Continuous Motion Tracking and Correction Using NMR Probes and Gradient Tones

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Introduction: As an alternative to optical motion tracking, NMR probes fixed to the subject have been used for rigid body motion correction [3]. This approach requires an additional position encoding sequence which prolongs imaging time and disturbs or even prevents certain readouts. Those two drawbacks have recently been solved by using the image encoding sequence itself for position encoding and long-lived ^{19}F NMR field probes to monitor the dynamic field evolution in the tissue frame of reference during the entire imaging experiment [4]. While not adding additional sequence elements, the method fails to continuously track motion in directions without permanent gradient dynamics. Rather than adding additional sequence elements in time, they can also be added as gradient tones in the frequency domain as was recently proposed for auto-calibrated magnetic field monitoring [1,2]. In this work we propose to use NMR probes in conjunction with gradient tones for continuous motion tracking and correction of rigid subject motion. The method is shown using the example of spin-warp GRE and EPI head imaging. **Methods:** In order to be frequency-orthogonal to a gradient trajectory waveform, reference tones must be applied in frequency bands that are unaffected by the trajectory dynamics (Fig. 2). Sometimes this means filtering the gradient trajectory waveform to suppress its spectrum around the desired reference tone frequencies. A probe's phase is given by Eq. 1:

$$\varphi_i(t) = \gamma \sum_{j=1}^{3} r_j \int_0^t \vec{G}_{tone,j}(\tau)\,d\tau + \gamma \int_0^t \vec{G}_{readout}(\tau)\,d\tau + \omega_i t$$

, where $G_{tones,j}$ denotes the waveform of the reference tone j, $G_{readout}$ the imaging gradients and ω_i the probe's individual (static) off-resonance frequency. The gyromagnetic ratio of the probe nucleus is denoted by γ, and t represents time. The probe's coordinates can be obtained by projecting its phase evolution onto the three tones, rendering the sensitivity of the proposed approach proportional to the tones' amplitude, the probe's SNR and the square root of the observation time. In a first experiment, a 10-interleave EPI sequence (FOV = 230mm^2, resolution = 1mm^2, T_{acq} = 40.3ms, TE = 35ms, TR = 340ms) was stop band filtered between 6.7 kHz and 9.7 kHz and tones on the x, y, and z gradient axes were inserted at 7.2 kHz, 8.2 kHz and 9.2 kHz, respectively (Fig. 2). The tones amplitudes were 2mT/m. ^{19}F field probes with a T_2 of 80ms were used to monitor dynamic fields during the entire EPI readout. In a second experiment, the image encoding was a spin-warp GRE sequence (TR = 21ms, T_{acq} = 4.5ms, resolution = 0.825mm^2, FOV = 250mm^2, 303 readouts). The tones were inserted at 10.0 kHz (x gradient), 8.9 kHz (y gradient), and 7.8 kHz (z gradient) and the waveform was filtered between 4.4 kHz and 13.3 kHz. ^{19}F field probes with a T_2 of 7ms, tailored to the repetition time of the sequence, were used for magnetic field monitoring. All experiments were performed on a Philips 3T Achieva system. ***In-vitro experiments:*** The field probes were rigidly mounted onto a phantom which was placed inside an 8-channel head coil. 10 repetitions of the EPI sequence and 1 repetition of the FFE sequence were acquired to assess the precision of the method. ***In-vivo experiments:*** The field probes were rigidly mounted on a pair of head phones (Fig. 1), firmly fitting on a healthy volunteer's head. In the EPI experiment, the volunteer was given the task to combine rotational and translational head movements while reference tones-based motion correction was switched on. Image quality and congruence were compared between two distinct phases with little motion (Fig. 3). The total scan time was 140s (40 repetitions). In the FFE experiment, the volunteer was asked to combine rotational and translational motion of different intensity during 5 repetitions of the scan (total scan time = 32s). Motion correction was switched on and off for comparison and motion patterns were calculated (Fig. 4). All images were reconstructed in Matlab® using the concurrently monitored readout trajectories. **Results and Experiments:** The average RMS error for a coordinate was 104µm in the EPI experiment and 124µm in the FFE; the shorter periods for tone analysis did slightly compromise the tracking precision. The tones' effect on the readout trajectory is shown in Fig. 2, confirming that the image encoding is affected by the tones but not impaired in the sense that the resulting encoding is dense in k-space. The spectrum of a probe's phase signal reveals the 3 sharp tone frequencies orthogonal to the underlying EPI waveform (Fig. 2, left). ***In-vivo experiments:*** The EPI reconstructions show a good congruence between two phases before and after an approx. 6° rotation (Fig. 3). The FFE experiments were performed under significant rigid body motion (Fig. 4). The reconstructions of the FFE data acquired without motion correction are heavily corrupted by motion artifacts when motion occurred, while the reference tones based prospective real-time motion correction successfully corrects for bulk motion in the acquisition stage resulting in superior image reconstruction quality free of motion artifacts despite substantial translational motion during the experiment**. Conclusions:** It was proposed to use reference tones for continuous motion tracking, prospective real-time slice updating and magnetic field monitoring based image reconstruction in-vivo. The injected reference tones allow for a tracking precision of 100µm-120µm, even for short spin-warp readouts. Although the k-space trajectories are affected by the reference tones, the reconstruction problem is still well posed and readily solved on the basis of field monitoring data.

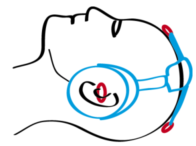

Figure 1: Headphones equipped with four ^{19}F NMR field probes.

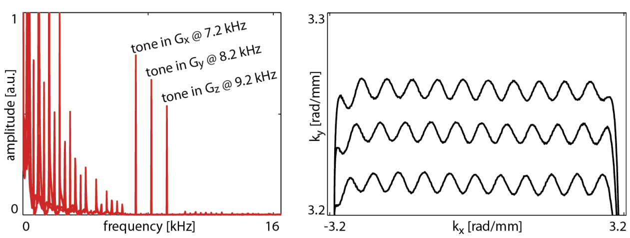

Figure 2: The magnitude of the spectrum of the probe phase signals (left) indicates the frequencies occupied by the EPI trajectory which was designed to keep dedicated frequency bands free for the three gradient tones. The tones introduce alterations, or 'wiggles', in the k-space trajectory of the EPI (right, the readout portions of the first three interleaves are shown) on the order of 1/2 Nyquist.

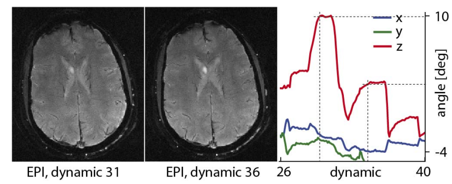

Figure 3: EPI, 10 interleaves, T_{acq} 40.3ms. Although acquired with a relative angulation of 6°, their motion corrected reconstructions are congruent.

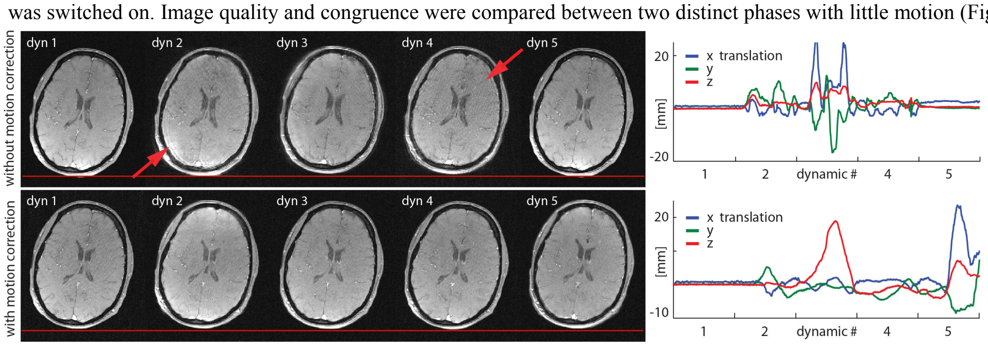

Figure 4: Five dynamics of a spin-warp GRE image are shown, acquired in the presence of head motion. The head translation during the acquisitions is shown on the right. Without motion correction (top row), head motion along x is clearly visible in the images of the five dynamics. Also, image quality is impaired (red arrows). Concurrent motion correction (bottom row) corrects for both - image shifts and artifacts - despite comparable head motion levels.

References: [1] Barmet et al. Procs. ISMRM, 2010, p.216. [2] Brunner et al. Procs. ISMRM, 2011, p.1814. [3] Ooi et al. MRM 62:943–954. [4] Haeberlin et al. Procs. ISMRM, 2011, p.4589.