Compressed sensing reconstruction with higher-order off-resonance correction using the cross-sampling and the time-segmented method

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TARGET AUDIENCE: MR scientists who are interested in the compressed sensing (CS) reconstruction of MRI with off-resonance effect.

PURPOSE: It is required to design incoherent sampling trajectories for an effective CS reconstruction[1]. Non-Cartesian sampling trajectories, such as spiral or radial trajectories, achieve better incoherence compared to conventional Cartesian trajectories[2,3]. In the case of non-Cartesian acquisition, the acquired MR image suffers from the image distortion and artifacts due to the off-resonance effect and the eddy current. To overcome these undesirable problems, a cross-sampling method[3-5], which can be implemented by using orthogonal readout gradients, with a first-order B_0 correction was proposed[5]. However, the first-order correction is insufficient in some cases because imperfect shimming and the sample-induced inhomogeneity make higher-order components. In this paper, we proposed a new CS reconstruction approach with a self-calibrated higher-order off-resonance correction and the cross-sampling method. Imaging experiments of a chemically fixed mouse using a 1T permanent magnet MRI system demonstrated the usefulness of our approach.

METHODS: To achieve better incoherence, the cross-sampling method[3-5] was used. The cross-sampling was achieved by acquiring the two k-space data set y_1 and y_2 using orthogonal readout gradients G_x, and G_z, respectively, as shown in Fig.1. A B_0 distribution map $\Delta(i,j)$ was obtained by estimating the distortion[6] between these two images S_x and S_z, which are inverse Fourier transforms (FT) of y_1 and y_2, respectively. Because MR images are distorted along their readout direction, S_x and S_z can be approximated to

$$S_x\left(i+\frac{\Delta(i,j)}{G_x},j\right)\sim S(i_0,j_0),\ S_z\left(i,j+\frac{\Delta(i,j)}{G_z}\right)\sim S(i_0,j_0) \qquad (1)$$

,where i and j are the pixel position along x and z, respectively, S is the ideal MR image, i_0 and j_0 are the ideal pixel position, and G_x and G_z denote the gradient field strength. In this study, we approximated $\Delta(i,j)$ to the polynomial function up to second order as follows: $\Delta(i,j)=c_0+c_1i+c_2j+c_3i^2+c_4j^2+c_5ij$, where c_0, c_1, c_2, c_3, c_4, and c_5 are the polynomial coefficients. The coefficients were determined by minimizing below cost function $f(x)$ using Levenberg-Marquardt method.

$$f(x)=\left\|S_x\left(i+\frac{\Delta(i,j)}{G_x},j\right)-S_z\left(i,j+\frac{\Delta(i,j)}{G_z}\right)\right\|^2 \qquad (3)$$

The acquired data sets were corrected using the time-segmented method[7]. And the phase distortion caused by eddy current was estimated from the lower resolution data[8]. Then, the equation which we should solve is:

$$\underset{x}{argmin}\|D_1x-y_1\|_2^2+\|D_2x-y_2\|_2^2+\|Wx\|_1 \qquad (4)$$

, where $D_1=F^{-1}\cdot R_1\cdot H_1\cdot P_1$ and $D_2=F^{-1}\cdot R_2\cdot H_2\cdot P_2$, W denotes the forward wavelet transform, F^{-1} is the inverse FT, R_1 and R_2 are the undersampling operatorfor for y_1 and y_2, H_1 and H_2 are the off-resonance correction (time-segment method[7]) operator along G_x and G_z, and P_1 and P_2 are the phase correction operators[8] for S_x and S_z respectively. Finally, the MR image x was reconstructed by solving Eq. (4) using the wavelet regularized split Bregman (WSpB)[9] method.

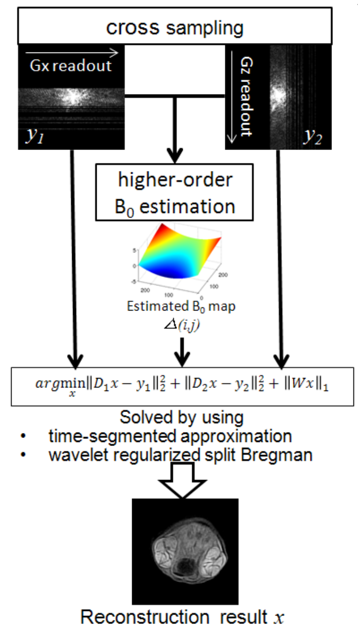

Fig. 1 Proceedure for proposed method

To demonstrate the performance of our method, imaging experiments using chemically fixed mouse and 1T permanent magnet were performed. Two-dimensional gradient echo sequences (TR/TE=60/8 ms, matrix size = 256^2, FA = 60 deg , FOV = $(38.4\ \text{mm})^2$, slice thickness = 2.5 mm) and a cross-sampling trajectory (cross trj., reduction factor (R) = 2.3) as shown in Fig. 2(a) were used. In addition to this, a Cartesian undersampling trajectory with G_x readout (Cartesian trj., R= 2.3) as shown in Fig.2(b) was used for the comparison of results between the trajectories. The k-space data set using the Cartesian trj. was reconstructed using WSpB. PSF analyses[1] were performed to evaluate the incoherence of the trajectories.

RESULTS AND DISCUSSION: Fig 2 (c)-(f) are the MR images acquired and reconstructed with (c) full sampling and 2D FT method, (d) the Cartesian trj. and WSpB method, (e) the cross trj. and WSpB method, and (f) the cross trj. and proposed reconstruction approach. As shown in Fig.2 (d), some structures indicated by red and blue arrows were blurred. And we see that there is an aliasing artifact in the image. The MR image shown in Fig.2 (e) was also unclear due to the off-resonance effect. On the other hands, as clearly shown in Fig.2 (f), the MR image acquired and reconstructed with proposed method had less artifacts and finer structures. Fig. 2 (g) shows the profile of PSF along the phase-encoding (G_z) direction for the Cartesian trj. and the cross trj. As clearly shown in the result, PSF for the Cartesian trj. had larger interference intensity compared to the cross trj. along the phase-encoding direction.

CONCLUSION: We developed the CS reconstruction method with the self-calibrated higher-order off-resonance correction. The imaging experiment demonstrated the usefulness of our method.

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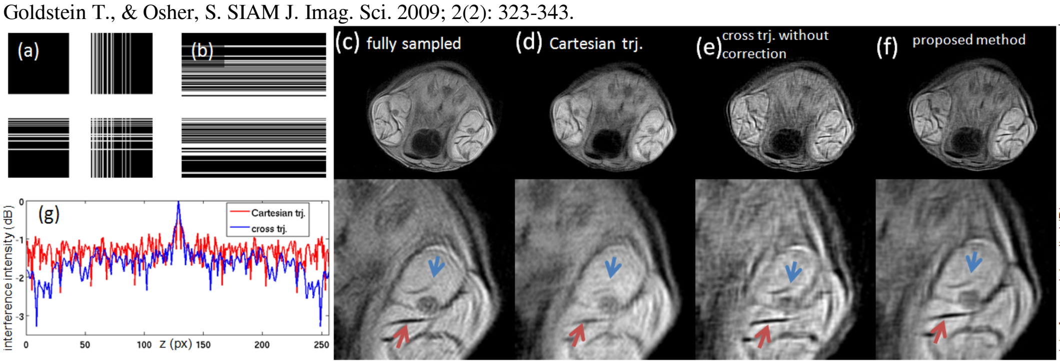

Fig.2 (a) cross trj. and (b) Cartesian trj. used in this study. (c-f) MR images of chemically fixed mouse acquired and reconstructed with (c) fully sampling and 2DFT (d) Cartesian trj and WSpB method, (e) cross trj. and WSpB method without off-resonance correction, and (f) proposed method. (g) PSF profile along the z axis (phase encoding direction for Cartesian trj.).