Automatic Functional and Anatomical Registration for fMRI using Optimized 3D Flyback Echo Planar Imaging

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INTRODUCTION: Echo planar imaging (EPI) is the most widely used method for functional MRI (fMRI). However, functional images are often distorted because EPI is highly sensitive to field inhomogeneities, eddy currents, and gradient delays. The slow traversal in *k*-space along the phase encode (PE) direction exacerbates these distortions. Hence, functional and anatomical image registration is complicated by these distortions and by the fact that each image is obtained with a different imaging sequence. Special fMRI sequences [1, 2] as well as linear [3, 4] and non-linear [5-7] registration methods have been developed to address this problem. However, none of these methods automatically yield usable anatomical and functional images that may be directly overlaid onto each other with no post-processing. This work investigates the use of an optimized 3D flyback EPI trajectory with echo time shifting (ETS) [8] to solve this issue efficiently and with no post-processing. Here, the robustness of flyback EPI to eddy currents and gradient delays is combined with the high SNR efficiency and reduced signal dropout offered by passband steady-state free precession (SSFP) fMRI [9-12], although the same optimization method applies to GRE BOLD. The result is high quality functional and high resolution anatomical images that have minimal distortions and are inherently self co-registered.

THEORY: In flyback EPI (Fig. 1), the phase accrued by off-resonant spins along the slow axis of *k*-space (k_y) causes distortions in the PE direction of the image. This phase accrual is proportional to the time taken to traverse the required extent in k_y. When phase accrual is linear over k_y, the functional and anatomical images will be self co-registered if the respective accruals are equal over their common extent in the k_y direction. This is illustrated in Fig. 2. ETS [8], which is a common solution employed to correct for ghosting in EPI, automatically imparts the linear phase modulation along the k_y axis. The proposed technique involves using ETS and optimizing a set of imaging parameters so that phase accruals of the anatomical and functional images are matched.

Table I summarizes acronyms used in the description that follows. Subscripts F and A correspond to functional and anatomical images, respectively. In fMRI, the bandwidth of the hemodynamic response, the required in-plane resolution, and the range of TRs necessary for functional contrast [11] dictate the choice of $N_{RO,F}$, $N_{PE,F}$, ETL_F, P_F, and BW_F. Anatomical T1-weighted scans, on the other hand, allow a wide range of parameters. A set of scan parameters can then be chosen to induce a matched phase accrual in the anatomical scan (Fig. 2b). When the anatomical in-plane resolution is fixed, matching the phase accrual reduces to choosing three parameters: P_A, BW_A, and ETL_A. This task is made easier by constraints on the values of these parameters. ETL_A is constrained by the maximum TR for a T1-weighted image, while $P_A N_{PE,A}$ is limited to integers greater than $N_{PE,A}/2$, but less than $N_{PE,A}$. Further, BW_A is limited by the maximum sampling rate of the scanner. Hence, a simple grid search over valid values in the parameter space can be performed. The set that yields the smallest error in phase matching can then be chosen.

TABLE I: ACRONYMS

N_{RO}	Number of Readout points
N_{PE}	Number of PE lines
BW	Readout Bandwidth
ETL	Echoes per excitation
P	Partial *k*-space fraction

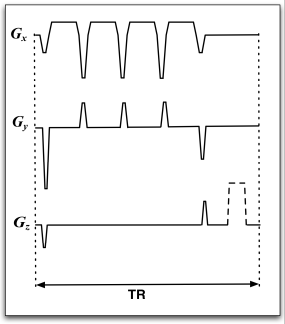

Figure 1: *3D Flyback EPI with echo train length 4. The crusher, denoted by the dotted trapezoid, is played out during the anatomical sequence, but not during SSFP fMRI.*

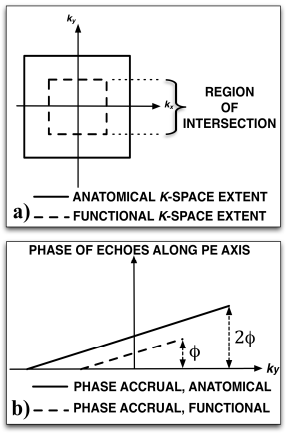

Figure 2: *Extent in k-space (**a**), and ideal phase accrual along ky axis (**b**). Here, the anatomical image has twice the resolution of the functional. For exact co-registration, twice the phase accrual has to occur over the extent of ky covered in the anatomical scan.*

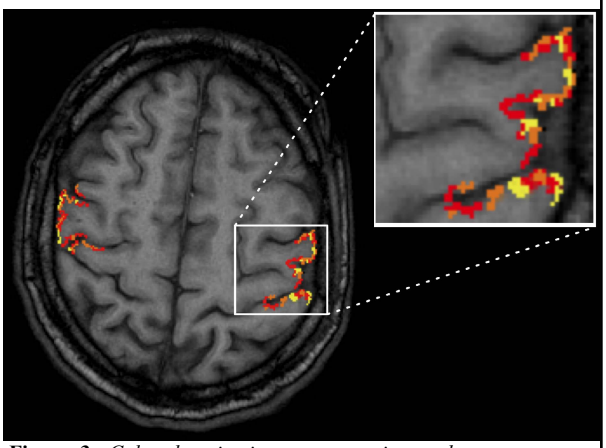

Figure 3: *Colored activation map superimposed onto anatomy. Both images are self co-registered and only a direct overlay of anatomical and functional images is required. Activations follow the sulcal and gray matter contours of the motor cortex.*

METHODS: The proposed method was tested on a 3 T GE Excite scanner (40 mT/m gradient strength with 150 mT/m/ms slew rate) using an eight-channel head coil.

Functional: An axial slab of the primary motor cortex (M1) was targeted, and the 3D flyback EPI trajectory in Fig. 1 was combined with a passband SSFP fMRI sequence. Imaging parameters were: TE/TR = 5/23 ms, 32 mm slab thickness, 2 mm slices, FOV = 19.2 x 19.2 cm^2, flip angle = 30°, $ETL_F = 8$, $BW_F = 83.3$ kHz, matrix size 128 x 128 x 16, and $P_F = 0.625$. The 3D volume was scanned every 3.7 s, and the traversal over the k_y axis of each 2D (k_x, k_y) plane was 25.9 ms. The task consisted of self-paced finger tapping with repeated thumb-to-index finger opposition movements with both hands. This was repeated for five ON/OFF blocks, each lasting 37 s.

Anatomical: A high resolution anatomical scan (0.75 x 0.75 x 2 mm^3) was performed over the same M1 region. The 3D flyback EPI trajectory was used with a spoiled gradient echo (SPGR) sequence with flip angle 45°. TE/TR were set to 10/42 ms for T1-contrast. The following imaging parameters were obtained using the proposed search: $ETL_A = 6$, $BW_A = 31.25$ kHz, and $P_A = 0.625$. The FOV, slab thickness, and number of slices were kept constant. This yielded a traversal time of 26.04 ms over the intersecting region of each 2D (k_x, k_y) plane, or a phase matching difference of 0.14 ms.

RESULTS & DISCUSSION: Figure 3 shows a slice from the experiment. The colored activation map was directly overlaid onto the anatomical scan. No other co-registration algorithm was applied to the data. Pertinent areas of activation have been enlarged. The activations follow the contours of the sulci and gray matter areas of the brain very closely. With an error of 0.14 ms, the self co-registration is accurate up to off-resonance frequencies of 7 kHz. For typical frequencies of 200–400 Hz, this corresponds to a misregistration of only 0.03–0.06 pixels. This is extremely robust and reliable. The proposed use of a 3D flyback EPI trajectory with passband SSFP fMRI and SPGR sequences and the simple grid search over parameters can provide high quality functional images that are inherently co-registered with anatomy.

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