An Improved Binning Strategy for 3D Image-Based Respiratory Motion Correction in Whole-Heart Coronary MRA

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INTRODUCTION: Accurate compensation of the respiratory motion is one of the major challenges of interleaved whole-heart coronary MRA [1]. However, current navigator-gated techniques are limited in both efficiency and accuracy. Self-navigation allows to estimate the one dimensional respiratory motion of the heart directly from readouts used for imaging and oriented along the superior-inferior (SI) direction [2, 3]. Although reliable results can be achieved with this method, 1D estimation is only a first approximation of the complex 3D motion induced by respiration [4]. Therefore, image-based motion correction techniques were recently proposed in a navigator-gated scenario [5] or in combination with self-navigation [6]. The basic idea is to straightforwardly group all interleaves into several equally spaced bins, according to the respiratory position, and to perform 3D affine registration on the resulting highly undersampled images. However, in cases of bins which just contain a few interleaves or if the distribution of the interleaves is not sufficiently uniform, image quality is degraded by streaking and undersampling artifacts. In these cases, artifacts can dominate the results of the registration and, therefore, such outlier bins are either discarded [5] or corrected only for 1D motion [6]. In the present work, an improved binning procedure is described, which aims to minimize the image artifacts by maximizing the uniformity of the interleaves within the bins. The goal is to allow successful 3D affine motion correction for all bins. Evaluation of the results was performed in comparison with the straightforward binning method.

METHODS: A 3D radial trajectory, adapted for self-navigation [3], was used in this work. As the radial interleaves intrinsically feature uniform polar distribution of the readouts, the spatial position of each interleave was associated with the azimuthal angle of the starting point of the first readout on top of a sphere in k-space (k_x-k_y). Henceforth, the angular difference between the azimuthal angles of two contiguous interleaves, within the same bin, will be referred to as azimuthal gap ($\boldsymbol{\varphi}$). Both the azimuthal angle and the SI position of the blood pool, derived from the self-navigation, were extracted for each interleave. All interleaves were fed into an iterative algorithm, which performed the binning procedure by minimizing the equally weighted product of the following criteria:

1. The sum of the standard deviations of all azimuthal gaps within each bin, $\Sigma_i(\sigma(\boldsymbol{\varphi}_i))$, where $\boldsymbol{\varphi}_i$ represents the set of azimuthal gaps within the bin B_i;
2. The sum of the intra-bin motion of all bins, $\Sigma_i(\sigma(\mathbf{z}_i))$, where $\mathbf{z}_i$ is the set of SI positions of the interleaves contained in the bin B_i;
3. The overlap between all pairs of adjacent bins B_i and B_j, defined as the total number of interleaves of B_i included in the interval $[\min(\mathbf{z}_j), \max(\mathbf{z}_j)]$, where $\mathbf{z}_j$ represents the set of SI positions of B_j,
4. The inverse of the distance between the centroids of all pairs of adjacent bins B_i and B_j, $1/|\mu(\mathbf{z}_i)-\mu(\mathbf{z}_j)|$, where $\mu(\mathbf{z})$ is the mean of the SI positions.

After binning, 1D motion correction was applied within each bin to additionally minimize intra-bin motion. A 3D undersampled image was obtained from each bin and registered, with 3D affine transformation [7], to a reference image. In this case, the image from the full dataset, corrected by 1D self-navigation, was used as reference. The SI displacement of the blood pool was extracted from the linear phase in k-space.

Whole-heart coronary MRA was performed on 4 healthy volunteers. A 3D radial, non-selective, T2-prepared, fat-saturated, balanced SSFP sequence, implementing 1D self-navigation, was acquired with the following parameters: TR/TE 3.0/1.51 ms, FOV $(220)\text{mm}^3$, matrix 192^3, voxel size $(1.15\ \text{mm})^3$, flip angle 90° and receiver BW 898 Hz/Px. A total of 377 interleaves of 31 radial readouts each were acquired for imaging, for an overall undersampling of 20%. All experiments were performed on a 1.5 T clinical MRI scanner (MAGNETOM Avanto, Siemens AG, Healthcare Sector, Erlangen, Germany). A total of 12 elements of a body matrix coil (anterior) and the spine matrix coil (posterior) were selected for signal reception. The final datasets were reformatted with CoronaViz (Work in Progress software, Siemens Corporate Research, Princeton, NJ, USA) to better visualize the coronaries. The novel optimized binning strategy was compared with the straightforward binning approach for the uniformity ($\sigma(\boldsymbol{\varphi})$), for the intra-bin motion ($\sigma(\mathbf{z})$) and for the visual image quality of the single bins. Eventually, the final reformatted images were visually compared.

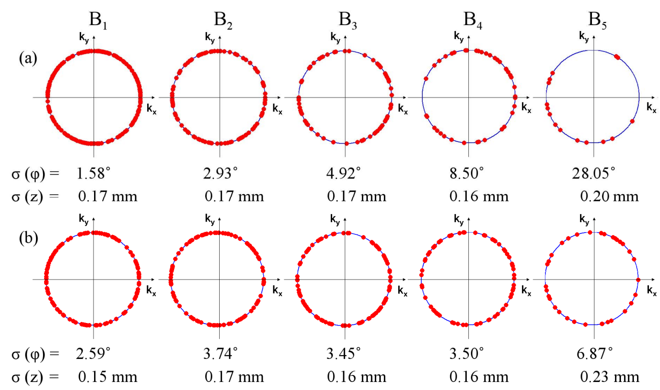

Fig. 1: The straightforward binning method of [5,6] (a) is compared to the described approach (b). The azimuthal angle associated with each interleave is represented, for each bin B_i, by a red dot on the unit circle in the k_x-k_y plane. Bins from 3 to 5 show that, while minimal intra-bin motion σ(z) is preserved, the described approach optimizes the uniformity of the distribution, as σ(φ) is minimized.

RESULTS: The improved binning strategy was successful in all datasets. The average value of $\sigma(\boldsymbol{\varphi})$ of all bins decreased from an average of 16.66°±19.10°, with the straightforward method, to 5.31°±2.93°, with the improved approach. Nevertheless, the average intra-bin motion remained practically unchanged with means of 0.25±0.07 mm and 0.26±0.13 mm, respectively. All images from the bins obtained with the improved approach could be correctly registered for all datasets. An example showing the superior uniformity of the bins obtained with the new approach is shown in Fig.1. As it can be inferred by the visual improvement in the image quality of the bins displayed in Fig.2, not only the binning algorithm allowed to perform a correct 3D registration on bins that were previously discarded (B_5), but also reduced imaging artifacts of the other bins (B_4). In average, less than one-tenth of all interleaves of each datasets were considered as outliers in the straightforward binning approach. For this reason, image quality of the full reformatted datasets obtained with the two methods did not show any visible difference.

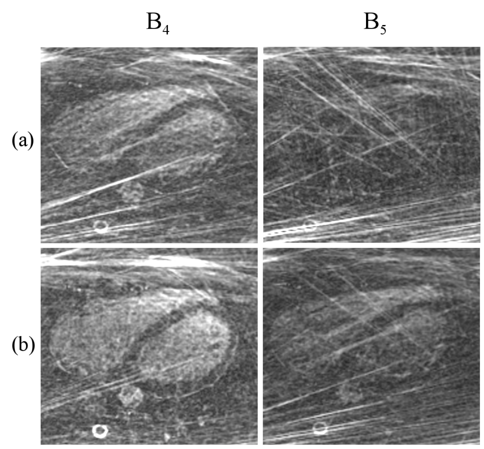

Fig. 2: Example of the image quality obtained with two of the bins of Fig.1. The number of interleaves in B_4 and B_5 is, respectively, 39 and 16 for the straightforward binning (a) and 65 and 33 for the improved approach. Correct registration was possible for B_5(b), but not for B_5(a).

DISCUSSION AND CONCLUSIONS: The presented method provides an optimized binning process for interleaved coronary MR acquisitions. The artifact reduction achieved with this approach always allows successful image registration of all bins. Although no significant differences in the quality of the final images in comparison with the straightforward binning approach could be observed in healthy volunteers, an improvement is expected in clinical cases. In a clinical scenario, in fact, respiratory motion might be very irregular, and, therefore, result in a critical percentage of outliers.

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