A Correction Method of Streak Artifacts in Gradient-Echo EPI Sequence Using a Spin Echo EPI Reference

J-Y. Chung[1], Y. Han[1], and H. Park[1]

[1]Dept. of EE, KAIST, Daejeon, Korea, Republic of

Introduction

Gradient-echo echo-planar-imaging (GRE-EPI) sequence is widely used for various applications which require high temporal resolution such as functional magnetic resonance imaging (fMRI) and cardiac imaging. GRE-EPI sequence has limitations in application areas due to two major artifacts, Nyquist ghost artifact and geometric distortion [1, 2]. In order to reduce the artifacts, Heid proposed a method that exploits either an even or odd line from a reference scan. An alternative method was proposed by Buonocore et al. where no additional reference scan is needed. The linear phase correction methods have limitations in their capacity to correct ghost artifacts. Therefore, nonlinear phase correction methods are preferred in many cases. However, phase errors at certain pixels along the readout (RO) direction may cause streak artifacts in the nonlinear phase corrected images. Although the nature of streak artifacts have been described in several literatures [3, 4], a correction method for streak artifacts has yet to be proposed. In this study, a method to correct the streak artifacts in a GRE-EPI imaging scan using a spin-echo (SE)-EPI reference scan is proposed.

Methods

We analyze the effect of a constant phase offset on the nonlinear phase correction scheme. Let $\tilde{S}_n^R(k_{RO})$ and $\tilde{S}_n^M(k_{RO})$ be k-space signals of the reference and main EPI scans, respectively, affected by field inhomogeneity, where the subscript *n* denotes the phase encoding or echo number. The corresponding ideal k-space signals without any distortions due to field inhomogeneity are $S_n^R(k_{RO})$ and $S_n^M(k_{RO})$, respectively. A 1D FT is applied along the RO direction and the corresponding 1D transformed signals are $P_n^R(x), \tilde{P}_n^R(x), P_n^M(x),$ and $\tilde{P}_n^M(x)$. If we assume that there is phase error $\Phi(x)$ in the projection data, the reference and main signals are then described as follows, $\tilde{S}_n^R(k_{RO}) \xrightarrow{1D\ FT} \tilde{P}_n^R(x) = P_n^R(x)\cdot e^{i\Phi_n^R(x)}$, $\tilde{S}_n^M(k_{RO}) \xrightarrow{1D\ FT} \tilde{P}_n^M(x) = P_n^M(x)\cdot e^{i\Phi_n^M(x)}$ [Eq. 1]. For the phase correction, a nonlinear phase term $\phi_n^R(x)$ is deduced from the reference scan. Using the phase term, the phase-corrected transformed signal $\hat{P}_n^M(x)$ is estimated as follows, $\hat{P}_n^M(x) = \tilde{P}_n^M(x)\cdot e^{-i\Phi_n^R(x)} = P_n^M(x)\cdot e^{i\Phi_n^M(x)}\cdot e^{-i\Phi_n^R(x)} = P_n^M(x)\cdot e^{i(\Phi_n^M(x)-\Phi_n^R(x))}$ [Eq. 2]. In general, we can assume the phase error in the reference scan is equal to that in the main scan ($\Phi_n^R(x) = \Phi_n^M(x)$), since the reference and the main scans have the same sequences except for the phase encoding gradients. The estimated signal $\hat{P}_n^M(x)$ is then equal to $P_n^M(x)$ in eq. [2]. However, if a nonlinear phase term has a constant phase offset as follows, $\Phi_n^R(x) = \Phi_n^M(x) - \phi_0$ [Eq. 3], then the estimated signal can be described as follows, $\hat{P}_n^M(x) = P_n^M(x)e^{i\Phi_n^M(x)}e^{-i\Phi_n^R(x)} = P_n^M(x)e^{i(\Phi_n^M(x)-\Phi_n^R(x))}e^{i\phi_0} = P_n^M(x)e^{i\phi_0}$ [Eq. 4]. In eq. [4], the constant phase term can be removed by taking the magnitude after another 1D FT along the phase-encoding (PE) direction, i.e., in the image space. To validate the effect of phase offset, we performed the phase correction procedures according to the spin diagrams, as shown in Fig. 1. In order to assess the proposed correction method, we acquired reference data using single-shot GRE-EPI and single-shot SE-EPI, and the main imaging scan using a single-shot GRE-EPI for a spherical water phantom with $NiSO_4$. The experiments were performed using 1.5 Tesla (Avanto, Siemens Medical Solutions, Erlangen, Germany) MRI system with a quadrature head coil, and using the following parameters: TE=40ms for GRE-EPI and SE-EPI imaging and reference scans, TR = 3000ms, matrix size = 64×64, number of slices = 36, slice thickness = 5mm, FOV = 25.6×25.6 cm^2, NEX = 1. The field homogeneity for these experiments was shimmed by an inbuilt 3D shimming procedure.

Results

In accordance with the relation of removing the constant phase term by taking the magnitude after another 1D FT along the PE direction, we analyze the effect of phase offset in various nonlinear phase correction procedures, as shown in Fig. 1. Figures 1a and 1b show spin diagrams of GRE-EPI and SE-EPI, respectively. As these diagrams demonstrate, the phase error in the GRE-EPI has the same characteristics as that in the SE-EPI except for the constant phase offset, which is ϕ_0 in Fig. 1a. For the phase-error correction process, we measured the phase of an individual projection of the reference scan after a 1D FT of the echo signal. The measured phase is applied to eq. [4] for the phase-error correction. By assuming that the higher-order phase errors of the main scan can be observed in the projection data of the reference scans, the nonlinear phase error is deduced and subtracted. Therefore, we can use both the GRE-EPI and SE-EPI reference data for correction of the GRE-EPI main scan, and vice versa. Figure 2 shows the original and the corrected phantom images acquired using EPI sequences. N/2 ghost artifacts are present along the PE direction in the non-corrected original image, as shown in Fig. 1a. When GRE-EPI reference data is used, most of the N/2 ghost artifacts are removed, but a new artifact (i.e. a streak artifact) is generated due to the phase correction error, as shown in Fig. 2b. Using the SE-EPI reference data, the N/2 ghost artifacts have been clearly reduced without generating streak artifacts, as shown in Fig. 2c.

Conclusions

The main difference between the GRE-EPI and SE-EPI reference data lay in broadening and weakening of the echo signal as the PE steps increased in GRE-EPI. Under real conditions, echo broadening is inevitable due to dephasing of spins under field inhomogeneity. The field inhomogeneity made spins dephased in the GRE-EPI reference data whereas the spins were rephrased in the SE-EPI reference data due to the 180° refocusing RF pulse. Consequently, better correction results without any streak artifacts were obtained by the SE-EPI reference data.

References

[1] Heid O. ISMRM 1997:p2014

[2] Buonocore MH, Gao L. Magn Reson Med 1997:38:89–100.

[3] Hu X, Tuong HL. Magn Reson Med 1996:36:166–171.

[4] Schmitt F, Stehling MK, Turner R. Berlin-Heidelberg:Springer; 1998.

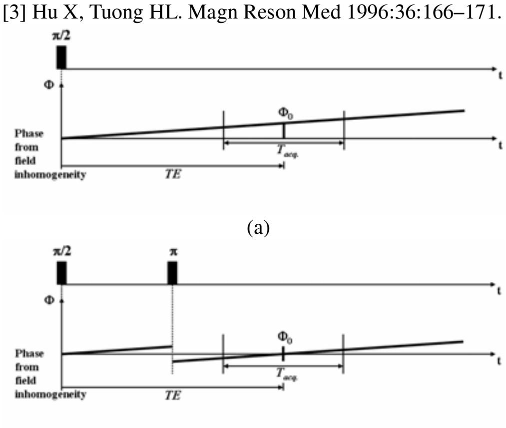

Figure 1. Phase diagram of a spin in two different EPI sequences. (a) Phase diagram of GRE-EPI, and (b) Phase diagram of SE-EPI imaging.

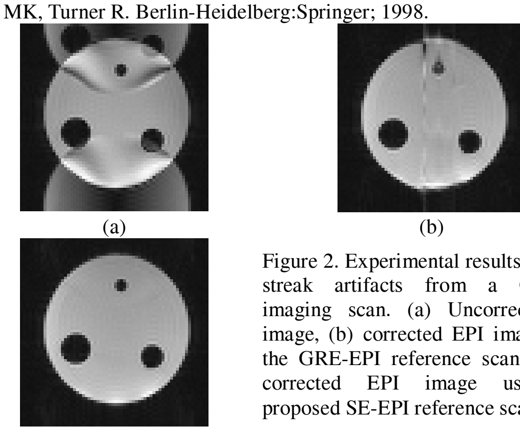

Figure 2. Experimental results o having streak artifacts from a GRE-EPI imaging scan. (a) Uncorrected EPI image, (b) corrected EPI image using the GRE-EPI reference scan, and (c) corrected EPI image using the proposed SE-EPI reference scan.