A correction of amplitude variation using navigators in an interleave-type multi-shot EPI at 7T

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Introduction. Interleave-type multi-shot EPI has some artifacts due to phase discontinuities and amplitude variations [1]. In previous studies, echo shifting technique was proposed to solve phase discontinuities along phase-encoding among segments in k-space, and it works well. For reducing amplitude variation, dummy shots are added prior to main shots for the steady-state. Another technique is variable flip angles to give same transverse magnetization at every shot in short repetition time, which reduce the perturbations among segments on the k-space [2]. An amplitude variation along phase-encoding on k-space causes not only the aliasing of image but also the low response of functional magnetic resonance image (fMRI). In previous study [3], the amplitude correction was proposed, which was performed on a point-by-point basis in the projection space. In this paper, we propose the technique to compensate amplitude variations on k-space comparing the energy of navigators in interleave-type multi-shot EPI with variable flip angle.

Methods. **(Pulse sequence)** The interleave-type multi-shot EPI with variable flip angle is that all segments are obtained during single T_R like a snapshot EPI, so called all-shot-in-one-T_R. Echo-shifting between segments was applied to the EPI. Navigator with 3 echoes in EPI was obtained without phase-encoding gradient prior to gather echo train in k-space. We obtained navigators of every segment.

(Correction) These navigators were used for an intra-segment correction and an inter-segment correction. An intra-segment correction means 1-D phase correction along read-out direction. Using navigator, following echo train was corrected by a conventional technique. This intra-segment correction has been essential on a reconstruction of EPI. All of k-space was done by intra-segment correction (phase correction) using navigator. For inter-segment correction, the amplitude variations among segments were evaluated by comparing the energy of signals of navigator of segment, and adjusted amplitude level of echo trains of each segment. The process is described by:

$$E_{N_i} = \alpha_{1,i} \cdot \sum_{r=0}^{RO,Max.-1} \left|N_{1,i,r}\right|^2 = \cdots = \alpha_{n,i} \cdot \sum_{r=0}^{RO,Max.-1} \left|N_{n,i,r}\right|^2$$

In equation, N and E_N mean navigator and energy of signal of navigator, respectively. Subindices n, i, and r in equation denote the number of segments, i-th echo of navigator, and r-th sample along read-out direction, respectively. *RO,Max.* is the number of samples along read-out direction. $\alpha_{n,i}$ means the ratio of energy of i-th echo of navigator of n-th segment to E_{Ni}. The first segment and the first echo of navigator were chosen as criterion, set $\alpha_{1,1}$=1, then calculated other ratio, $\alpha_{2,1}$ to $\alpha_{n,1}$. When echo trains of each segment of k-space are adjusted using these values ($\alpha_{n,1}$), the amplitude correction was done by dividing complex number of signals of n-th segment by the square root of $\alpha_{n,1}$. The dividing do not affect the phase of signals in k-space, because the square root of $\alpha_{n,1}$ is a positive and real value. For comparison, off-line reconstruction was performed with and without the amplitude correction using raw data obtained from scanner.

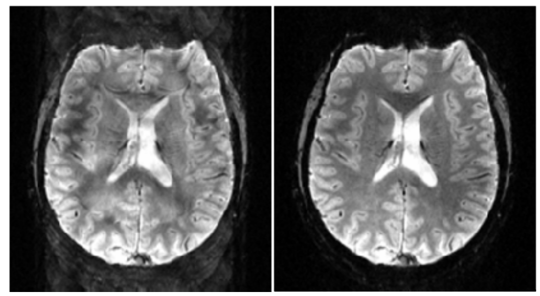

Figure 1. The acquired brain images reconstructed without the amplitude correction (left) and with (right).

(Data acquisition) We acquired data of slices with 8 segments (multi-shot GRE-EPI, all shot in one T_R, variable flip angle, matrix 220x220; FOV 220mm^2; Sl.thick.=2mm ; T_E=18ms; T_R=3500ms) in 7T magnetic field (MAGNETOM, SIEMENS, Erlangen). Furthermore, we acquired fMRI data of slices with 3 segments of other multi-shot EPI (multi-shot GRE-EPI, all shot in one T_R, variable flip angle, matrix 220x220; FOV 220mm^2; Sl.thick.=2mm; T_E=23ms; T_R=666ms; T_A=2000ms, 96 repetitions during 192sec.) in the same magnetic environment.

(fMRI stimulus and analysis) The visual stimulus was a high-contrast, flickering (8Hz) checkerboard. The rest period was a cross with a black background. The rest period and the visual stimulus alternated every 12 seconds, which are repeated 8 times. For analysis, Statistical Parametric Mapping (SPM, ver.8) software was used on MATLAB. All data of fMRI was realigned. Model specifications for estimating functional response were made from our experiment protocol. We evaluated the correlation with the expected homodynamic response function and obtained pixels with p-value was less than 0.001.

Results. In figure 1, images were obtained using all-shot-in-one-T_R EPI. Images were reconstructed without (left) and with (right) amplitude correction. The aliasing of image is observed at the original image (left), while it is eliminated at the amplitude-corrected image (right). Figure 2 shows that the corrected images (upper) have more activation of fMRI than the uncorrected. We chose a single pixel in the uncorrected and corrected images as shown in figure 2. The location of the pixel has no activation in the uncorrected, but some activation in the corrected for $p<0.001$. In the lower graphs of figure 2, a time-course of the single pixel in the corrected data is more separate of signal level between the rest and stimulus period and less signal variation on the stimulus period than in the uncorrected data.

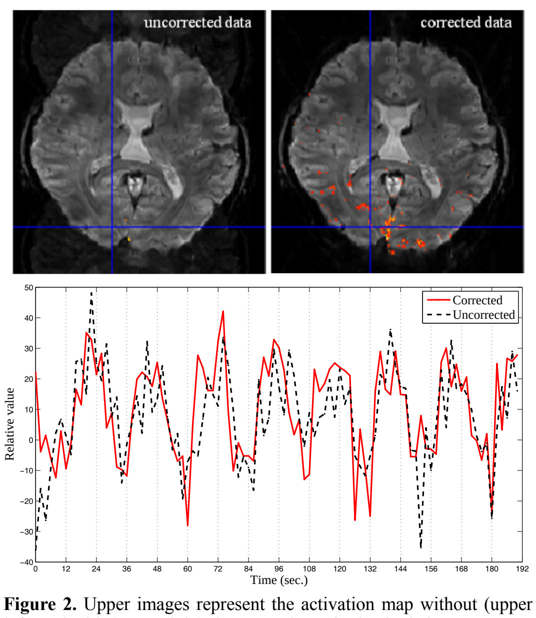

Figure 2. Upper images represent the activation map without (upper left) and with (upper right) the correction. Single pixel chosen was not activated in the uncorrected, but done in the corrected. Two time-courses are plotted about the pixel.

Discussions and conclusions. The present work demonstrates the application of an amplitude correction between segments in interleave-type multi-shot EPI with all-shot-in-one-T_R. Acquiring navigator has been essential for phase correction, and we re-used navigators of segments to compensate the amplitude variation between segments in not only conventional T2* image but also images for fMRI on k-space. Variable flip angle of excitation pulse is a basic technique to achieve the same-distributed transverse magnetization in short interval between segments, and the proposed amplitude correction as a post-processing adjusts the amplitudes of segments to hold the same transverse magnetization. In high-resolution EPI images, the length of echo train or the number of segments are increased. The increased length of echo train leads to increase a time interval between segments, then T_1 effects become significant and the amplitude correction is required. On the other hand, increasing the number of segments may affect SNR of images with high-resolution, because the longitudinal magnetization is divided by the number of segments in all-shot-in-one-T_R. The proposed amplitude correction method would be robust against noise, because this method calculates the energy of navigators and compares them. We believe that it will be possible to measure high-resolution fMRI images using multi-shot EPI and the proposed correction.

Reference. [1] F. Hennel, Multiple-Shot Echo-Planar Imaging, Magnetic Resonance 9(1):43-58(1997) [2] D. N. Guilfoyle et al., Interleaved snapshot echo planar imaging of mouse brain at 7.0T, NMR Biomed. 19:108-115(2006) [3] S. G. Kim et al., Fast Interleaved Echo-Planar Imaging with Navigator: High Resolution Anatomic and Functional Images at 4 Tesla, Magn. Reson. Med. 35:895-902(1996)

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