A Robust Field-map Estimation Method Using Dual-echo GRE with Bipolar Readout Gradient Structure

D. Yeo[1,2], T. L. Chenevert[2], J. A. Fessler[1,2], B. Kim[2]

[1]Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI, United States, [2]Radiology, University of Michigan Medical School, Ann Arbor, MI, United States

Introduction: Field-maps are typically required to correct for field-inhomogeneity artifacts like geometric distortion in EPI and blurring in spiral acquisitions [1,2]. With a few exceptions, a static field-map is typically estimated by taking the phase difference of gradient-echo complex images acquired at two different echo times [3,4] using the same pulse sequence twice. However, this method is prone to motion-induced errors since the subject's positions at two separate acquisitions are not guaranteed to be consistent. In this work, a dual-echo fast gradient echo (DEFGRE) pulse sequence (Fig. 1) employing two back-to-back readout gradients of opposite polarity is used for static field-map estimation. This pulse sequence, typically used for fat-water applications, acquires two echoes efficiently with one RF pulse with minimal idle time in-between echoes. The image data can be used to compute field-maps with greatly reduced motion-induced errors. A caveat in this sequence is that the imperfect symmetry of the readout gradient in opposite directions causes an evident phase error. We model the phase error as an affine term in the readout direction and estimate the unknown parameters with MR data. Results from several sets of phantom and patient data acquired on the same scanner over a period of two years suggest that the linearly varying correction term does not change for a given scanner over time and hence can be applied to the field-map estimation of different data sets. The DC correction term changes with time but can be estimated empirically for different scans.

Theory: In the standard field-map estimation method, the field-map is estimated with $\Delta\hat{\omega}_{std}(\boldsymbol{r}) = \angle[I_{TE2,std}(\boldsymbol{r}) I^{*}_{TE1,std}(\boldsymbol{r})] / \Delta TE_{std} \approx \Delta\omega_{std}(\boldsymbol{r})$ where $\Delta\omega_{std}(\mathbf{r})$ is the true field-map (rad/s). In DEFGRE, the two sampled echoes are not aligned to each other in the readout direction. This frequency shift causes a spatially linear phase error in the readout direction x that would cause significant phase wrapping if uncorrected (top rows of Fig. 2). This can be written as $\Delta\hat{\omega}_{dual}(\boldsymbol{r}) = \angle[I_{dual}(\boldsymbol{r})] / \Delta TE_{dual} = \Delta\omega_{std}(\boldsymbol{r}) + (\alpha x + \beta)/\Delta TE_{dual} + \eta(\boldsymbol{r})$ where η is field-map noise and $(\alpha x+\beta)$ is an affine term used to model the phase error. The DC term β is added to correct for any global phase drift. The affine phase term is estimated by minimizing the following cost function with data from a spherical phantom:

$$\alpha, \beta = \underset{\alpha,\beta}{\arg\min} \sum_{x=0}^{N} \left| \angle \exp(\, j[\Delta\hat{\omega}_{\text{dual}}(x, y_0) \cdot \Delta TE_{dual} - (\alpha x + \beta)]) - \angle \exp(\, j \Delta\hat{\omega}_{\text{std}}(x, y_0) \cdot \Delta TE_{std}) \right|^2 \qquad (1)$$

where $\Delta\hat{\omega}_{std}(x, y_0)$ and $\Delta\hat{\omega}_{dual}(x, y_0)$ are off-resonance values of column y_0 of a slice from the standard field-map estimate (ground truth) and the uncorrected DEFGRE estimate respectively. Using the Nelder-Mead algorithm to minimize Eq. (1), the estimated value of α was constant for all phantom data but β varied with different scans. Similar results were obtained with a simpler optimization strategy using a line search for α followed by an analytical maximum likelihood solution for β. An empirical method to determine β for any new human subject scan is to compute, over several homogeneous regions, the difference between the mean standard field-map value from several previously scanned subjects and the corresponding mean DEFGRE field-map value of the new subject after linear phase correction with α.

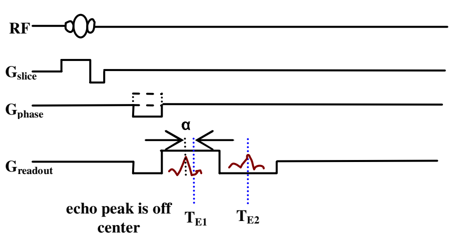

Figure 1. Simplified DEFGRE pulse sequence

Methods: To estimate the affine correction parameters and test their reliability over time, phantom and human subject scans were performed over a period of two years on the same 1.5T GE SIGNA MR scanner (GE Medical Systems, Milwaukee, WI). A spherical phantom and a phantom with an air-column suspended in water were each scanned with two MRI protocols: (i) 2D dual-echo fast gradient echo (T_R=200ms, T_{E1}=2.6ms, T_{E2}=5.3ms, image matrix=256×256×68); (ii) 2 single-echo SPGR (T_R=200ms, T_{E1}=2.7ms, T_{E2}=4.2ms, image matrix=256×256×68). In addition, three human volunteers were scanned with two MRI protocols: (i) 2D dual-echo fast gradient echo (TE1=2.7ms, TE2=5.3ms, image matrix=256x256x54); (ii) 2 single-echo 3D SPGR (TE1=2.4ms, TE2=4.2ms, image matrix=256x256x128).

Results: Using Eq. (1) on phantom data, α was consistently estimated to be -0.10 rad and is used to correct both phantom and human DEFGRE data. Estimated values of β (2.26, 0.11, 0.27 corresponding to the first three columns of Table 1) using Eq. (1) are then used to correct the DEFGRE phantom data while empirically estimated values of β (-2.4, 2.44, -2.78 corresponding to the last three columns of Table 1) are used to correct the DEFGRE human data. Fig. 2 and Table 1 demonstrate qualitative and RMSE results of the corrected DEFGRE field-maps compared to field-maps estimated using the standard method. The RMSE values are relatively small (<0.55ppm) for all datasets and the corrected DEFGRE field-map estimates are observed to be close to the standard field-map estimates.

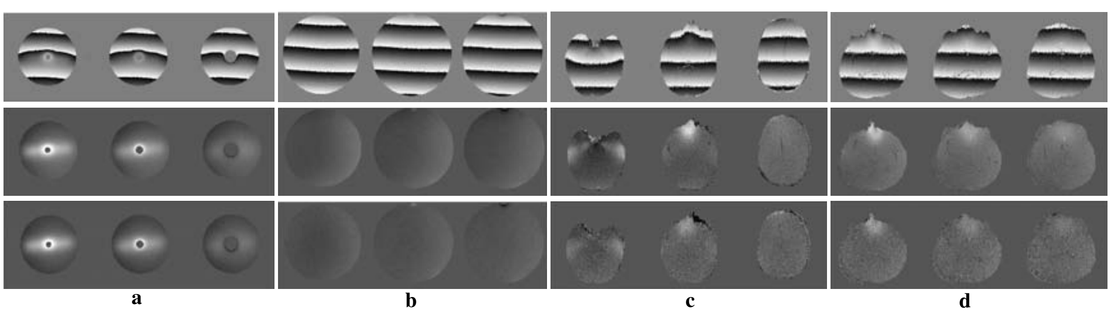

Figure 2. Field-maps for (**a**) air phantom (scan 1), (**b**) sphere phantom (scan 2), (**c**) subject 1, (**d**) subject 2. **Top row:** *Uncorrected* DEFGRE field-maps (scale: -1kHz to 1kHz). **Middle row:** *Corrected* DEFGRE field-maps. **Bottom row:** Field-maps from 2 *separate* single-echo acquisitions. The middle and last rows are displayed on the same scale from -100Hz to 300Hz.

Table 1. Field-map RMSE values between *corrected* DEFGRE and standard field-maps for phantom and human subject data.

Off-resonance RMSE (Hz, ppm at B_0=1.5T)					
Scan 1 (**air**)	Scan 2 (**sphere**)	Scan 2 (**air**)	Subject 1	Subject 2	Subject 3
27.26 Hz, 0.43 ppm	11.16 Hz, 0.17 ppm	23.43 Hz, 0.37 ppm	33.88 Hz, 0.53 ppm	27.98 Hz, 0.44 ppm	32.03 Hz, 0.50 ppm

Discussion: The DEFGRE technique offers an efficient way to compute static field-maps that have reduced motion-induced errors compared to the standard static field-map acquisition method. Test results of the proposed method with phantom and human data show that the linear phase error term does not change with time on the same scanner which allows a "one-time" calibration to be done for each scanner. The DC phase error changes with different scans but may be estimated empirically. Relatively low RMSE values, especially for phantom data where there is no motion, strongly suggest that the affine correction term used with DEFGRE data can yield good field-maps without the need for complicated phase unwrapping procedures.

Acknowledgements: This research is supported in part by NIH grants 1P01 CA87634 & R01 EB00309.

References: [1] Jezzard P, et al, MRM, 1995;34:65-73
[2] Cusack R, et al, Neuroimage 2003,18:127-142
[3] Schneider E, et al, MRM, 1991;18:335-347
[4] Webb P, et al, MRM, 1991;20:113-122
[5] Roopchansingh V, et al, MRM, 2003;50:839-843