Efficient Phase-Encoding for 3D Turbo-Spin-Echo Imaging with Very Long Echo Trains

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Introduction: For the conventional phase-encoding method used with turbo/fast spin-echo (TSE) imaging, echoes from a given excitation are allocated in an interleaved fashion to a specific line of *k* space along one phase-encoding direction. This approach becomes very inefficient for 3D-TSE imaging with a large number of echoes, such as can be achieved by using refocusing RF pulses with variable flip angles [1]. For example, by using an optimized configuration for T2-weighted imaging, up to several hundred echoes can be acquired following each excitation RF pulse. The goal of this work was to develop a phase-encoding scheme for 3D-TSE imaging that permits efficient use of echo trains for which the number of echoes is on the order of the number of in-plane phase-encoding steps.

Sequence Design: The basic principle of our phase-encoding scheme for very long echo trains is to interleave the echoes from a given excitation (or "shot") along both the in-plane and through-plane phase-encoding directions such that the product of the echoes allocated along the two directions equals the total echo train length. Figure 1 shows examples for cases when the maximum echo train length (ETL) for each shot is either 2/3 or 3/2 of the number of in-plane phase-encoding steps (N_{2DPE}). (For simplicity, the examples in Fig. 1 use an artificially low number (30) of in-plane phase-encoding steps. In practice, the ETLs and the number of in-plane phase-encoding steps would be approximately an order of magnitude larger.) For the first case (Fig. 1a), the ETL is 2/3 of N_{2DPE}. For conventional TSE phase encoding, 2 shots would be used to fill each line of *k* space along the in-plane phase-encoding direction and thus 4 shots would be required to fill the *k*-space data for the k_{3DPE} coordinates labeled i and j in Fig. 1a. Either 5 echoes for each shot would be discarded, or the number of echoes per shot would be decreased from the maximum of 20 to 15. For the proposed phase-encoding scheme, the echoes in each shot are allocated to both of the k_{3DPE} coordinates as well as being interleaved along the in-plane phase-encoding direction, permitting all echoes for each shot to be used. For this arrangement, the acquisition is accelerated (compared to conventional SE imaging) by a factor of 10 in the in-plane direction and thus the corresponding in-plane "turbo factor" (TF) is 10. By analogy, the acceleration by a factor of 2 in the through-plane (slice) direction corresponds to a slice TF of 2. For the example in Fig. 1a, the proposed phase-encoding scheme reduces the total acquisition time by 25% compared to conventional phase encoding. A similar analysis applies to the example in Fig. 1b, where the ETL is 3/2 of N_{2DPE}. For conventional TSE phase encoding, one shot would be used to fill each line of *k* space along the in-plane phase-encoding direction and 3 shots would be required to fill the *k*-space data for the k_{3DPE} coordinates labeled i, j and k in Fig. 1b. For the proposed phase-encoding method, the echoes in each shot are allocated to all three of the k_{3DPE} coordinates (slice TF = 3) as well as being interleaved along the in-plane phase-encoding direction. For the example in Fig. 1b, the proposed phase-encoding method thus reduces the total acquisition time by 33% compared to conventional phase encoding.

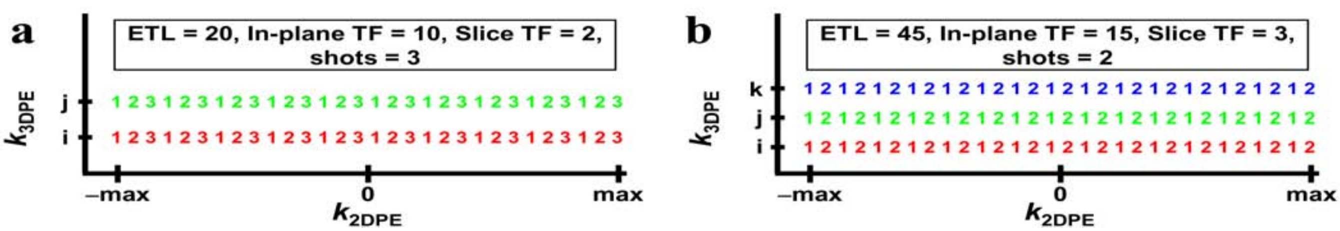

Figure 1. Examples of the proposed phase-encoding scheme. Echoes from the first shot are denoted by "1", from the second shot by "2", and so on. The number of in-plane phase-encoding steps and ETLs are reduced from practical values by about a factor of 10 to simplify the diagrams. (**a**) Each ETL of 20 is allocated among two values of k_{3DPE}; odd echoes (red) are used for coordinate i and even echoes (green) for j. (**b**) Each ETL of 45 is allocated among three values of k_{3DPE}; every 3rd echo starting with the 1st (red) is used for coordinate i, every 3rd echo starting with the 2nd (green) for j, and every 3rd echo starting with the 3rd (blue) for k.

Methods: A single-slab 3D-TSE pulse sequence that incorporated the proposed phase-encoding scheme was implemented on a 1.5-T whole-body scanner (Avanto; Siemens Medical Solutions). The refocusing RF-pulse flip angles required to achieve a prescribed signal evolution (exponential decay, constant, exponential decay [1]) were calculated, based on the relaxation times for the selected reference tissue (brain gray matter) and the timing parameters for the pulse sequence, by using a rapid calculation algorithm that was integrated into the sequence [2]. The echo time for the center of *k* space (TE_{eff}) was set to the center of the prescribed signal evolution. This particular signal evolution shape has been previously demonstrated to produce contrast that is comparable to conventional T2-weighted spin-echo imaging [1]. Following preliminary testing in water phantoms, the 3D-TSE pulse sequence was used to acquire single-slab 3D image sets of the brains of healthy volunteers after obtaining informed consent.

Results: Representative images from a 3D dark-fluid acquisition of the whole brain, acquired with a slice TF of 3, are shown in Fig. 2. For this example, the ETL equals 3/2 of N_{2DPE}, analogous to Fig. 1b (parallel imaging was used along the in-plane phase-encoding direction to reduce the required number of views). No significant artifacts attributable to the phase-encoding scheme were observed in either the phantom or *in-vivo* image sets.

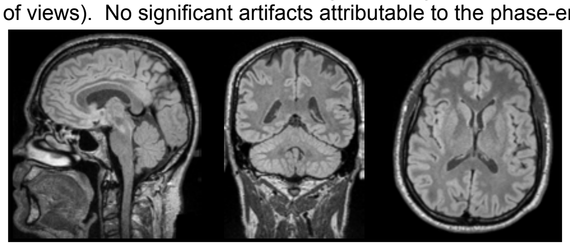

Figure 2. Images acquired using the proposed phase-encoding scheme with an in-plane TF of 57 and a slice TF of 3. The dark-fluid (FLAIR) acquisition with 1.0 x 1.0 x 1.1-mm resolution was acquired in 8.4 min. Parameters included: TR/TE_{eff}/TI, 6000/354/2200 ms; matrix, 256 x 204 x 144; ETL, 171; echo-train duration, 700 ms; 7/8 partial Fourier in slice-encoding direction. Parallel imaging (acceleration factor 2) was used along the in-plane phase-encoding direction to reduce the required number of views to slightly more than one-half of the corresponding matrix size (204→114).

Conclusions: We developed a phase-encoding scheme for 3D-TSE imaging that makes efficient use of the very long echo trains that can be achieved with variable-flip-angle refocusing RF pulses. By accelerating the acquisition along both the in-plane and through-plane phase-encoding directions, this method takes full advantage of the reduction in imaging time offered by such long echo trains and, when combined with parallel imaging strategies such as GRAPPA or SENSE, yields imaging times that are clinically practical for single-slab 3D-TSE imaging of large volumes such as the whole brain.

References: 1. Mugler JP, Kiefer B, Brookeman JR. Proc ISMRM 8 (2000); 687. 2. Mugler JP, Meyer H, Kiefer B. Proc ISMRM 11 (2003) 203.

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