Effective Removal of fMRI Nyquist Artifact Using Temporal Domain Data Mixing / Filtering

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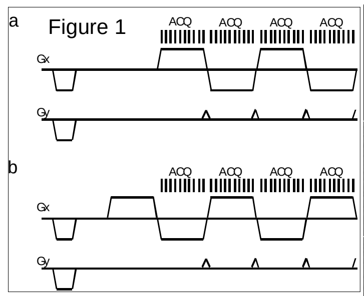
Introduction

Because of the odd-even-echo asymmetry in echo-planar imaging (EPI), images reconstructed with Fourier transformation are usually affected by the Nyquist artifact. This artifact impacts EPI based functional MRI data in two ways. First, it induces mis-representation of spatial information, and may lead to inaccurate interpretation of fMRI data. Second, the Nyquist artifact decreases the signal-to-noise ratio and thus the functional sensitivity. It has been reported that the Nyquist artifact can be reduced with various approaches, such as pulse sequence calibration [1] and post-processing with nonlinear phase correction [2]. However, effective removal of Nyquist artifact (originating from high order eddy current) usually requires a higher computation cost or users' manual interaction [2], which limits the performance of real-time or near real-time fMRI data processing in surgical guidance or neurofeedback research. In general, a faster and more effective Nyquist artifact correction method is desirable in EPI based functional MRI studies.

This article presents a novel approach for an effective removal of the Nyquist artifact in functional MRI. In the proposed method, EPI data at odd and even functional time points are acquired with opposite readout gradient polarities, and therefore the pattern of Nyquist artifact alternates during dynamic scans. The time-varying Nyquist artifact can then be removed with either temporal domain data mixing / filtering or conventional nonlinear phase correction. The proposed technique is especially valuable for fMRI based neurofeedback and pre-surgical evaluation, in which fast reconstruction of high-quality functional data is needed.

Theory and Method

In the proposed method, the image phase terms of the Nyquist signals are made to alternate during dynamic scans, so that the Nyquist signals can be removed with temporal domain data processing. This is achieved by acquiring EPI data at odd and even functional time points with opposite readout gradient polarities, as shown in Figure 1, which was originally developed by Hu and Le for nonlinear phase correction [3]. Reconstructed images (with Fourier transformation) corresponding to odd and even functional time points can be represented by Equations 1 and 2 [2], indicating that the phase term of the Nyquist signals varies between two consecutive scans, while that of parent signals does not change.



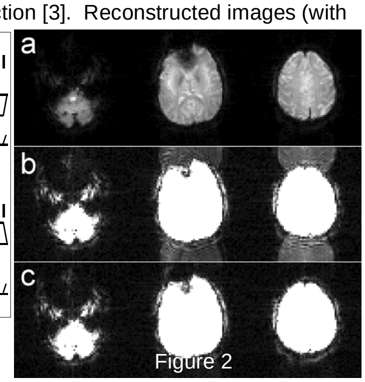


Figure 2

$$I_1(x,y) = \frac{\rho(p,q)}{2} + \frac{\rho(p,q-\frac{FOV}{2})}{2} + \frac{\rho(p,q)}{2}e^{i\Theta(p,q)} - \frac{\rho(p,q-\frac{FOV}{2})}{2}e^{i\Theta(p,q-\frac{FOV}{2})}$$
$$= \frac{\rho(p,q)}{2}(1+e^{i\Theta(p,q)}) + \frac{\rho(p,q-\frac{FOV}{2})}{2}(1-e^{i\Theta(p,q-\frac{FOV}{2})}) \quad (1)$$
$$I_2(x,y) = \frac{\rho(p,q)}{2} - \frac{\rho(p,q-\frac{FOV}{2})}{2} + \frac{\rho(p,q)}{2}e^{i\Theta(p,q)} + \frac{\rho(p,q-\frac{FOV}{2})}{2}e^{i\Theta(p,q-\frac{FOV}{2})}$$
$$= \frac{\rho(p,q)}{2}(1+e^{i\Theta(p,q)}) + \frac{\rho(p,q-\frac{FOV}{2})}{2}(e^{i\Theta(p,q-\frac{FOV}{2})}-1) \quad (2)$$

Because of the phase variation of Nyquist signals, the Nyquist artifact can be effectively eliminated by simply averaging (i.e. temporal domain data mixing) the data from two consecutive time points, as indicated in Equations 1 and 2. This reconstruction approach is well suited for real-time fMRI display, since the temporally smoothed functional data with minimal ghost artifact can be obtained with a very low computation cost.

The Nyquist artifact can also be removed by low-pass filtering the functional data along the temporal domain, since the varying Nyquist signals correspond to a high-frequency fluctuation over time. The proposed temporal domain low-pass filtering approach is similar to that reported by Madore for his partial Fourier MRI artifact correction technique [4], in which the effective temporal resolution is not reduced. It should be emphasized that functional data acquired with the proposed strategy can also be processed with conventional Nyquist artifact correction methods.

The proposed Nyquist artifact removal techniques were implemented in a 3T MR scanner (GE Medical Systems), and evaluated with a finger-tapping motor fMRI study on three healthy subjects. Functional data reconstructed with the proposed and conventional Nyquist correction techniques were then compared in terms of the residual ghost levels and the derived BOLD activation patterns ($p<10^{-5}$ in t-test).

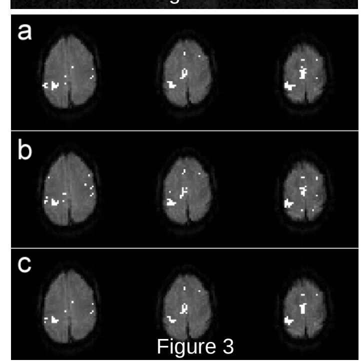


Figure 3

Results and Discussion

Figure 2 compares the EPI image quality of three selected slices, corresponding to different Nyquist artifact removal methods. Images obtained with nonlinear phase correction (based on a non-phase encoded reference scan) were shown in Figure 2a. By adjusting the display scale, the Nyquist artifacts are visible, as shown in Figure 2b (ghost-to-signal ratios: 2.9%, 7.9%, 11.9% in three slices). Using the temporal-domain data processing algorithm, the Nyquist artifacts can be reduced more effectively. For example, images obtained with temporal-domain low-pass filtering are shown in Figure 2c (ghost-to-signal ratios: 1.6%, 2.2%, 1.7%), with the same display scale of Figure 2b. No apparent Nyquist artifact is identified with this display scale. Using temporal-domain data averaging, the Nyquist artifacts can be suppressed to a level comparable to Figure 2c (ghost-to-signal ratios: 1.4%, 1.9%, 1.9%; images not shown), indicating the effectiveness of the proposed artifact correction technique.

Functional maps in three selected slices from a subject, reconstructed with different Nyquist artifact removal methods, are presented in Figure 3. Figure 3a show the activation maps derived from EPI data processed with conventional nonlinear phase correction (based on a non-phase encoded reference scan). Activation in sensorimotor area and supplementary motor area is identified. Functional maps derived from EPI data processed with temporal-domain low-pass filtering algorithm and temporal-domain averaging are presented in Figures 3b and 3c, respectively. It can be seen that, in this data set, virtually the same activation areas are identified with three Nyquist artifact removal methods, even though one of the data sets actually presents the temporally smoothed images (Figure 3c). Because of its reduced computation cost and data processing, the new temporal domain data mixing approach (Figure 3c) is more suited for real-time or near real-time fMRI data processing. It should be emphasized that the proposed acquisition strategy (Figure 1) is compatible with conventional Nyquist artifact removal methods based on nonlinear phase correction.

References

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