A comparative investigation of scatter correction in 3D PET

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Abstract. In 3D PET scatter degrades image quality and quantification. The currently most popular scatter estimation method is the single scatter simulation (SSS) which accommodates for multiple scattering by scaling the single scatter estimation. However, it has not been clear yet how accurate this approximation is for cases where multiple scatter is significant, raising the specific questions: “How important double scatter correction is, and how accurately do we simulate the total scatter events by appropriate scaling?” This project aims to clarify the improvements in terms of quantification due to scatter correction, using: (i) single scatter events only, (ii) single and double scatter events, (iii) total scatter events, or (iv) scaled single scatter, and evaluate the analytic scatter estimation algorithm as implemented in the open source reconstruction software STIR. The analytic SSS scatter estimation implemented in STIR is compared with the SimSET Monte Carlo package. Scatter correction accuracy is examined for different levels of scattering and scaling approaches. A large anthropomorphic phantom was reconstructed with FBP. The images have been compared quantitatively: Areas with high scatter fraction are compared with single scatter corrected images and show a 50% bias reduction after performing single and double scatter correction. Scaled single scatter correction results are in good agreement with SimSET true events, less than 10% difference. Total-fit and tail-fit scaled single scatter results in approximately equal mean values. SSS correction with tail-fit scaling in STIR is very close with SimSET true events, 10% difference. The results show that multiple scatter correction improves accuracy and scaling single scatter is an efficient method to compensate for multiple scattering for standard PET scanning acquisitions.

1. Introduction
In 3D PET scattered photons constitute 30-50% of the total measured data degrading not only image quality but also quantification. The currently most popular scatter estimation method is the single scatter simulation (SSS) [1, 2]. SSS uses emission and transmission images to estimate the scattered events along each line of response. The scatter distribution is calculated by summing the estimated scatter probabilities for each possible scatter point in the transmission image and each detector pair [3-4]. This algorithm was implemented within the open-source library software for tomographic image reconstruction (STIR release 2.1) [5], where the single scatter distribution is computed with SSS [6]. As suggested by Watson et al [7], the simplest approach to accommodate for multiple scatter is by scaling the scatter projection data for each plane to the tails of the measured data.
2. Methods
A larger version of an anthropomorphic numerical phantom was used [8]. PET data was simulated using the Simulation System for Emission Tomography (SimSET) [9] and the GE Discovery™ STE scanner. SimSET data included true, single scatter, double scatter and multiple scatter events.

STIR implementation of the three-dimensional filtered reprojection algorithm (3DRP) has been used. The x, y matrix size was 128×128 pixels with pixel size 5.27 mm, while along the z direction were 47 pixels with pixel size 3.27 mm. The cut-off frequency of the ramp filter was set to 0.5 cycles.

Scatter scaling was performed using the tail-fit or total-fit method. During tail fitting, the scale factor was estimated per slice so as to be equal with the counts in the tails of the emission (total non-scatter corrected) sinogram, where only scatter events are expected. To define this region, we use the attenuation correction factors sinogram with minimum and maximum threshold of 0.4 and 1.4, respectively. For total fit, one global scale factor was used by scaling the single scatter such that the total counts of single scatter are equal to the total scatter counts.

The different scatter orders were examined using the following sinograms (based on SimSET data):
- total (non-scatter corrected) - summation of the data of all events,
- single scatter corrected - summation of the data of all events apart from single scatter,
- single plus double scatter corrected - data of all events apart from single and double scatter,
- total scatter corrected - only the true (unscattered) events,
- total-scaled single scatter corrected - estimated by scaling the single scatter data using the total-fit and subtracting the result from the total data,
- tail-scaled single scatter corrected - estimated by scaling the single scatter data using the tail-fit and subtracting the result from the total data.

Finally, the scatter distribution was computed with the SSS algorithm implemented in STIR [6] using emission and transmission data together with the detector geometry. The emission data were the total (non-scatter corrected) SimSET data. The scatter estimation was applied to the emission data iteratively to perform scatter correction [2]. Firstly, the emission data are corrected for attenuation and reconstructed for input to SSS. The SSS sinogram was “subsampled” by using the same scanner dimensions but with less number of rings and detectors. After upsampling the SSS, it is subtracted from the emission data to get a scatter-corrected sinogram. Then the SSS is repeated using as input the scatter-corrected reconstructed sinogram. Finally, the two scatter estimates are averaged and the result is used for scatter correction.

3. Results
Figure 1 illustrates the coronal planes for the 3DRP reconstructed images of SimSET data for total (non-scatter corrected), single scatter corrected, single plus double scatter corrected, total scatter corrected, total-scaled single scatter corrected and tail-scaled single scatter corrected data. Figure 2 shows plotted profiles through the same transaxial plane of the images of SimSET data for true events, single scatter corrected and single plus double scatter corrected or for true events, total-scaled single scatter corrected and tail-scaled single scatter corrected.

![Figure 1](image1.png)

Figure 1. SimSET data: (i) total, (ii) single scatter corrected, (iii) single plus double scatter corrected, (iv) total scatter corrected, (v) total-scaled single scatter corrected, (vi) tail-scaled single scatter corrected.
Figure 2. Image (top right) profiles of different investigated cases.

Figure 3 presents transverse slices of 3DRP reconstructed images for the scatter corrected data with STIR and SimSET unscattered events.

Figure 3. Images of (i) SimSET scatter corrected data with STIR, and (ii) SimSET total scatter corrected.

Figure 4 illustrates histogram of the ROI mean values of the ideal distribution and all the investigated cases.

Figure 4. Histogram of ROI mean values of the ideal distribution and all the investigated cases.
4. Discussion
Figures 1 and 4 indicate that scatter affects quantitative accuracy and show visual and quantitative differences after performing double scatter correction. In figure 4, for areas with high scatter fraction, comparing single scatter correction and single plus double scatter correction, there is important mean value reduction after performing single plus double scatter correction.

Previous studies showed that multiple scattering broadens the scatter distribution and thus single and total scatter distribution can have different shapes depending on the object attenuation and the detector settings [10]. In our simulations, figure 1 shows that the image of single plus double scatter corrected has similar appearance to the single scatter corrected. Figures 1 and 2 show that the tail- or total-fit scaled single scatter corrected images is in a good approximation with the free of scatter image. In addition, figures 2-4 verify that scaled single scatter correction is in good agreement with SimSET true events with a difference no more than 10%. Total-fit and tail-fit scaled single scatter results have approximately equal mean values.

Finally, in figure 3 and 4, SSS correction with tail-fit scaling in STIR has very close visual and quantitative results with SimSET true events, 10% difference.

5. Conclusions
Multiple scatter correction appears to improve image contrast and accuracy, and therefore it is essential in PET imaging for precise estimation of activity distribution. The results show that for standard PET scanning acquisitions, scaling single scatter is an efficient method to compensate for multiple scattering. Finally, SSS correction with tail-fit scaling in STIR is in good agreement with SimSET simulations.

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