Variable Flip angle Single-slab 3D GRASE with Phase-independent Image Reconstruction

H. Kim[1], S. Park[2], D-H. Kim[1], and J. Park[3]

[1]Electrical and Electronic Engineering, Yonsei University, Shinchon-Dong, Seoul, Korea, Republic of, [2]Medical Science, Yonsei University, Seoul, Korea, Republic of, [3]Radiology, Yonsei University, Seoul, Korea, Republic of

Introduction: Single-slab 3D turbo/fast spin echo (SE) imaging (1), which employs short non-selective pulses and variable flip angles in the refocusing pulse train, was recently developed to increase imaging efficiency. Parallel imaging based under-sampling speeds up data acquisition but directly trades off with signal-to-noise ratio (SNR). In this work, to enhance the imaging efficiency without the direct trade off with SNR, we propose variable-flip-angle single-slab 3D GRASE imaging, incorporating multiple echo planar imaging (EPI) readouts into a framework of turbo/fast SE imaging and developing phase-independent image reconstruction to avoid phase-discontinuity related artifacts.

Sequence design and Reconstruction: The proposed single-slab 3D GRASE pulse sequence is shown in Fig. 1a, consisting of short non-selective excitation radio-frequency (RF) pulse followed by non-selective refocusing pulses trains with variable flip angles and EPI readout gradients. Variable flip angles are calculated using a flat prescribed signal evolution specific to gray matter (GM). EPI readout gradients are incorporated to collect multiple phase encoding signals. To increase a T1-weighted contrast as an example of the proposed pulse sequence, a flip-down composite restore pulse train is applied at the end of the refocusing pulse train to achieve partial inversion recovery for the next excitation (2). Multiple phase encoding signals for each RF pulse are denoted using the subscripts of refocusing pulse number and EPI echo number. Multiple echoes for each RF pulse are grouped (e.g., e_{11}, e_{12}, e_{13} for the 1st refocusing RF pulse and three EPI echoes) and then linearly phase-encoded in k-space while those located in the central region of k-space are acquired with the same phase encoding. As a result, full k-space is evenly distributed into multiple echoes, wherein the central region of k-space is sampled at the Nyquist rate for all the EPI echoes while the peripheral region of k-space is under-sampled by an EPI factor and the under-sampled point is shifted with increasing EPI echoes (Fig. 1b). Since phase encoding signals are reordered as mentioned above, amplitude modulations along the phase encoding direction are smooth while phase modulations the same direction have discontinuities, potentially resulting in ghosting artifacts. To tackle the phase discontinuity induced problems, phase-independent image reconstruction is performed, in which each echo k-space is regenerated by GRAPPA-like parallel imaging technique employing both within-and between-group k-space correlations and then averaged to retain SNR efficiency (Fig. 1c).

Materials and Methods: Numerical simulation of the Bloch equation is performed to investigate amplitude and phase modulations in k-space along the phase encoding direction. The phase accumulation between two neighboring EPI echoes was set to 0.1π radian. Brain data is acquired in a healthy volunteer at 3T whole-body MR scanner (MAGNETOM Trio, Siemens Medical solutions) using both conventional single-slab 3D turbo SE imaging (1) and the proposed single-slab 3D GRASE for comparison. The imaging parameters of the proposed imaging were: TR/TE = 630/22ms; FOV = 256x208x160 mm^3; resolution = 1x1x1mm^3; echo train length (ETL) = 25; EPI factor = 3; shots/partition = 4; echo spacing (ESP) = 6.74 ms; bandwidth = 930Hz/Pix; imaging time = 6:45 min. The imaging parameters specific to conventional imaging were: TE = 10ms; no EPI factor; shot/partition = 10; ESP = 2.92ms; bandwidth = 781Hz/Pix; and imaging time = 16:55min.

Result: Numerical simulations in Fig. 2 show that amplitude modulation is smooth while phase modulation produces severe periodic discontinuity, resulting in oscillating point-spread-function (PSF) and thus potentially leading to ghosting artifacts. Fig. 3 represents that phase independent reconstruction preserve contrast and reduce ghosting artifact. Fig.4 shows that comparison of SNR considering data acquisition time. Proposed pulse sequence shortens data acquisition time rather than 3D turbo SE imaging, and also maintains contrast rather than under-sampled 3D turbo SE imaging.

Conclusion: The proposed variable-flip-angle single-slab 3D GRASE has been successfully demonstrated with phase-independent image reconstruction, enhancing imaging efficiency with no apparent loss of signal and image contrast. However, the proposed method needs to be further investigated for a variety of clinical applications. Since the proposed method generates T2- and T2*-weighted images simultaneously, it is expected that the proposed method not only enhances imaging efficiency but also provides susceptibility-induced contrast.

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References: 1. Mugler et.al, Proc ISMRM, 203; 2003; 2. Park et al. MRM, 58:982, 2007;

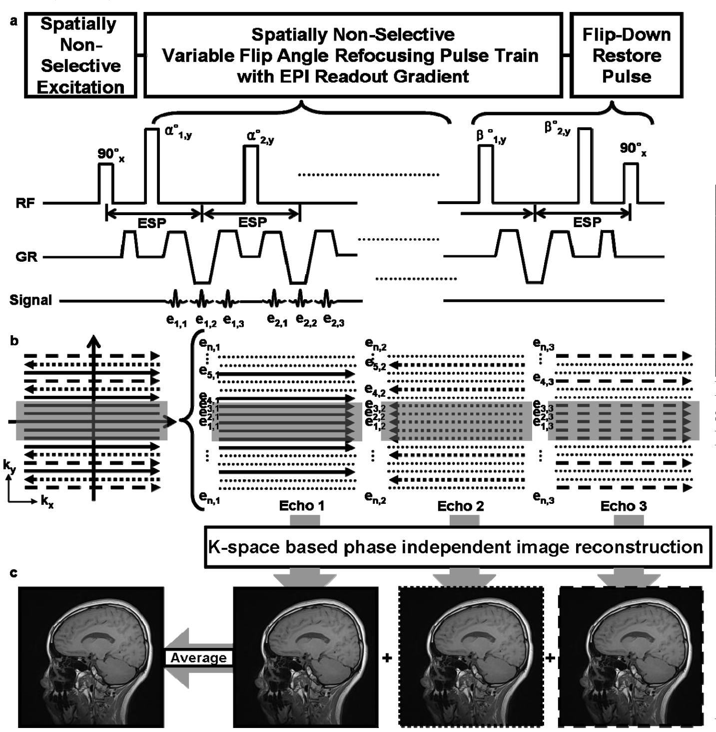

Fig. 1. Timing diagram of the proposed Single-slab 3D GRASE pulse sequence (a) and the flow chart of phase-independent image reconstruction (b,c).

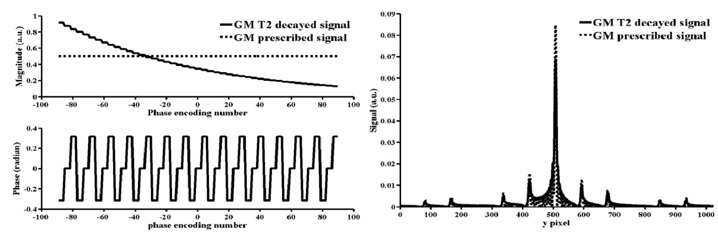

Fig. 2. Simulated signal from a point source at the image center along the phase encoding step. PSF derived from the simulated signal.

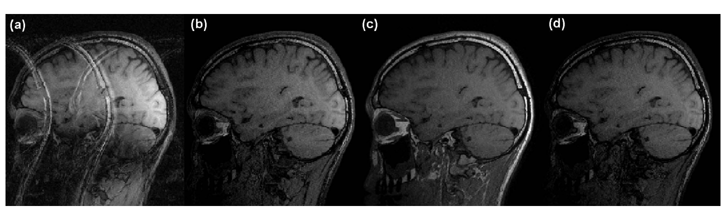

Fig. 3. Note that, overlapped Nyquist sampled region of each echo is averaged in k-space (a). Phase-independently reconstructed image using Echo1 (b), Echo2 (c), Echo3 (d).

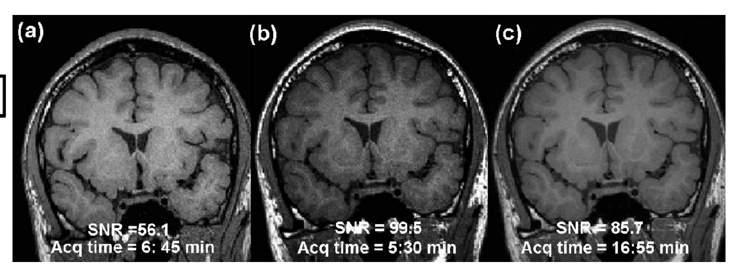

Fig. 4. T1-weighted image: proposed pulse sequence (a), under-sampled 3D turbo SE imaging (b), 3D turbo SE imaging (c).