FB, LMOSEM-RR FB could still useful for low counting statistics in measurement.

Index Terms— Compton camera, OSEM reconstruction, resolution recovery, detector response function, image-space convolution

1. INTRODUCTION

Compton camera is an innovative imaging modality providing three-dimensional (3D) image for radiation emitting distribution within an object [1-3]. Comparing to the conventional imaging modality in nuclear medicine, i.e. SPECT (single photon emission computed tomography) and PET (positron emission tomography), Compton camera may has a great potential as next generation imaging modality. Compton camera can be used in multi-tracer imaging which is useful imaging technique in pre-clinical and clinical research [4-5]. PET system which consists of block-detectors arranged in a ring can only detect two 511-keV gamma rays emitted in opposite directions after annihilation, whereas Compton camera can detect simultaneously multiple gamma rays of different energies with more compact geometry than PET. Of course, SPECT can perform a multi-tracer imaging, however its image quality is suffered from the count cross talk between the different energy windows. Moreover, since the Compton camera uses electronic collimation relating to Compton scattering principle in order to form an image, Compton camera can give a superior sensitivity than SPECT which uses a mechanical collimator to accept the traveling gamma rays in the wanted direction [6].

The 3D image formation process in Compton camera consisted of scatterer and absorber detectors can be expressed by the integral of source distribution over the conical surface which is defined from a detected position pair and a scattering angle. Fundamentally, the tomographic image reconstruction that is the inverse problem of the conical surface integration over the 3D source distribution requires the considerable computational burden. Moreover, the spatial resolution of the 3D reconstruction is degraded by the various physical phenomena arising during detection process of measurable events on the scatterer and absorber.

In this study, we investigated the accelerated statistical image reconstruction such as LMOSEM (listmode ordered subset expectation maximization) in which system matrix included a resolution recovery (RR) modeling.

2. 3D GAUSSIAN RESOLUTION MODEL

The spatial resolution on image reconstruction which is defined as inverse problem of the conical surface integration
is dependent on the uncertainty of determination on scattering angles (called by angular uncertainty) and detected position pairs (called by geometric uncertainty) that define the cones.

The scattering angle \( \omega \) is computed from the measured energy lost \( (E_1) \) after Compton scattering as in Eq. (1) where \( E_0 \) is the initial emitted gamma ray energy:

\[
\cos(\omega) = 1 + mc^2 \left[ \frac{1}{E_0} - \frac{1}{E_0 - E_1} \right] \quad (1)
\]

In Eq. (1), the angular uncertainty is closely related to the measurement error of the energy \( E_1 \) due to limited energy resolution \( (\sigma_E) \) of scatterer detector. If the electron has a momentum before interaction with a photon, Eq. (1) may lead to the erroneous determination of scattering angle known as Doppler broadening effect \( (\sigma_D) \), since Eq. (1) is derived from the assumption that the gamma ray interacts with a free electron at rest. As shown in figure 1, the segmented detectors provide approximations \( (\sigma_S) \) of real interaction positions with uncertainties corresponding to their segment size [7].

We considered a 3D Gaussian resolution model for the integrated angular and geometric uncertainties as follows:

\[
G(x, y, z) = \frac{1}{\sqrt{8\pi^2\sigma_x\sigma_y\sigma_z}} e^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} - \frac{z^2}{2\sigma_z^2}} \quad (2)
\]

In Eq. (2), the variance for each axis can be expressed by squared summation of the decomposed angular \( (\sigma_E, \sigma_D) \) and geometric \( (\sigma_S) \) uncertainties as in Eq. (3).

\[
\sigma^2 = \sigma_E^2 + \sigma_D^2 + \sigma_S^2 \quad (3)
\]

To test the effect of resolution-degrading factors, the Monte Carlo (MC) simulation is performed for a point source of 140 and 511 keV placed apart from the Compton camera by 6 cm. As shown figure 1, the Compton camera consisted of the segmented DSSD (double-sided silicon strip detector) and the 25-SEGD (25-segmented germanium detector). Five different MC data (counts of 10^6) for each gamma ray energy were generated as the simulator turned on or off the physical factors: ideal (when no angular and geometric uncertainties), Doppler broadening, energy resolution, segmentation (only turn on each corresponding factor), and overall (turn on all factors).

Figure 2 and 3 showed the central yz-planes of the LMOSEM reconstructions (64^3 array with a voxel volume of 1.56 cm^3) with 10 subsets and 3 iterations for data of 140 and 511 keV, respectively. The NEMA-FWHM (national electrical manufacturers association – full width half maximum) is computed from profiles produced on three (xy-, xz-, and yz-) central-planes of LMOSEM reconstructions as shown in figure 4. The angular uncertainty is dependent on gamma ray energy, in that, the lower the gamma ray energy, the greater angular uncertainty. And segmentation of detectors most greatly affected on degradation of spatial resolution.
3. LMOSEM RECONSTRUCTION ALGORITHM INCLUDING GAUSSIAN RESOLUTION MODEL

LMOSEM reconstruction algorithm which is performed by iterating forward and backward projection in given subset provides two major advantages, acceleration on computation and including elaborate system matrix [8-11]. The 3D Gaussian resolution model mentioned in previous section is incorporated into LMOSEM using image-space convolution operation which is suggested in Ref. [12] for RR and it is denoted by LMOSEM-RR.

\[
\hat{f}_i^{(k+1,1+1)} = \frac{\hat{f}_i^{(k,1)}}{S_i} \left\{ \sum_{j \in B_1} \frac{H_{ij}}{\sum_p \left( R_p \otimes G_p \right) H_{ij}} \right\}
\]  

(4)

\[
\hat{f}_i^{(k+1,1+1)} = \frac{\hat{f}_i^{(k,1)}}{S_i} \left\{ \sum_{j \in B_1} \frac{H_{ij}}{\sum_p \left( R_p \otimes G_p \right) H_{ij}} \right\} \otimes G_i
\]  

(5)

We investigated two different LMOSEM-RR algorithms as shown in Eq. (4) and (5). In both equations, the geometric system matrix, \(H_{ij}\), is implemented by ray-tracing method described in our previous work [13]. In Eq. (4), the imagespace convolution is only performed with the integrated Gaussian resolution model in forward projection procedure (denoted by LMOSEM-RR\(^F\)) before calculating error between measured and estimated values. In Eq. (5), as well as the forward projection, the backward projection is performed with the convolution procedure (denoted by LMOSEM-RR\(^FB\)) every iteration except convolution over sensitivity image (\(S_i\)) [12].

Figure 5. Central xy-, xz-, and yz-planes of LMOSEM reconstructions for MC data of a point source of 140 keV; (a) LMOSEM for ideal data, (b) LMOSEM without RR, (c) LMOSEM-RR\(^F\), and (d) LMOSEM-RR\(^FB\) for overall data.

Figure 6. Central xy-, xz-, and yz-planes of LMOSEM reconstructions for MC data of a point source of 511 keV; (a) LMOSEM for ideal data, (b) LMOSEM without RR, (c) LMOSEM-RR\(^F\), and (d) LMOSEM-RR\(^FB\) for overall data.

Figure 7. NEMA-FWHM (mm) computed from LMOSEM reconstructions without and with RR model for MC data for a point source of 140 and 511 keV.

The MC data for two point sources of 140 and 511 keV which are located at center and 1 cm off center were generated on ideal and overall case, respectively. And then LMOSEM of 3 iterations without and with RR were performed for the data. For LMOSEM without RR, the scattered listmode data were splitted into the 20 subsets. LMOSEM-RR\(^F\) and LMOSEM-RR\(^FB\) were performed with 50 and 100 subsets, respectively. Figure 8 and 9 showed the central-planes of the LMOSEM reconstructions without and with RR for MC data of two point sources of 140 and 511 keV, respectively.
4. CONCLUSION

We investigated two RR approaches for LMOSEM including 3D Gaussian resolution model using MC data of 140 and 511 keV. Both RR approaches gave an improvement on spatial resolution for overall data including all angular and geometric uncertainties. Although LMOSEM-RRF provided better resolution than LMOSEM-RRFB, LMOSEM-RRFB can still useful for low counting rate.

5. REFERENCES


