Five-Dimensional Respiratory and Cardiac Motion Compensation for Simultaneous PET/MR

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Introduction

One major challenge to accurate quantification in simultaneous PET/MR imaging is patient motion during measurements, such as respiratory and cardiac motion. Patient motion leads to image blurring and, in case of PET, to an underestimation of the reconstructed activity. A widely used motion handling strategy is gating. Here, the motion cycle is divided into several motion phase bins and images are reconstructed from the data of each individual phase separately. However, for double-gated (respiratory and cardiac) reconstructions, gating suffers from very low statistics of each individual gate resulting in poor signal-to-noise and contrast-to-noise ratios of the reconstructed images. Since the advent of fully-integrated PET/MR systems several new approaches for respiratory motion handling have been proposed. They use MR information to estimate motion vector fields (MVFs), which describe respiratory patient motion between the different phases and allow for a retrospective motion compensated (MoCo) reconstruction of PET images [1].

Here, we propose a new method for 5D MoCo PET reconstruction, which accounts for both respiratory and cardiac patient motion using information from a radial MR sequence acquired simultaneously with the PET acquisition.

Materials and Methods

Simultaneous PET/MR data covering the thorax of four free-breathing patients were acquired with a Biograph mMR system (Siemens Healthineers, Erlangen, Germany). Data acquisition and evaluation was in accordance with the local ethics committee and informed consent was obtained from each patient. We applied a vendor-provided radial stack-of-stars sequence with golden angle radial spacing and sagittal slice orientation: field of view: 400 × 400 × 396 mm^3, voxel size: 1.6 × 1.6 × 4.5 mm^3, TR/TE = 3.75/1.70 ms, 88 slices (55% slice resolution, 6/8 partial Fourier), flip angle: 10°, fat suppression activated. For PET imaging the radionuclide fluorodeoxyglucose ^{18}F-FDG was used. The total acquisition time of the PET/MR measurement was set to 5 min per bed position. Respiratory and cardiac motion signals used for self-gating were estimated from the k-space center for each acquired spoke. A bandpass filter was applied to distinguish between respiratory motion (filter range: 0.1 to 0.5 Hz) and cardiac motion (filter range: 0.5 to 2.0 Hz) and the signals were corrected for a baseline drift. MR data and PET list mode data were sorted retrospectively into 20 overlapping respiratory motion phase bins with a width of 10% and 12 overlapping cardiac motion phase bins with a width of 17%. Respiratory and cardiac MVFs were estimated sequentially [2] employing the measured MR data and a newly-developed iterative algorithm, which alternates between image reconstruction and motion estimation [3].

To increase the robustness of motion estimation, deformable registrations were carried out between adjacent motion phases and regularized by cyclic constraints [2, 3].

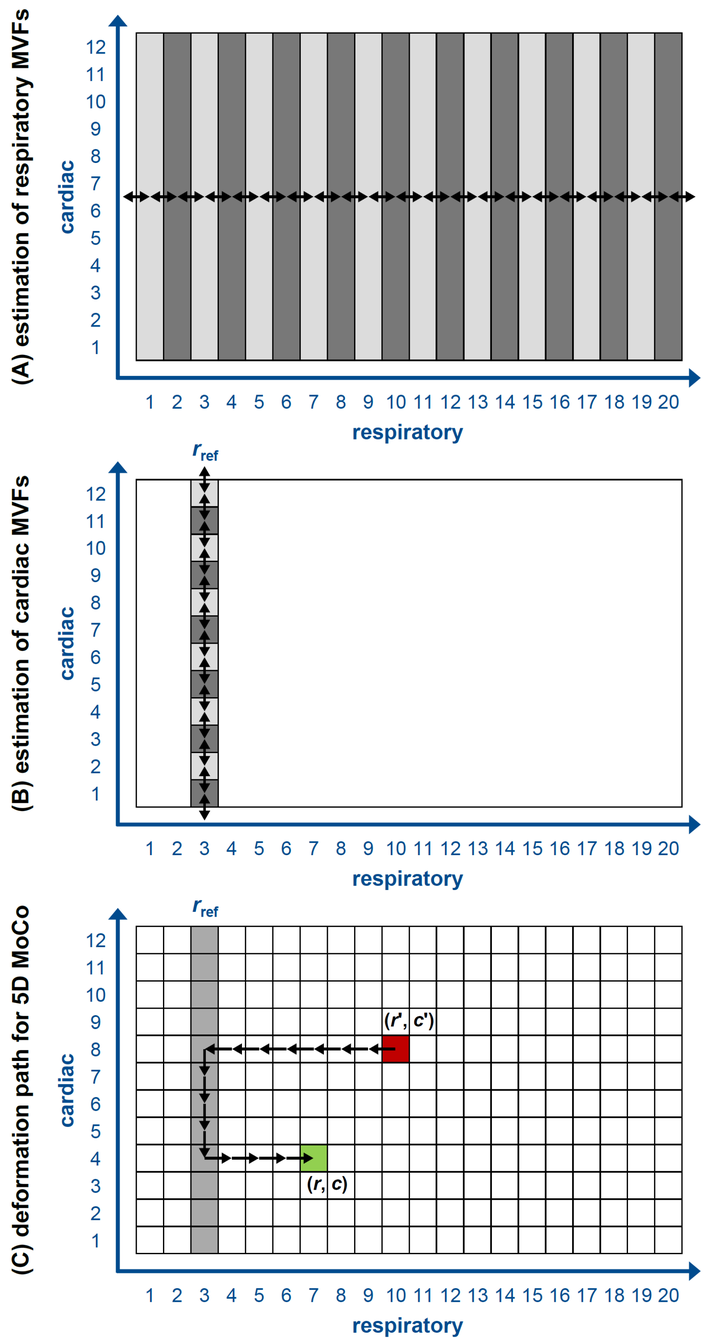

Fig. 1: Gating schemes for the estimation of respiratory and cardiac patient motion and 5D MoCo image reconstruction.

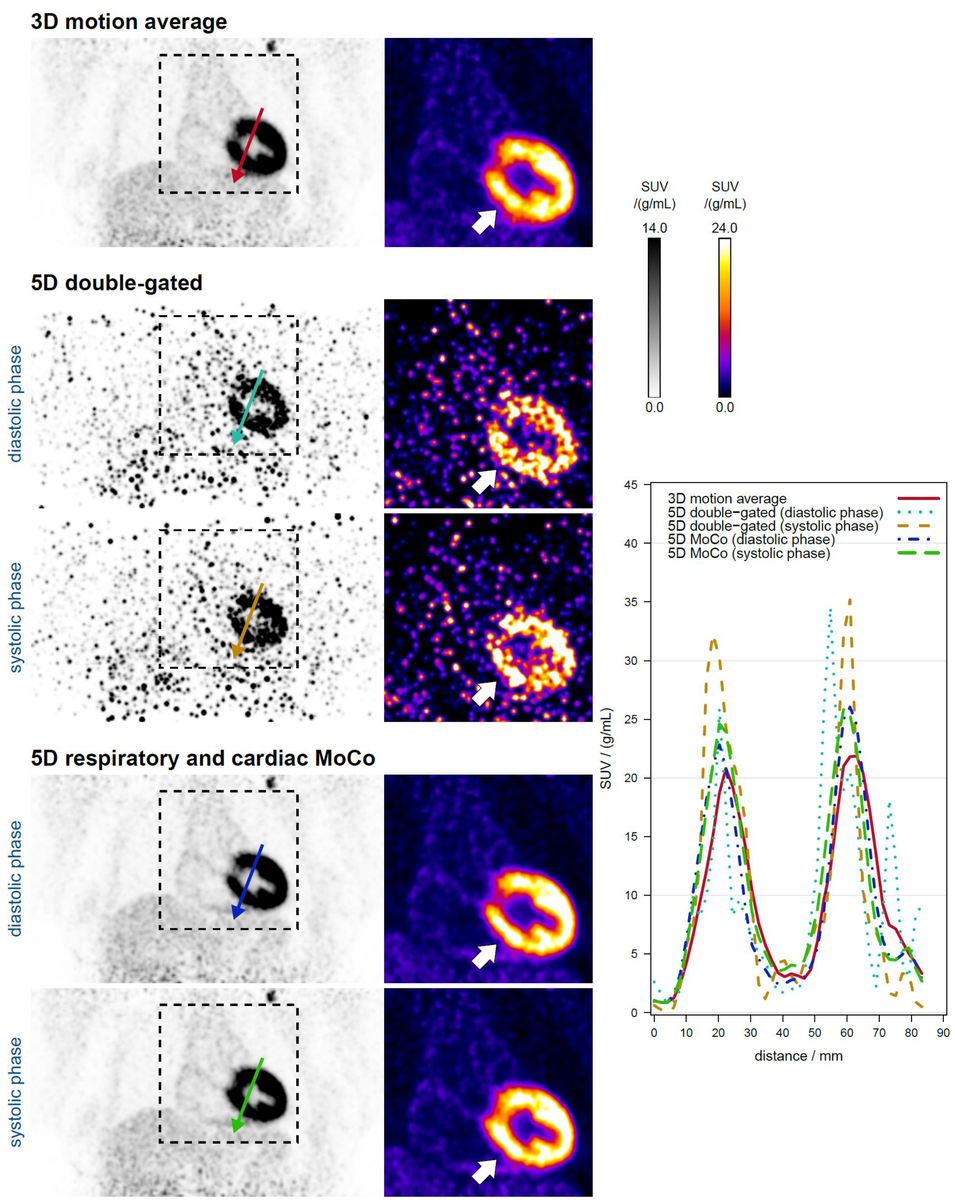

Fig. 2: Comparison of different PET image reconstructions of the heart of a 56-year-old female patient in coronal orientation.

In a first step, respiratory MVFs were estimated using N_r = 20 overlapping respiratory motion bins with a width of Δr = 10% and neglecting cardiac motion (Fig. 1A). In a second step, respiratory motion-compensated MR raw data were generated and subsequent estimation of cardiac MVFs was performed for N_c = 12 overlapping cardiac motion bins with a width of Δc = 17% (Fig. 1B). Applying the estimated respiratory and cardiac MVFs allowed for warping an image volume of an arbitrary combination of respiratory and cardiac motion phase (r, c) onto any other combination (r', c') and vice versa (Fig. 1C).

3D PET and 5D double-gated PET images were reconstructed using a standard 3D OSEM algorithm. For 5D MoCo PET reconstructions, the algorithm was extended incorporating respiratory and cardiac MVFs derived from MR into the system matrix. For all PET reconstructions, 3 iterations with 21 subsets were used and a Gaussian smoothing filter (FWHM = 3.2 mm) was applied at the end of each iteration. For quantitative analysis of the reconstructed images, SUV_{mean} and contrast of the myocardium of all four patients were evaluated.

Results

Figure 2 presents 3D motion average PET, 5D double-gated PET and 5D respiratory and cardiac MoCo PET images. For the latter two reconstruction techniques, different cardiac motion phases are shown demonstrating that cardiac motion was resolved appropriately in these images. 3D motion average images exhibited motion blurring resulting from respiratory and cardiac motion. As gating was performed in two temporal dimensions for 5D double-gated reconstructions, individual sinograms contained less than 2% of the total number of counts on average. Thus the resulting images revealed very high noise levels impairing the delineation of the myocardium. In contrast, 5D respiratory and cardiac MoCo reconstructions showed noise levels comparable to the 3D motion average. In addition, this reconstruction technique yielded reduced motion blurring revealing steeper line profiles through the myocardium than the motion average. This improvement of edge sharpness is demonstrated for diastolic and systolic motion phases.

Quantitative evaluation of the myocardium of all four patients in a diastolic cardiac phase demonstrates that, in comparison to 3D PET reconstructions, 5D MoCo PET yielded an average increase of SUV_{mean} and contrast of 2.8 ± 1.1% and 4.8 ± 2.0%, respectively. 5D double-gated images were excluded from evaluation as robust segmentation of the myocardium was not possible due to the very high noise level of the images.

Acknowledgements

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