

## Motion Correction of EPI sequences using their intrinsic high-frequency content

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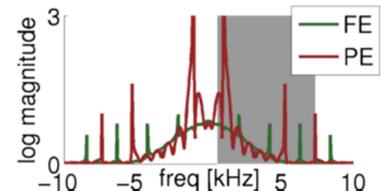
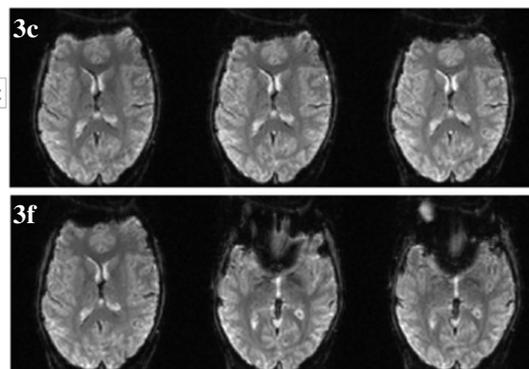
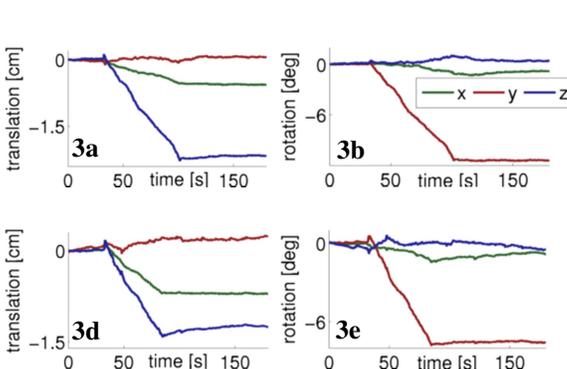
**Introduction:** Echo-planar imaging (EPI) sequences are widely used in BOLD fMRI, diffusion-weighted and perfusion imaging of the brain. These applications suffer from rigid body motion, which results in image artifacts and misalignment if not corrected for. Several methods have been proposed to prospectively account for that by updating the scan geometry to the head's position in real-time<sup>1-4</sup>. These methods perform sequence update by tracking external optical<sup>1-2</sup> or NMR-based markers<sup>3</sup> that are rigidly attached to the object of interest. NMR based methods typically rely either on tracking modules inserted between imaging readouts, which however prolong the scan time and suffer from unreliable field behavior at low frequencies. Recently, it has been shown that NMR field probes can also be accurately tracked by inserting high-frequency sinusoidal gradient oscillations ("tones") into empty bands of an existing imaging readout<sup>4</sup>. The strengths of the tones approach include its robustness against low-frequency field perturbations (main field drifts, physiologically-induced dynamic fields). However, gradient tones demand additional amplitude and slew rate from the gradient system which are no longer available for the image encoding task, requiring compromises in the image encoding sequence design. This is a problem in neuroimaging applications where the use of the maximally available gradient performance is crucial for efficient image encoding. However, EPI readouts intrinsically contain considerable power in the high frequency range which can be readily exploited for robust field probe tracking and prospective real-time sequence update without any compromise in the image encoding design. In this work, a method is proposed which extracts the field probe's coordinates directly from the high frequency content of an unmodified single-shot EPI readout for real-time prospective motion correction. The method's field probe localization precision is presented and real-time slice tracking is shown *in vivo*.

**Theory:** The spectrum of the derivative of an NMR field probe signal at position  $\mathbf{r}$  monitoring an EPI trajectory is given by  $\dot{\phi}(\mathbf{r}, f) = \gamma g_0(f) + \gamma \sum_{i=1}^3 g_i(f) r_i$  (Eq. 1).  $g_i$  denotes the complex-valued frequency component of the gradient waveform along the spatial dimension  $l$ ,  $g_0$  denotes its coupling into the homogeneous field component,  $r_i$  denotes the probe's coordinates,  $\dot{\phi}$  is the temporal derivative of the field probe signal, and  $\gamma$  the probe's gyromagnetic ratio. To calibrate the 4 unknowns,  $g_{0-3}(f)$ , the field evolution needs to be measured at 4 known positions. Recovery of the field probe coordinates is obtained by solving Eq. 1 for  $\mathbf{r}$  via a linear least-squares inversion. The frequencies used for localization can be selected freely: For instance, they may be excluded in order to be robust against low frequency field perturbations or if they contain too little power.

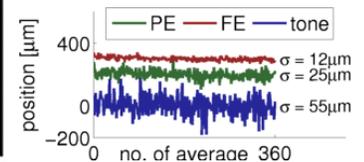
**Methods: Benchmarking** To assess the precision of the proposed method, an array of four <sup>19</sup>F NMR field probes<sup>5</sup> was placed onto an acrylic glass mount within the FOV of a 3T Philips Achieva MR system and a single-shot EPI sequence that could be used in fMRI was played out (resolution = 2.5 mm, FOV = 21 cm, T<sub>Acq</sub> = 40 ms, 360 repetitions). A sinusoidal gradient tone was added to the through-plane direction (nominal amplitude = 3 mT/m) for 3D position tracking. Reference positions for the calibration were acquired by measuring the probes' NMR frequency shifts under constant gradients. The frequencies used for localization in the frequency encoding (FE) direction ranged between 600 Hz and 7.4 kHz, the ones in the phase encoding (PE) direction ranged between 2 kHz and 8.4 kHz, and a single frequency of 9.6 kHz was used for the tone. The precision was obtained by computing the standard deviation of the calculated position for each axis. *In vivo experiment* In order to validate the method *in vivo*, the field probe array was mounted on a volunteer's head who was instructed to perform a single nodding movement during a 180 s long series of EPI readouts (15 slices, TE = 35 ms, TR = 3s, slice update rate = 5 Hz). Two repetitions were done, one with real-time sequence update and one without. The sequence update consisted of rotating all gradients and adjusting the RF excitation center frequency and was computed by performing a rigid body motion fit between the updated probes positions and the ones at the beginning of the scan. The probes positions were obtained using the proposed method. Additionally, k-space trajectory information was obtained from the same field probe data and used for image reconstruction. Images are shown for one representative slice acquired before, during, and after the nodding movement (after 6 s, 75 s, and 150 s).

**Results:** Fig. 2 shows the precision obtained with the PE gradient (25  $\mu\text{m}$ ), the FE gradient (12  $\mu\text{m}$ ), and the tone (55  $\mu\text{m}$ ), respectively. Figs. 3a and 3b show the rigid body motion of the head during the experiment with EPI based motion correction. The nodding motion is reflected by a rotation around the y axis (Fig. 3b, red graph) and a head translation in the negative z direction (Fig. 3a, blue graph). Fig. 3c illustrates the corresponding image reconstruction showing successful slice tracking. The images differ in their static B<sub>0</sub> distortions, which depend on the head's orientation and are visible at the top of Fig. 3c, which was not accounted for. Figs. 3d and 3e show the motion pattern in the case without motion correction. Note that the nodding motion was very well reproduced in both experiments, but it was somewhat smaller in the case without motion correction. Without slice tracking, motion causes the erroneous excitation of three entirely different slices, whose reconstructions are illustrated in Fig. 3f.

**Discussion:** It is proposed to use the field evolution of the EPI trajectory itself to perform prospective sequence updates by measuring the positions of a field probe array. The method is very precise (12  $\mu\text{m}$  in FE) and works without any modifications to the prescribed EPI gradients. The method allows to freely choose frequencies for probe tracking at which the MR system's field behavior is reproducible, which renders it very robust against undesired field fluctuations. It is particularly applicable in neuroimaging applications such as fMRI.



**Fig. 1** Logarithmic spectrum of an EPI trajectory with the frequency band used for probe tracking (gray).



**Fig. 2** Precision of the field probe localization with the proposed method.

**References:** [1] Zaitsev et al. Neuroimage 31:1038–1050. [2] Aksoy et al. MRM 59:1138–1150. [3] Ooi et al. MRM 62:943–954. [4] Haeberlin et al. Procs. ISMRM, 2012, #595. [5] Barmet et al. Procs. ISMRM, 2010, #216.

**Fig. 3 Top:** Head translation (left) and rotation (center) for the experiment with EPI based motion correction. Corresponding image reconstruction (right) shows successful slice tracking using the proposed method. **Bottom:** Head translation (left) and rotation (center) in the uncorrected case. The corresponding image reconstructions (right) show three different slices due to unaccounted head motion.