Evaluation of two approaches to motion-corrected PET image reconstruction

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Abstract. Motion correction is a major task in PET. This study aims to understand the behaviour of different approaches to motion-corrected image reconstruction in terms of convergence rates and the properties of the images obtained. We have studied two approaches that have been suggested to motion-correct PET gated data. The first method, RRA, is based on independent reconstructions of each gate which are then registered to a reference gate and averaged. On the other hand, in the second method, MCIR, all data are used with the motion information within a single reconstruction. As a first step, this investigation compares the methods with no motion present. Multiple simulations have been produced with counts approximating a 5 min PET thorax acquisition. The image bias and variance are the main figures of merit. The results show different convergence and statistics performance between the two methods. RRA converges faster than MCIR but not at the correct value. Considering the trade-off between bias and variance, it is seen that MCIR outperforms RRA. It has been also demonstrated that, although at higher iterations RRA has lower variance and higher bias than MCIR, at a low number of iterations the performance of the methods becomes closer. This investigation has revealed the statistical and computational discrepancies between RRA and MCIR when motion is not present and MCIR is shown to be clearly superior.

1. Introduction
Respiratory motion is an important source of resolution degradation and hence quantification, being a major challenge in PET research. A common method to overcome motion is gating, during which respiratory positions can be reconstructed producing a “motion-free” noisy image. For this reason it has been proposed to motion-correct by estimating motion between gates, thus using all the measured data for the final image. The most common approaches to motion-correction are the Reconstruct-Register-Average (RRA) and Motion-Compensated Image Reconstruction (MCIR).

The RRA is based on independent reconstructions of each position which are then registered to a reference position and averaged [1-2]. During this method, the final image is obtained post-reconstruction without taking into account the non-linearity effects of OSEM reconstruction algorithm which are exaggerated due to the relatively low counts in each gate.

Several investigators proposed to modify the reconstruction algorithms by incorporating motion information into the system model, referred to as MCIR [3]. Considering all data allows the total emission statistics to contribute to the final image. However, modifying the system model makes the reconstruction process computationally more demanding and might also affect convergence properties.
Although, there has been a comparative study [2], there is still not enough evidence that clearly supports which method is practically better for PET respiratory motion correction. Comparison of the methods requires assessment in terms of noise and bias. This investigation reveals the statistical discrepancies between RRA and MCIR when motion is not present providing a complete characterization of the source and extent of the differences without the additional complications of how motion is incorporated.

2. Methods
The RRA and MCIR methods have been compared without motion. Reconstructions were performed with the Software library for Tomographic Image Reconstruction (STIR) [4]. A procedure to simulate realistic clinical FDG-18 PET simulation data was used [5]. The PET data were forward projected simulating a 2D-acquisition of the Philips Gemini scanner. Following forward projection, attenuation and Poisson noise were added such that the overall acquisition corresponds to a 5 min 2D PET thorax acquisition, but with 3D noise levels (i.e. 5x10^7 counts). One thousand statistically independent realizations of the acquisition were simulated. For MCIR, each realization was reconstructed, whereas for RRA, each replication corresponded to ten sets of projection data preserving Poisson statistics. FBP (with ramp filter) and OSEM (23 subsets) reconstruction algorithms were performed. Each slice consists of 128x128 pixels with size 4 mm each, and the entire volume consists of 87 slices with 2 mm thickness. The comparison of the two methods is assessed by computing voxel-wise figures of merits using the reconstructed images of the 1000 realizations. The following statistical information is presented: bias, standard deviation, and variance.

3. Results
Figure 1 shows the transverse planes of the bias images obtained from 1000 realizations using the RRA and MCIR methods with the FBP and OSEM algorithms (40 iterations with 23 subsets). The reconstructed images are 3D and thus only one transverse plane (i.e. 67) is illustrated. Figure 2 presents the plots of the percentage bias (%) for different regions of interest (ROIs) as a function of the iteration number for OSEM, whereas lines are plotted for the FBP algorithm cases.

Figure 1. Bias images from 1000 realizations using the RRA and MCIR methods with the algorithms: (a) FBP, and (b) OSEM (40 iterations).

Figure 2. Plots of percentage bias as a function of iteration number using the RRA and MCIR methods and, the OSEM and the FBP algorithms for (a) lungs, (b) myocardium, (c) tumor.
Figure 3 illustrates the transverse planes of the variance images obtained from 1000 realizations using the methods RRA and MCIR for the FBP and OSEM (40 iterations with 23 subsets) algorithms for. In figure 1, only the transverse plane 67 is illustrated.

Figure 3. Variance images from 1000 realizations using RRA and MCIR with the algorithms: (a) FBP, and (b) OSEM (40 iter.).

Figure 4 presents the plots of the bias in respect to the standard deviation for the OSEM algorithm using different number of iterations. Different ROIs are presented.

Figure 4. Plots of bias versus standard deviation for RRA and MCIR using OSEM (1 to 40 it.) for (a) tissue, (b) myocardium, (c) lungs, (d) tumor.
4. Discussion
The FBP results of figures 1 and 2 point out low and equal bias for RRA and MCIR in areas and edges which can be attributed to reconstruction artefacts. Substantial differences are observed between RRA and MCIR using OSEM; overestimations and underestimations in low and high counts areas respectively. For all regions, higher bias is observed for RRA than MCIR while for both methods the bias is progressively decreased as the number of iterations is increased. In figure 2, the percentage bias after a high number of iterations in lungs was -11 % for RRA, and -3 % for MCIR whereas in tumour was 10 % for RRA, and 2 % for MCIR.

Figure 3 demonstrates that the variance of the FBP for both RRA and MCIR is identical and fairly uniform for all regions. Comparing RRA and MCIR using the OSEM algorithm in figure 3, it can be clearly seen that the two methods have similar variance for a low number of iterations; whereas when the number of iterations is increased, the difference between the two methods becomes larger, in particular for MCIR.

Figure 4 verifies the trade-off between bias and variance. RRA increased faster than MCIR, especially for low or high count areas. It is also clearly demonstrated that although at higher iterations RRA has lower variance and higher bias than MCIR, at low number of iterations (i.e. 1 or 2), which currently is the typical setting for clinical PET, the performance of the two methods becomes closer. The MCIR has lower bias than RRA at matched levels of variance.

5. Conclusions
This investigation has revealed the statistical and computational discrepancies between RRA and MCIR when motion is not present. The main finding is the substantially different convergence and statistical performance between them. RRA causes high levels of overestimation and underestimation in cold and hot regions respectively. It is found that even for a small iteration number (e.g. 2), MCIR has lower bias and similar variance. The trade-off between bias and variance for both methods shows that MCIR outperforms RRA. The next step is the integration of motion correction and the study of its impact.

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