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Zero and first-order phase shift correction for field map estimation with dual-echo GRE using bipolar gradients☆

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Abstract

A simple phase error correction technique used for field map estimation with a generally available dual-echo gradient-echo (GRE) sequence is presented. Magnetic field inhomogeneity maps estimated using two separate GRE volume acquisitions at different echo times are prone to dynamic motion errors between acquisitions. By using the dual-echo sequence, the data are collected during two back-to-back readout gradients in opposite polarity after a single radio frequency pulse, and interecho motion artifacts and alignment errors in field map estimation can be factored out. Residual phase error from the asymmetric readout pulses is modeled as an affine term in the readout direction. Results from phantom and human data suggest that the first-order phase correction term stays constant over time and, hence, can be applied to different data acquired with the same protocol over time. The zero-order phase correction term may change with time and is estimated empirically for different scans.

Keywords: Field-inhomogeneity; Field map; Dual-echo; Phase correction

1. Introduction

The static magnetic field passing through an object in a magnetic resonance imaging (MRI) scanner is perturbed by disjoint object regions with different magnetic susceptibilities that augment the magnetic field inhomogeneity caused by imperfections in the gradients and main magnet. Field inhomogeneity causes image artifacts that increase in severity as the static magnetic field strength, B_0, increases. Such artifacts are especially apparent in high-speed MRI techniques like echo-planar imaging and spiral imaging, where geometric distortion and blurring are observed, respectively, because of the longer readout time. Most correction methods for field inhomogeneity effects require an accurate estimate of the field map [1,2]. These methods assume that the data from two different echo times acquired for field map estimation are free of acquisition dependant errors, i.e., position changes due to motion.

A static field map can be estimated by taking the phase difference of a pair of gradient-echo (GRE) images acquired at two different echo times [3–5]. The echo time difference is typically constrained to be small to prevent phase wrapping. With a few exceptions, field maps are generated using two separate image acquisitions with different echo times. However, this method is prone to motion-induced and position-dependent errors that degrade the field map. Using two separate radio frequency (RF) excitations with different echo times would produce accurate field maps only in the absence of motion, i.e., phantom studies. Ideally, B_0 field maps may be computed from the phase changes between two time points of the same images. In human data sets, a common problem of computing field maps from two different images, acquired at two different echo times, is the change in B_0 during the time delay due to the motion, either bulk head motion or physiological brain motion, which causes the error in field map measurement. Typical acquisition times for 3D spoiled GRASS (SPGR) volumes used for the field map computations are approximately 3–4 min. With a normal subject,

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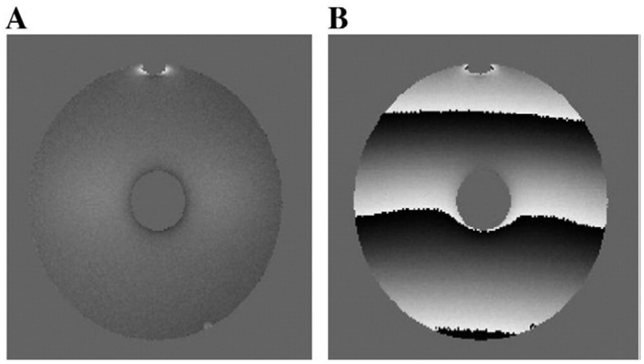

Fig. 1. Off-resonance maps of phantom estimated by standard off-resonance method (A) and uncorrected dual-echo method showing linear phase wrapping in readout direction (x direction downwards) (B).

the mean translation and rotation of the head were observed to be 2.25 mm and 0.71°, respectively, in a 3-min scan time [6]. Even if the head is restrained, brain tissue velocity for normal subject could be 0.94±0.26 mm/s due to the physiological motion [7]. The corresponding images from the two separate volumes with typical 3-min acquisition time will then be misregistered, resulting in the field map estimation error. There is a clear advantage in measuring a field map from the same images acquired at two different echo times, i.e., using a dual-echo sequence.

Partial k-space techniques for dynamic field map estimation can greatly reduce motion-induced errors but may suffer from decreased field map resolution [8]. Some echo planar imaging-based dynamic field map estimation methods acquire the field maps in distorted space, obviating the need for registration between the field maps and the geometrically distorted echo planar images [8,9]. Other field inhomogeneity correction methods assume that the field map is available in undistorted space [10,11]. In some dynamic field mapping techniques, dual-echo images are acquired by using the same positive polarity in the read out gradient, but that would require pulse sequence modifications, an option that may not be available on all clinical scanners.

This work presents a zero- and first-order phase shift correction technique used in conjunction with a simple dual-echo fast GRE (DEFGRE) pulse sequence employing two back-to-back readout gradients, continuous but of opposite polarity, for static field map estimation. This work describes a relatively straightforward technique that allows computation of field maps without the need to modify a commonly available sequence in a clinical setup where the sequence modification is not accessible. The pulse sequence, DEFGRE, acquires two echoes efficiently with one RF pulse, and the image data can be used to compute field maps without motion-induced position errors. A caveat in using this sequence is that, due to the asymmetry of the readout gradients, artifactual phase shifts causing phase wraps are evident in the phase difference map. This study focuses on correcting this residual phase error to remove the phase wraps without using elaborate phase unwrapping algorithms [12,13]. We formulate a hypothesis of how the asymmetric readout pulses cause the artifactual phase shift and then model the phase error as an affine term in the readout direction. The unknown affine model parameters are then estimated using motionless phantom data. Results from several sets of phantom and patient data acquired on the same scanner with the same scan parameters over a period of 2 years suggest that the first-order phase 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 zero-order phase correction term may change with time but can be estimated empirically from the dual-echo data for each new scan.

2. Methods

2.1. DEFGRE pulse sequence

In the generally used static field map estimation method, two complex images, $I_{\mathrm{TE1,sep}}$ and $I_{\mathrm{TE2,sep}}$, are acquired

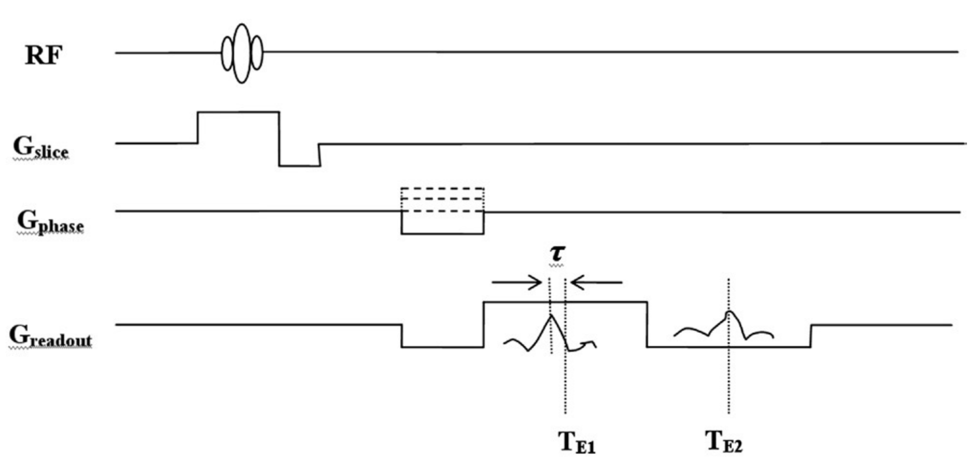

Fig. 2. Simplified dual-echo pulse sequence with back-to-back G_{readout} pulses with opposite polarity. Readout data from T_{E1} may be off-center relative to data from T_{E2}. The first-order phase shift correction term α is proportional to the time delay τ.