Generic Eddy-Current Compensation in Balanced Steady-State Free Precession

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Introduction. In contrast to non-balanced SSFP sequences, b-SSFP sequences are sensitive to residual spin dephasing leading to imperfections in the balanced acquisition scheme. While a certain amount of dephasing or off-resonance frequencies can be refocused during the steady-state a sudden change of dephasing during consecutive excitation pulses will generate significant oscillations and thus image artifacts. These types of rapid changes can be caused by eddy-currents produced by the PE gradients and thus depend on the chosen PE scheme (see figure 1).

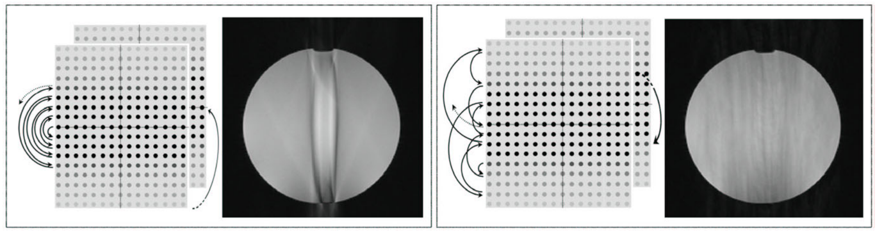

Fig. 1: Image artifacts produced by eddy currents due to large changes in the encoded k-space trajectories. The image degradations depend on the chosen PE scheme (centric: left, random: right)

Methods. The time dependence of additional magnetic fields induced by eddy-currents have been measured in space and time. The induced fields $\mathbf{B}_{\text{eddy}}(t)$ of a switching gradient G(t) can be described by a constant hub $\Delta B_0(t)$ of the main magnetic field and linear term $\Delta G(t)$ parallel to the applied gradient field. Hence, eddy-current induced dephasing over each TR intervall (n) in the excitation train is of form

$$\Delta\phi_{x,y,z}(n) \equiv \phi_{x,y,z}(n+1) - \phi_{x,y,z}(n) = \gamma \int_{t=nTR}^{(n+1)TR} \left\langle \mathcal{B}^{(n)}_{\text{eddy}}(t) \middle| \mathbf{r} \right\rangle_{x,y,z} dt = \gamma \int_{t=0}^{TR} \Delta G^{y(n)}_{x,z(2D)}(t)dt + \gamma \int_{t=0}^{TR} \Delta B^{y(n)}_{x,z(2D)}(t)dt$$

Typically, time constants of main residual eddy currents are less than 10ms and produce an additional dephasing of more than 10° for large PE steps (Siemens Sonata System). Steady-state dephasing in read & slice (2D) direction is essentially constant, in contrast to PE direction, and can thus easily be compensated for. We propose three mechanisms to compensate for eddy-current related PE dephasing: (i) "direct" compensation of additional linear fields by switching annihilating gradients, (ii) "double cycle" (see figure 2) as a golden rule which groups k-space in adjacent pairs, and due to the alternating rf-scheme such a pair intrinsically cancels the preceding dephasing by simply reproducing the same phase error into the succeeding step, and (iii) "through slice EQ" (EQ: equilibration) for which artificially induced low angle dephasing (less than 20^{o} within TR) in slice direction averages out signal oscillations (2D only).

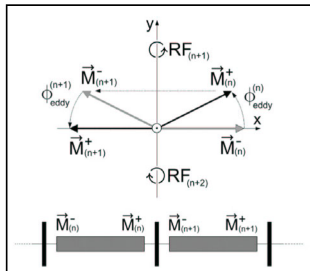

Fig. 2: Schematics of the generic "double cycle" compensation.

Results. Measurements have been performed in 3D and 2D. Figure 3 depicts a comparison between the proposed compensation strategies in 2D for a centric and randomized k-space trajectory. Artifacts for both generic strategies "double cycle" & "through slice EQ" clearly disappear, whereas residual image degradation in the "direct" compensation strategy is still present, most probably due to residual non-linear eddy-current effects.

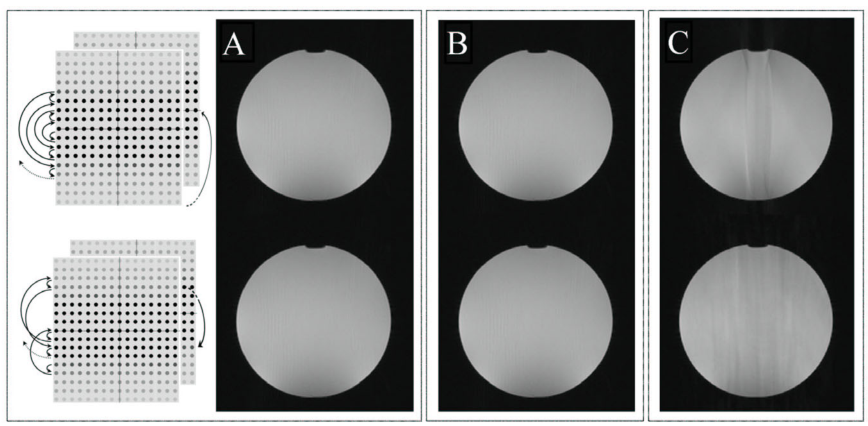

Fig. 3: Eddy-current compensation strategies for centric (upper row) and random (lower row) PE trajectories . (A) "double cycle", (B) "through slice EQ", (C) "direct".

Discussion. For the balanced SSFP scheme large jumps between different k-space positions generate significant signal instabilities and thus image artifacts. In contrast to the linear PE trajectory, where large encoding jumps are inherently avoided, all alternative k-space sampling strategies, such as centric, random and others inhibit significant eddy-currents related imperfections and thus compensation strategies are essential. On the first sight, direct annihilation of the additional induced magnetic fields by additional opposing fields seems to be promising, however, its implementation is complex and likely to be system related. Whereas generic – and thus system unrelated – compensation strategies such as "double cycle (2D & 3D)" and "through slice EQ (2D)" are simple to implement, offer great flexibility, are easy to use and allow arbitrary k-space trajectories for b-SSFP.

References.
[1] Foxall DL. Frequency-modulated steady-state free precession imaging. MRM 2002; 48:502-508.