Off-Resonance Artifact Correction with Convolution in k-space (ORACLE)

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Introduction

Despite their advantages in imaging speed and motion compensation, non-Cartesian imaging methods (e.g. radial and spiral) suffer from their sensitivity to off-resonance artifacts. While B_0 inhomogeneity usually does not introduce any visible artifact for non-EPI Cartesian scans, it can cause severe blurring in radial and spiral images, particularly when a longer readout window is used. For EPI, B_0 inhomogeneity could cause severe geometric distortion.

In this work, a rapid <u>o</u>ff-<u>r</u>esonance <u>a</u>rtifact <u>c</u>orrection method is proposed based on data convolution in k-space (ORACLE). When compared with the widely-used conjugate phase correction technique [1-2], the proposed method does not require a separate B_0 map. This reduces the scan time and makes the method insensitive to possible motion between the B_0 mapping and the actual imaging scan. Phantom and *in vivo* results demonstrated the applicability of the proposed method to radial, spiral and EPI datasets.

Theory

For an arbitrary k-space sampling trajectory $k(t)$, the Fourier encoding equation for a k-space signal f in the presence of B_0 inhomogeneity $\omega(r)$ is:

$$f[k(t)] = \int \rho(r)\exp[-jk(t)r]\phi(r,t)dr, \qquad \phi(r,t) = \exp[-j\omega(r)t]. \qquad (1)$$

At any given readout time point t, the encoded spatial signal is the original signal $\rho(r)$ multiplied by a spatial-dependent phase term $\phi(r)$. Since multiplication in image-space is equivalent to convolution in k-space, an artifact-free k-space signal f_0 can be derived by convolving the corrupted signal f with a kernel Φ:

$$f_0 = f \otimes \Phi, \qquad \Phi = FT[\exp[j\omega(r)t] \qquad (2)$$

The calibration of the kernel could be performed using a separate B_0 mapping scan. Alternatively, the imaging data itself (for radial and spiral) or a reference scan (for EPI) could be used for kernel calibration in a procedure similar to the auto-calibration in the GRAPPA parallel imaging method [3], as will be shown next.

Methods

The procedure to apply ORACLE to radial, spiral and EPI data is shown in Fig. 1. A radial dataset acquired with alternate readout directions allows self-calibration for all ORACLE kernels (Fig. 1a). Data is first separated into two k-spaces with opposite radial spoke directions. Each k-space is then further divided into concentric segments with distinct readout time and off-resonance phase terms. The kernel correcting for the segment with a readout time of T is derived by using two segments with readout times of T/2 and –T/2 as the source and the target during the calibration process. Fig 1b-c shows the k-space segmentation pattern for EPI and spiral datasets, respectively. Unlike radial datasets, however, only one basis kernel Φ_0 is calibrated and used to estimate a field map $\omega(r)$. Kernels for different segments are then determined using Eqn. (2). For EPI scans, an echo-train with a shifted echo time ΔTE is used to calibrate Φ_0 [4]. For spiral scans, a spiral in-out sequence which samples a small circle near the k-space center at two different echo times will allow self-calibration.

To investigate the performance of the proposed method, both phantom and in vivo brain studies were performed on a 3.0T clinical scanner (Achieva, Philips, Best, Netherlands), using an eight-channel head coil (Invivo, Gainesville, FL) and a multi-slice 2D T_2-weighted gradient echo sequence. Scan parameters: FOV 230×230 mm, slice thickness 5mm, TR/TE = 500/16 ms, flip angle = 18^0. Radial, spiral and EPI datasets were acquired followed by the ORACLE correction. The kernel size was fixed to 8 × 8 for all datasets. Both radial and spiral datasets were segmented into 16 concentric rings with different convolution kernel, while EPI data was corrected line by line. In this preliminary study, a separately acquired B_0 map is used for Φ_0 calibration for spiral datasets.

Results and Discussions

ORACLE correction results for radial, EPI and spiral datasets were shown in Fig. 2. For radial and spiral images, blurring caused by the B_0 inhomogeneity was removed after ORACLE correction. For the EPI image, significant geometric distortion was corrected with ORACLE. The resulting image quality is similar to Cartesian images which are acquired using much longer scan times.

The computation time for ORACLE is about 5 seconds for an 8-channel 256 × 256 dataset. This process can be further accelerated by using a channel compression technique [5]. Alternatively, a channel combination scheme can be applied before ORACLE processing, if the coil sensitivity maps are available. In conclusion, a rapid off-resonance artifact correction method is proposed based on k-space data convolution. Results in radial, spiral and EPI datasets demonstrate the potential of this novel unified approach.
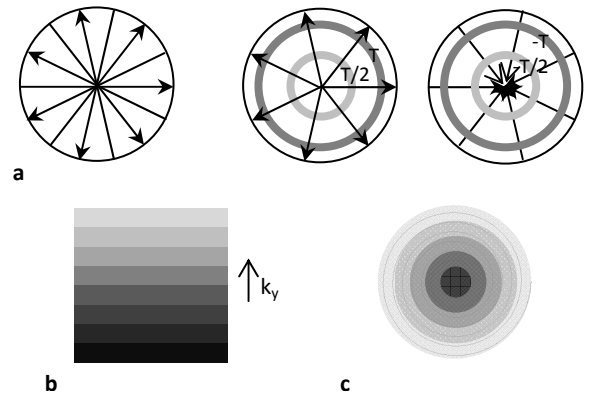

Figure 1 ORACLE procedures. (a) For a radial trajectory with alternate readout directions, data is separated into two k-spaces with opposite spoke directions. Each k-space is then further divided into segments with distinct readout time. The kernel to correct for segment T is calibrated using segment T/2 and –T/2. (b-c) k-space segmentation schemes for EPI (b) and spiral (c) datasets.
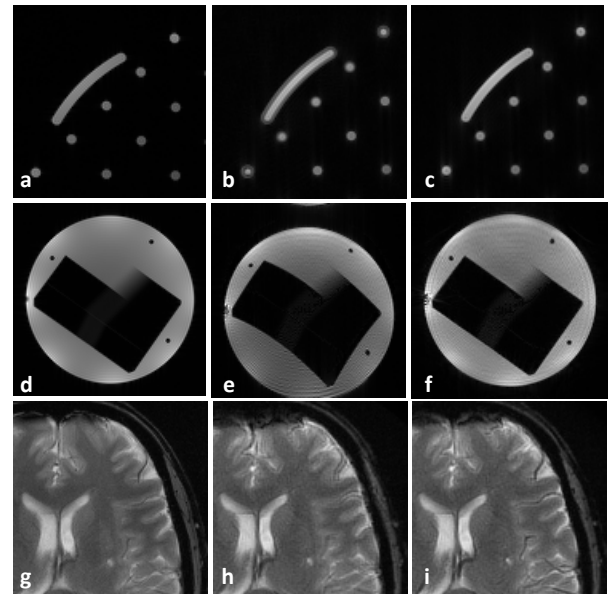

Figure 2 ORACLE correction results. (a-c): Cartesian (a) and radial images without (b) and with (c) correction. (d-f): Gradient echo (d) and EPI images without (e) and with (f) correction. (g-i): *In vivo* Cartesian (g) and spiral brain images without (h) and with (i) correction.

References

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