Major Speed-Up of Nyquist Ghost Correction in ramp-sampled EPI

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Introduction: In echo planar imaging (EPI), even and odd k-space lines are acquired using positive and negative readout gradient lobes. Small undesired timing differences between these gradient waveforms will cause misalignments between odd and even echoes leading to FOV/2N or in the image, where N is the number of interleaves. These ghosts are normally corrected for by applying a phase correction map to the odd or even lines in hybrid-space (x-k_y). This correction map, consisting of constant and linear phase terms (Φ_0 and Φ_1), is commonly derived by an external reference scan [1] or by using an iterative post-processing method such as e.g. entropy minimization [3,4,5]. As a means to reduce the echo spacing and the geometric distortions even further, most modern systems acquire k-space data during the attack and decay of each EPI readout trapezoid (i.e. ramp sampling). Ramp sampling leads to non-linear k-space sampling and requires resampling of the N_a acquired data points onto a Cartesian k-space (N_{kx} points). The resampling of the acquired k-space data is usually implemented as a simple matrix-vector multiplication using V ($N_a \times N_{kx}$) as a look-up table for the convolution operation of each sampling point. For minimum ghost levels, the linear gradient time delays that lead ultimately to ghosting are to be corrected before ramp sampling rather than afterwards, as the gradient time delay is constant for each sample prior to, but not after gridding (see Fig. 2) [2]. This, however, requires two additional computationally expensive non-power-of-two 1D-FFT's in the k_x direction. For dynamic EPI acquisitions, this may cause prohibitively long delays in the image reconstruction time. In this work, we demonstrate that, by embedding a previously estimated phase correction in the ramp sampling correction, a major speed-up in EPI reconstruction can be achieved at identical FOV/2N ghost level.

Method: The time consuming 1D-FFT to hybrid space for ghost correction and back to k-space for ramp sampling correction (Fig. 1a), is avoided by performing the correction directly in k-space during gridding (Fig. 1c). The constant term Φ_0 is identical in hybrid space and k-space and can be estimated in either space. The linear phase term Φ_0, needs to be implemented as a delay, Δk_x, in the gridding sinc kernel. This will lead to an augmented ramp sampling reconstruction, in which the modified resampling can be carried out as a k-space shift correction matrix P ($N_a \times N_a$) that operates on the true gridding matrix. Odd (a) and even (b) lines are then corrected as follows:

$$\begin{cases} \underbrace{\mathbf{a}_{corr}}_{N_{kx}\times N_{ky},odd} = \underbrace{\mathbf{V}}_{N_{kx}\times N_a} \underbrace{\mathbf{a}}_{N_{kx}\times N_{ky},odd} \\ \underbrace{\mathbf{b}_{corr}}_{N_{kx}\times N_{ky},even} = \left(\underbrace{\mathbf{V}_{shifted}}_{N_{kx}\times N_a}\right)\left(\underbrace{\mathbf{b}}_{N_a\times N_{ky},even} e^{i\phi_0}\right) = \mathbf{V}_{shifted}\left(\underbrace{\mathbf{b}}_{N_a\times N_{ky},even} e^{i\phi_0}\right) \end{cases}$$

V is the ramp-sampling gridding kernel. $V_{shifted}$ is constructed by adding the time delay corresponding to the estimated Δk_x to the known gradient before integration, as shown in Fig. 3. We have chosen to perform the ghost correction on the even echoes only, since it reduces estimation calculations.

A dynamic single-shot SE-EPI was acquired using an 8-channel coil (20 slices, 25 time frames) to demonstrate the efficacy of our method. Image matrices of 128×128 and 64×64 with N_a = 264 and N_a = 264, respectively, were used. To determine 0th and 1st order phase terms entropy based phase correction was performed once in hybrid space on the center slice, after the average over coils where taken. The different reconstruction paths, shown in Fig. 1 were timed. All FFT's were performed on a coil-by-coil basis, leading to a total of $N_{coils} \times N_{slices} \times N_{frames}$ calculations.

Results: By incorporating the FOV/2N ghost correction into the gridding portion of the ramp sampling reconstruction, simply by treating it as a gradient time delay when computing the underlying k-space trajectory, a major reduction in reconstruction time could be achieved (see fig. 4). Reconstruction time was approximately 5× faster in both cases (64×64 and 128×128 matrix), with ghost correction being 85% of the total reconstruction time in the conventional method, compared to ca 25% in the new approach. Despite the faster reconstruction there was no change in ghost artifact removal and image quality (see fig. 5).

Discussion: This new reconstruction method is simple but has very important consequences for EPI reconstruction. Particularly, for increase in dynamic scan numbers the method has dramatic potential.

References: [1] Bruder H et al. 1992. MRM 23:311-323. [2] Schmitt F et al. 1998. Echo Planar Imaging. Berlin: Springer [3] Buonocore MH et al. 2001. MRM 45(1):96-108. [4] Clare S, ISMRM 2003, Toronto. [5] Skare S et al. ISMRM 2006, Seattle.

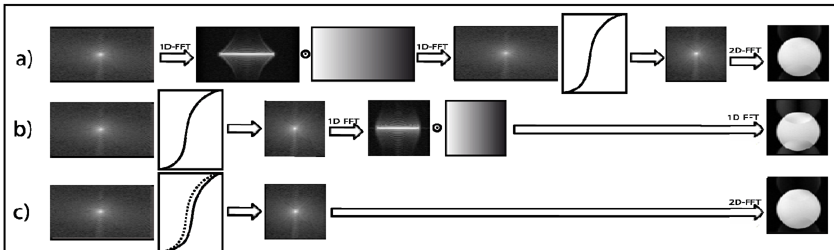

Fig 1 shows the compared methods for ghost correction. 1.a corrects for ghosting in hybrid space before correcting for ramp sampling. 1.b is vice versa, which saves one FFT, but increases ghosting. 1.c corrects for ramp sampling and ghosting in one step. All three methods, assumes that correction parameters have been estimated.

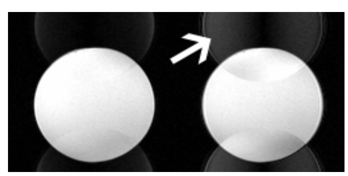

Fig 2. Comparing residual ghost using method 1.a (left) and 1.b (right).

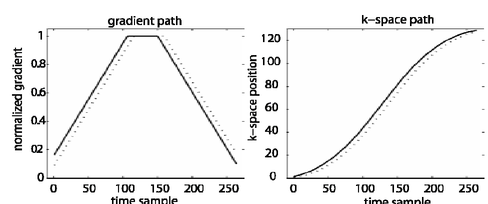

Fig 3. The estimated linear phase is translated into a gradient waveform delay (left dashed). Integration of the gradient waveform, gives the shifted k-space path (right dashed) used to construct $\mathbf{V}_{shifted}$.

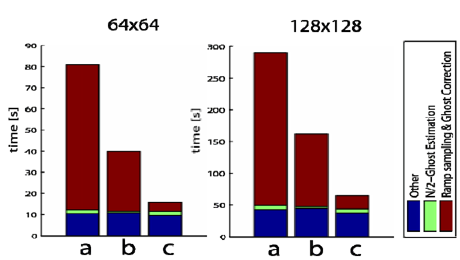

Fig 4. Speed performance test, reconstructing 8×25×20 images using the methods shown in figure 1.a, 1.b and 1.c.

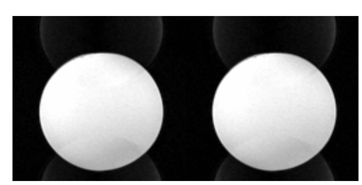

Fig 5. Method 1.c (left) and 1.a (right), has an equally amount of residual ghost left but method 1.c is 5× faster.