Prospective Motion Correction During Fast Movements: Velocity Compensation of Gradient Moments and RF-Phases

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Purpose: Higher velocities (rather than displacement) are not accounted for in traditional prospective motion correction implementations; i.e. motion during a single TR of the acquisition is assumed to be zero. This assumption may be valid for sequences like FLASH where each data acquisition is presumed to be independent of any motion effects of previous TRs, fast spin echo or steady stade sequences may suffer from the influence of motion during long echo trains. This sensitivity to motion during one TR becomes even more pronounced for certain contrasts, such as diffusion weighting. Here, we review the effects of motion during gradient pulses and suggest correction techniques to account for such higher order motion.

Theory: Two types of motion during a gradient can be considered separately: rotations and translations, both seen in relation to the gradient direction.

Rotations: The phase changes due to a small rotation Ω(t) during a gradient G(t) are described as

$$\Delta \mathrm{k} = \gamma \int_0^{\tau} \mathrm{G(t)} \times \Omega(\mathrm{t})\,\mathrm{dt}$$

which corresponds to a phase ramp with a constant gradient. Expanding Δk gives

$$\Delta k_x(\tau) = \gamma \int_0^{\tau} \left[G_y(\mathrm{t})\,\Omega_z(\mathrm{t}) - G_z(\mathrm{t})\,\Omega_y(\mathrm{t})\right] \mathrm{dt},$$

$$\Delta k_y(\tau) = \gamma \int_0^{\tau} \left[G_z(\mathrm{t})\,\Omega_x(\mathrm{t}) - G_x(\mathrm{t})\,\Omega_z(\mathrm{t})\right] \mathrm{dt},$$

$$\Delta k_z(\tau) = \gamma \int_0^{\tau} \left[G_x(\mathrm{t})\,\Omega_y(\mathrm{t}) - G_y(\mathrm{t})\,\Omega_x(\mathrm{t})\right] \mathrm{dt}.$$

$G_x(t)$, $G_y(t)$, $G_z(t)$ are the gradients applied in the x-, y- and z-directions and $\theta_x(t)$, $\theta_y(t)$, $\theta_z(t)$ describe the rotation around the x-, y- and z-axis of the scanner coordinate system. In the image domain, this corresponds to a linear phase ramp orthogonal to the direction of the applied gradient and proportional to the displacement in gradient direction (Figure 1).

Translations: In the case of fast motion along a magnetic field gradient, an effect known from flow imaging has to be taken into account. The precession frequency and therefore the phase of a spin in a static gradient field G(t) depends on its changing position r(t) in the gradient. Assuming a constant velocity this phase can be calculated as

$$\Delta\varphi(\tau) = -\gamma \int_0^{\tau} G(t) \times \mathrm{r(t)dt}.$$

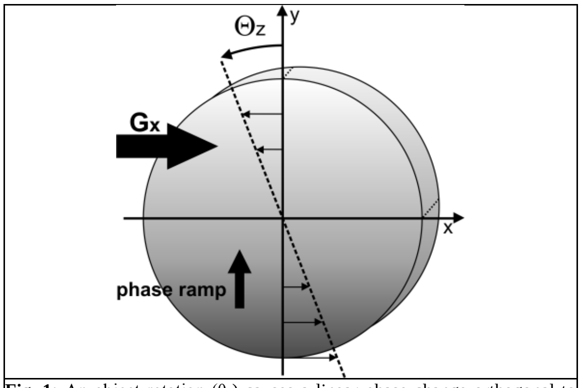

Fig. 1: An object rotation (θ_z) causes a linear phase change orthogonal to the direction of the applied gradient and proportional to the displacement in gradient direction.

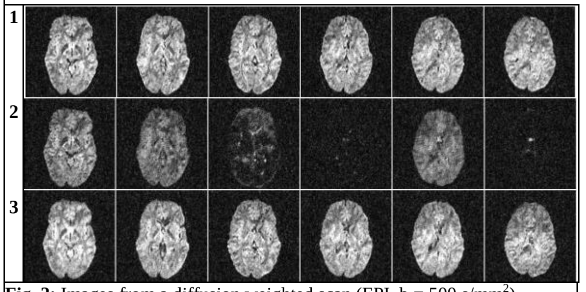

Fig. 2: Images from a diffusion weighted scan (EPI, b = 500 s/mm^2)
1) No voluntary head motion and no motion correction,
2) Motion with coordinate updates on each slice excitation,
3) Additional continuous update of the diffusion gradients.

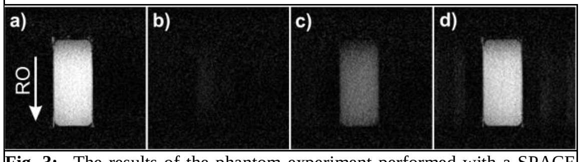

Fig. 3: The results of the phantom experiment performed with a SPACE protocol. First the stationary phantom was imaged in the original position for comparison (a). Then the phantom was continuously moved in readout direction indicated by the arrow. b) Position updates for each excitation pulse, d) continuous correction, and e) additional phase adjustments.

Methods: The effect of spins moving in a magnetic field gradient on the aquired image essentially depends on the sequence. However, some general guidelines for the necessary corrections can be formulated.

Rotation compensation: It has been shown that the continuous adaption of long diffusion weighting gradients can correct for rotational motion [1]. However, this technique cannot be applied to every gradient (e.g. during signal readout) or with every tracking method and scanner hardware. Alternatively, additional gradient moments can be applied after a sequence of gradients to restore the original phase evolution [2].

Translation compensation: Phase changes due to translation have an effect on subsequent RF pulses and the received signal. While the received signal can be corrected retrospectively by applying the calculated phase change to the data, an RF pulse (e.g., a refocusing pulse of a TSE sequence or an excitation pulse of a steady state sequence) requires a prospective adaption to the acquired phase [3].

Pitfall velocity calculations: Most of the tracking techniques used in MR measure position rather than velocity. Note that depending on the level of tracking noise in the position data, the use of basic filtering techniques might be required.

Hardware: All experiments were performed on a 3T TIM Trio system (Siemens Healthcare, Germany) using an optical in-bore system [4] to track head position.

Results: Figure 2 shows images from a diffusion weighted experiment with a b-factor of 500 s/mm². First, images without head motion are shown. In the subsequent two scans, the volunteer was performing comparable head motioin. Slice-by-slice correction (second row) results in better slice alignment and object consistency. In the third measurement additional gradient adjustments were applied during the entire encoding period. In comparison with the previous measurement a clear improvement in the images can be seen.

In Figure 3 the effect of the phase adjustments during the long echo trains of a SPACE sequence is displayed. First, the phantom was imaged in the original position for comparison (a). Then, the phantom was moved continuously along the readout direction and different levels of motion correction were applied. The relatively high velocity of 30-35 mm/s used leads to complete signal dropout when traditional motion correction (update once per slice excitation) was used (b). The continuous correction during the readout train still results in substantial signal loss (c). However, the additional adjustment of RF pulses and readout phases yields an image (d) comparable to the original.

Discussion: This work shows that prospective motion correction allows for the correction of intra-scan motion by continuously adapting the applied gradient fields and all RF signals to the patient motion. Artifacts from intra-scan motion are not negligible and can significantly reduce image quality. For other motion correction methods, intra-scan motion remains a major problem that only can be solved by rejecting and possibly reacquiring the affected data. In conclusion, this work shows that the correction for higher velocities during MR sequences is both a possible and advantageous extension to prospective motion correction.

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References: [1] Herbst et al., MRM 2012;67(2):326–338 [2] Norris et al., MRM 2001;45:729–733 [3] Weigel et al., FRIAS Motion Correction Workshop 2013, Freiburg, Germany [4] Maclaren et al., PLoS ONE 2012;7(11):e48088