Double Average Parallel Imaging for Optimized Eddy Current Compensation and Steady State Storage in balanced SSFP Imaging

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Introduction: k-space segmented time-resolved (CINE) balanced SSFP imaging is widely used in cardiac MR-imaging [1]. Drawbacks include sensitivity to the disruption of the steady state and limitations regarding non-linear k-space reordering which is problematic for SSFP imaging since large jumps in phase encode amplitudes lead to non-constant eddy current induced phase shifts across k-space and artifacts.

An optimized acquisition strategy is presented which utilizes scan time reduction by parallel imaging (PI) for optimized 'double average' (dAVE) eddy current compensation. In combination with a suitable reverse centric k-space trajectory both eddy current induced phase shifts and artifacts from imperfect steady state storage are compensated while maintaining *SNR* and total scan time of a standard CINE SSFP acquisition.

Theory: For applications that rely on added functional information, such as recently reported SSFP-Tagging [2,3], the SSFP steady state needs to be interrupted to include an appropriate preparation. To avoid severe image distortions the preparation is therefore embedded into a steady-state-storage scheme ('$\alpha/2$–technique') [4]. However, sensitivity to off-resonance effects results in substantial signal fluctuations depending on the resonance offset $\Delta\Phi_{TR}$ (Fig. 1). Associated artifacts can be reduced by suitable k-space reordering which moves the signal oscillations to outer k-space regions.

A method that permits the use of arbitrary k-space trajectories for SSFP imaging was recently proposed by Bieri et al [5]. The technique is based on 'paired phase encoding' and the observation that the SSFP steady state consists of a 'dual' magnetization configuration. As a consequence, eddy current induced phase shifts can be refocused by the acquisition of a subsequent similar phase encode line that compensates for the initial error. Here, ideal compensation for eddy current induced phase effects (as in Fig. 2) was performed which requires two-fold acquisition and signal averaging (dAVE) for each phase encoding line and doubles the total acquisition. The prolonged scan time is therefore compensated by the application of PI such that the resulting images provide identical spatial resolution and similar *SNR* as for the standard SSFP acquisition.

Methods: All experiments were performed on a 3T system (TRIO, Siemens, Erlangen, Germany). Data were acquired using prospective gating for k-space segmented linear (Fig 3, A) and reverse centric interleaved reordering (Fig 3, B). Sequence parameters: tag spacing=10mm, FOV=(320x240)mm^2, slice=8mm, matrix=256x192, TE=1.7ms, TR=3.4ms, α=50^o, BW=890Hz/pixel, 16 phase encodes per time frame, temporal resolution = 16*TR*=54ms. For human studies the FOV was somewhat larger ((360x270)mm^2) and the flip angle had to be reduced to 30^o due to SAR limitations at 3T. Data were acquired with 8-channel head and torso coils for phantom and human studies, respectively. PI and dAVE was combined with reverse centric interleaved reordering (Fig 3, C) and consisted of a GRAPPA reconstruction with an acceleration factor of 2 and 32 reference lines [6].

Results: Figure 3 shows phantom study results for different k-space reordering strategies (left column). As expected, steady state storage artifacts (Fig. 3A, white arrows) are reduced by suitable k-space reordering (Fig. 3, B) but eddy current induced artifacts are substantially increased in all time frames (figure 3B, black and open white arrows). If dAVA and PI and introduced (Fig. 3, C) both eddy current and steady state storage artifacts are mostly absent from all images. SNR analysis revealed slightly increased *SNR* of the PI & dAVE acquisition strategy in comparison to conventional k-space reordering which can be explained by the slight scan time increase as a result of the acquisition of additional reference lines needed for PI.

Consistent with the results of the phantom experiment, in-vivo results show that SSFP-Tagging acquisition can be considerably improved using the proposed reordering scheme in combination with PI and dAVE. Artifacts related to the off-resonance sensitivity of the steady-state storage are clearly visible in the first time frame for conventional linear k-space ordering (Fig. 4A, solid white arrows). If reverse centric encoding is applied steady state storage artifacts are generally reduced (Fig. 4B) but severe eddy current artifacts are introduced in all phases of the cardiac cycle (Fig. 4B, open white arrows). Reduction of eddy current induced artifacts is clearly visible if data acquisition with PI & dAVE is compared to images acquired with identical k-space reordering but no double averaging.

Discussion: Although the combination of averaging and parallel imaging may at first seem redundant it offers the possibility to utilize scan time reduction to integrate optimized eddy current compensation by double averaging and thus permits the selection of advanced k-space trajectories. Artifacts from steady state storage as well as eddy currents can be considerably reduced while maintaining *SNR*. Our current implementation resulted in a slight increase of the total acquisition time due to the fixed GRAPPA acceleration factor of 2 and the need to acquire additional reference scans. However, this is not a general limitation and it is possible (using non-integer acceleration factors) to adjust the total number of acquired k-space to provide identical total acquisition time and *SNR*. Similar artifact behavior can be expected for any preparation that is inserted in the $\alpha/2$ steady state storage scheme. Additional techniques that could benefit from the properties of the proposed method include navigator gating for respiration control and fat saturation.

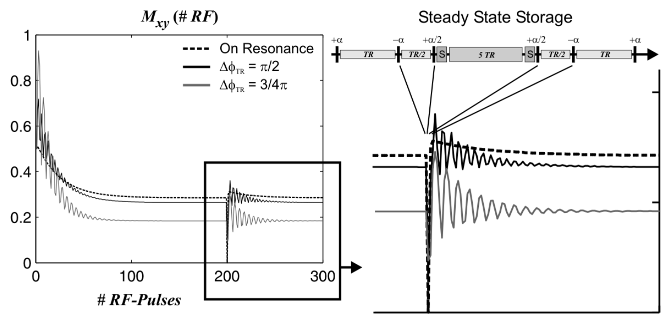
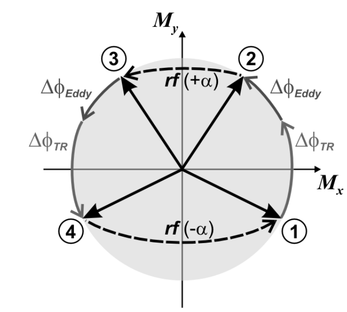


Fig. 1: Bloch-simulated SSFP signal intensities for different resonance offsets $\Delta\Phi_{TR}$. Parameters: $T_1 = 2T_2 = 25TR$, $\alpha = 60^o$. 'S' = spoiler gradients.

Fig. 2: Evolution of M_{xy} in the steady state for successive rf-pulses (+α, -α). **1->2:** in addition to the off-resonance phase $\Delta\Phi_{TR}$ eddy current induced phase shifts $\Delta\Phi_{Eddy}$ increase dephasing prior to rf-excitation (**2->3**). **3->4**: For dAVE the same phase encoding is repeated and $\Delta\Phi_{Eddy}$ remains unchanged resulting in identical dephasing as in the prior *TR* and the dual steady state is preserved.



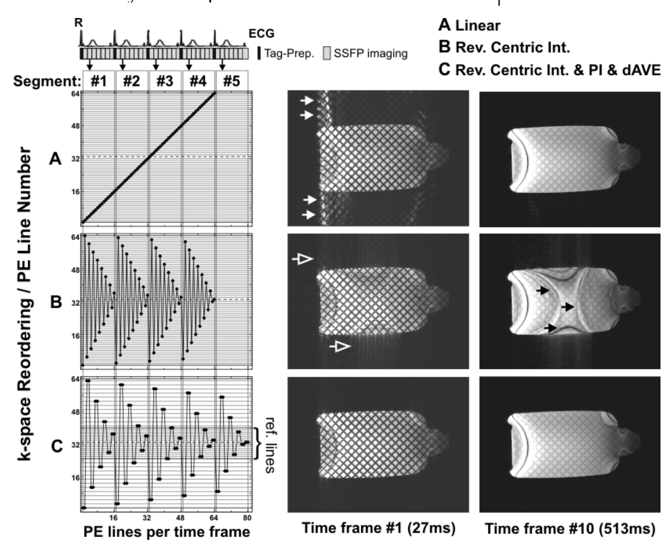


Fig. 3: SSFP-Tagging phantom data. For simplicity reordering schemes are depicted for 64 phase encodes and 16 reference lines for PI. Note that for PI & dAVE an additional ECG cycle is needed to acquire all data.

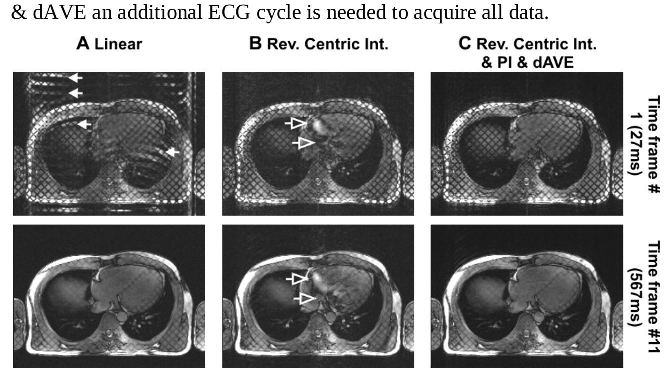


Figure 4: Axial SSFP grid tagging measurements in a normal subject

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