Spiral Off-Resonance Distortion Correction for Tagged MRI Using Spectral Peak Matching and HARP Refinement

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INTRODUCTION: Tagging MRI is a gold standard technique [1] to estimate regional myocardial motion and strain. Harmonic phase (HARP) [2] processing is commonly used to extract motion and strain from tagged images. However, in the presence of B0 inhomogeneity, tagging lines can be significantly corrupted due to the phase accumulated during the echo time and, spatial distortion and blurring associated with the data acquisition pattern. Segmented spiral data acquisition [3] is commonly used for tagged MR imaging due to its efficient and fast acquisition, SNR benefits and the associated very short echo times. While peak combination HARP [4] (PC-HARP) can be employed to correct for the accumulated errors in the phase during the already very short echo times, blurring and distortion remains a major concern for spiral data acquisition. Although several spiral off-resonance correction techniques [5] have been proposed, they require the prior knowledge of data acquisition parameters like acquired k-space trajectory, raw data, and B0 field inhomogeneity map, which may not be readily available. In this work we developed a post-processing spiral distortion correction technique for tagged MR imaging that does not require prior knowledge about data acquisition parameters and can be performed during HARP analysis using the reconstructed tagged MR images acquired using spiral k-space trajectory.

METHODS: The Fourier transform of tagged MR image contains spectral peaks with their locations depend upon the applied tag spacing and tagging profile. As shown in Fig 1, these spectral peaks are located away from the center of k-space where the spiral trajectory can be approximated as an EPI Cartesian data acquisition with phase encoding direction being the radial direction $\vec{r}$. Therefore, the spatial distortion due to off-resonance for the images obtained from a spectral peak translates to a displacement along the direction $\vec{r}$ in the spatial domain [6]. The amount of displacement error at a spatial location depends on the off-resonance at that location and the radial velocity of the spiral trajectory while traversing the center of the spectral peak. Since segmented spiral acquisition exhibits radial symmetry with radial velocity dependent primarily on the radial distance from the center of the k-space, the amount of displacement is dependent only upon the radial distance of spectral peaks from the center of k-space.

Fig 1: Magnitude and k-space of horizontal and vertical zHARP tagging. The inset shows almost-Cartesian spiral trajectory over the spectral peak

The ZHARP technique [7] is an extension of slice following CSPAMM to estimate the 3D dense motion fields of all the points on the acquired slice image and includes benefits of PC-HARP to exclude the inhomogeneity phase error from the acquired tagged data.. In this work, zHARP dataset is acquired and as shown in Fig. 1, the centers of the four spectral peaks present in the k-space are located at the same radial distance from the center of the k-space. Therefore, all the spectral peaks will experience same displacement error. The directions of displacement error and harmonic phases for the four spectral peaks are given in Table 1. Here, Φ_x, Φ_y, and Φ_z are phase images encoding motion and spatial location of the underlying voxels in x, y, and z direction, respectively. It is important to note that Φ_z will be zero for the CSPAMM dataset. Therefore, the proposed technique is also applicable for CSPAMM. Since the harmonic phases [2] are properties of the material points and not their locations in the distorted image, the displacement error $r(x,y)$ can be estimated by matching the harmonic phase of four spectral peaks by solving,

Table 1: Harmonic phase and displacement direction for the four spectral peaks shown in Fig. 1.

Spectral Peak	Harmonic Phase	Disp. direction
$I_{a,h}(x,y)$	$\Phi_{a,h}(x, y) = \Phi_y(x,y) + \Phi_z(x,y)$	+y
$I_{b,h}(x,y)$	$\Phi_{b,h}(x, y) = -\Phi_y(x,y) + \Phi_z(x,y)$	-y
$I_{a,v}(x,y)$	$\Phi_{a,v}(x, y) = \Phi_x(x,y) - \Phi_z(x,y)$	+x
$I_{b,v}(x,y)$	$\Phi_{b,v}(x, y) = -\Phi_x(x,y) - \Phi_z(x,y)$	-x

$$\Phi_{a,v}(x + r(x,y), y) + \Phi_{b,v}(x - r(x,y), y) + \Phi_{a,h}(x, y + r(x,y)) + \Phi_{a,h}(x, y - r(x,y)) = 0 .$$

Since the estimated phases are wrapped between $-\pi$ and $+\pi$, and may have large distortions, region growing based HARP refinement with fast marching technique [8] is modified to solve the above harmonic phase matching equation.

To test the proposed algorithm a zHARP scan was performed in a healthy adult subject on a 3T clinical MR scanner (Achieva, Philips Medical Systems, Best, NL) equipped with a 6-element cardiac phased array surface coil and vector ECG technology. The scan was performed using segmented k-space spiral acquisition with spectral-spatial excitation and a ramped flip angle [3]. Twenty short axis systolic cine frames at mid-cavity with a temporal resolution of 30 ms were acquired from end-diastole to end-systole. Each image was acquired using 9 spiral readouts per image, with a 10 ms acquisition window and TE = 2.1ms. Acquired images were of FOV = 300 mm, voxel size = 2x2 mm^2, recon resolution = 1.04x1.04 mm^2, slice thickness = 8 mm, tag spacing = 7 mm and z-encoding of 0.157 rad/mm.

Fig 2: Absolute value of the real part and Magnitude of the spectral peaks shown in Fig 1. Arrow marks the distortion. Yellow point marks the seed point used in PM-zHARP.

RESULTS: Fig 1 shows the magnitude and Fourier transform of the horizontal and vertical zHARP tagged images at end-diastole. The four spectral peaks are isolated by HARP filtering. The absolute value of real part and magnitude of the filtered spectral peaks are shown in Fig 2. As shown in Fig 2, the images from the four spectral peaks are distorted (arrow) as described in Table 1. A seed point (yellow dot), required for HARP refinement is selected over the myocardium to estimate the displacement error $r(x,y)$ as shown in Fig 3. The free wall has the maximum displacement error, on the order of 7mm, due to the increased magnetic field inhomogeneity and susceptibility artifacts from heart lung interface. The estimated x, y, and z motion encoded phase images using the zHARP analysis and proposed PM-ZHARP and, the absolute difference between the two methods is shown in Fig 3. The two techniques differ mostly over the free wall. zHARP assumes that there is no spatial distortion between the spectral peaks, therefore in the presence of large amount of distortion, for example over the free wall in Fig 3, the results from two techniques shows significant difference.

CONCLUSION: We have presented a spiral off-resonance correction technique (PM-zHARP) that is especially tailored for tagged MR images. We used the fact that the blurring effect caused by the off-resonance for spiral acquisition translates to displacements in the images obtained from spectral peaks present in the k-space of the tagged MR images. We have successfully demonstrated the proposed technique in an in-vivo study. However, further validation is required.

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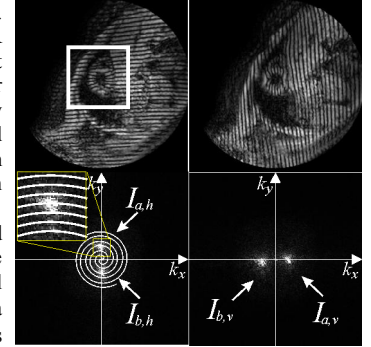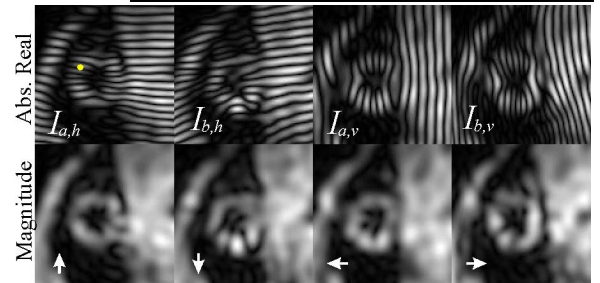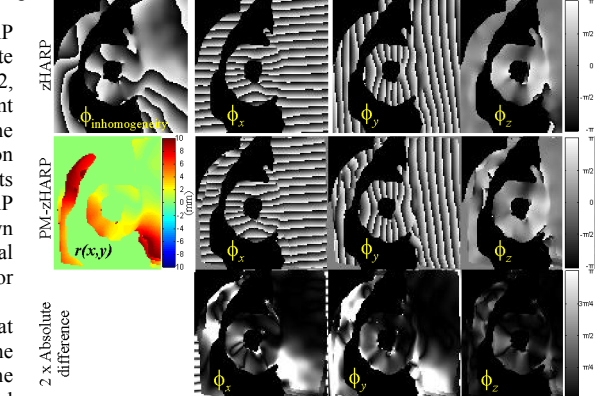
Fig 3: x, y and z motion encoded phase estimated using zHARP and PM-ZHARP, and also the absolute difference between the two techniques. Phase inhomogeneity and spatial distortion (in mm) estimated by zHARP and PM-zHARP respectively