Compensation of artifacts from eddy current and transient oscillation in Balanced Steady-State Free Precession

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Introduction Balanced Steady-state free precession (bSSFP) is commonly used in clinics due to its excellent signal-to-noise ratio (SNR) and short scan time. The centric phase-encoding (PE) scheme is often preferable for bSSFP in physiological MR imaging, to maximize signal contrast. However, the centric PE scheme in bSSFP can cause artifacts due to eddy current and transient oscillation. There have been several compensation strategies such as pairing [1] and double-averaging [2], but there are some limitations such as incomplete compensation or increased data readout time for physiological imaging. In this study, we propose three new compensation schemes for reducing the artifacts. One is about complex averaging of two datasets with different number of dummy scans. The other two schemes are about complex averaging of datasets with two different pairing schemes.

Ordering scheme \ Acquisition order		1	2	3	4	5	6
Conventional centric	k_y	0	-1	1	-2	2	-3
	FA	+α	−α	+α	−α	+α	−α
Pairing	k_y	0	1	-1	-2	2	3
	FA	+α	−α	+α	−α	+α	−α
Double averaging	k_y	0	-1	1	-2	2	-3
	FA	+α, −α	+α, −α	+α, −α	+α, −α	+α, −α	+α, −α
Dummy Averaging	k_y	0	-1	1	-2	2	-3
	FA	+α (−α)	−α (+α)	+α (−α)	−α (+α)	+α (−α)	−α (+α)
Pairing + Dummy Averaging	k_y	0	1	-1	-2	2	3
	FA	+α (−α)	−α (+α)	+α (−α)	−α (+α)	+α (−α)	−α (+α)
Pairing averaging	k_y	0 (1)	1 (0)	-1 (-2)	-2 (-1)	2 (3)	3 (2)
	FA	+α	−α	+α	−α	+α	−α

Table 1. An example of conventional centric PE ordering scheme and five artifact compensation schemes. k_y : phase-encoding (PE) line, FA : flip angle. The total number of PE lines is set at six for simplicity. Comma (,) represents the inner complex averaging for "Double averaging". The indices without parenthesis are for the first acquisition, and those with the parenthesis are for the second acquisition.

Theory The bSSFP utilizes alternating flip angles of α and −α between successive excitations. The phase shifts due to eddy current and transient oscillation show opposite polarities between the successive excitations [1]. We propose three artifact compensation schemes termed "Dummy averaging", "Pairing + Dummy averaging" and "Pairing averaging". "Dummy averaging" is complex averaging of two datasets with even and odd numbers of dummy scans such as 0 and 1. "Pairing + Dummy averaging" stands for complex averaging of two paired k-space dataset with different numbers of dummy scans (0 and 1). "Pairing averaging" is about complex averaging of two datasets acquired with the same pairing scheme except the order in each pair. (**Table. 1**).

Data Acquisition Measurements were performed with a Siemens 3T Tim Trio system (Siemens Medical Solution, Erlangen, Germany) with maximal gradient 40mT/m and a slew rate 200mT/m/ms. The experiments were performed for a doped water phantom and head of an *in vivo* volunteer. The bSSFP imaging was performed with the imaging parameters: TR = 4.64ms, TE = 2.32ms, flip angle = 40°, matrix = 256×256, slice thickness = 10mm, the number of measurements = 5, and the bandwidth = 781Hz/px. The half alpha preparation was performed. Various PE ordering schemes tested in this study are described in Table 1. Measurements were performed 5 times repeatedly for each bSSFP scan, in order to investigate the differences between the transient state (#1 image) and the steady state (#5 image).

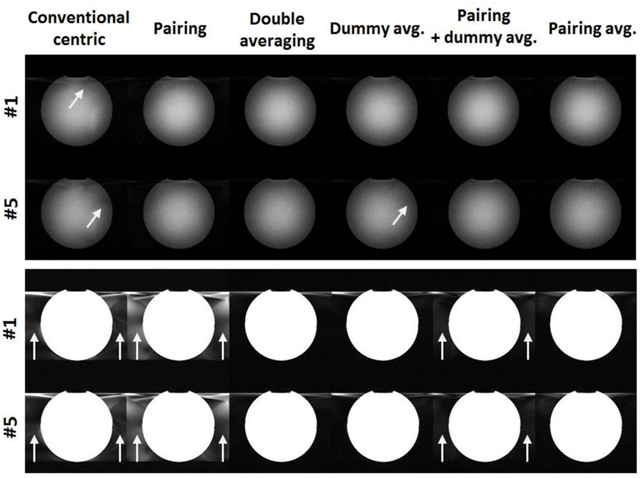

Fig 1. Phantom results with different k-space reordering with bSSFP. Top row represents the first image among 5 measurements (Transient- state), and second row represents the last image (Steady-state). Bottom two rows represent the higher scale images for highlighting background artifact. Arrows represent regions with artifacts.

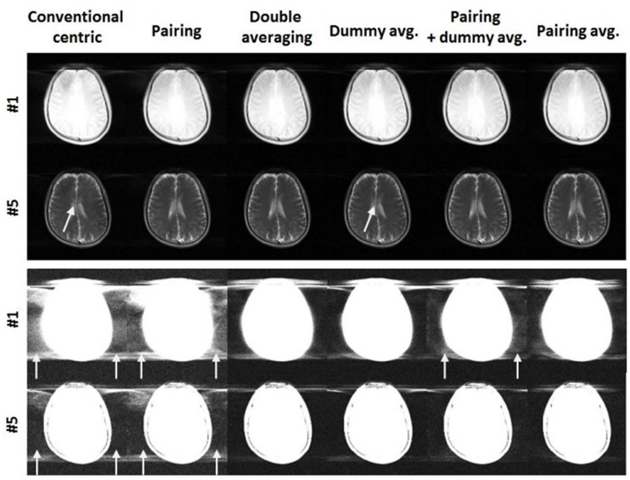

Fig 2. in vivo results with different k-space reordering with bSSFP. Top row represents the first image among 5 measurements (Transient- state), and second row represents the last image (Steady-state). Bottom two rows represent the higher scale images for highlighting background artifact. Arrows represent severe regions with artifacts.

Results Two different sets of 2D images are shown: (1) Transversal doped water phantom images to show the artifact behavior of different acquisition schemes (**Fig.1**), (2) Transversal in vivo images of a healthy volunteer (**Fig.2**). Conventional centric PE scheme showed artifacts inside and outside the phantom (arrows in Fig. 1). "Pairing" reduced artifacts within the phantom, but increased artifacts outside the phantom. "Dummy averaging" removed most of the artifact outside the phantom as good as double averaging, however, it showed small residual artifacts inside the phantom, which were suppressed in "Pairing + Dummy averaging". "Pairing averaging" suppressed artifacts both inside and outside the phantom, as good as double averaging. In vivo results were consistent with those of the phantom (**Fig.2**).

Discussion and Conclusion Pairing strategy could not perfectly remove the artifacts due to the small difference between amplitude of phase encoding gradients of each paired lines. Double averaging requires averaging the same k-space line twice before moving to the next k-space line, which is not preferred in physiological MR imaging due to reduced contrast from twice longer time window. The proposed schemes enable to overcome these limitations and maintain the temporal resolution the same as the original centric scheme, while suppressing artifacts from the eddy current and transient oscillation efficiently especially for the "Pairing averaging" scheme.

References: 1. Bieri, Magn Reson Med 2005; 54:129-137.   2. Markl, Magn Reson Med 2005; 54:965-974