Quantitative signal and phase analysis of a field-cycled MRI scanner

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Introduction: Field-cycled MRI employs two actively controlled electromagnets to polarize a sample and to provide the magnetic field environment during data acquisition [1,2]. The polarizing field (B_p) needs only to be strong, while the readout field (B_r) needs to be homogeneous. Instabilities in the readout magnetic field cause phase errors and artifacts in the phase-encode direction of images. To reduce these artifacts, bandwidth must be increased, which decreases SNR. A field-cycled MRI scanner, intended for small animal imaging, was previously built by the authors [3]. In this study, the stability of the readout magnetic field was investigated, along with expected signal trends. Images presented show no visible artifacts in the phase-encode direction while using a moderate bandwidth.

Theory: SNR is different in coil-noise-dominated (CND) and body-noise-dominated regimes, as discussed by Gilbert et al. [2]. In the CND regime, RF noise is dominated by Johnson noise in the coil, and SNR is given by: $SNR_{CND} \propto B_p B_r^{3/4} B_1$ [Eq. 1]. The field-cycled system built by the authors operates at 4 MHz. At this frequency, the system operates in the CND-SNR regime [4].

Methods: A negative feedback circuit was used to stabilize the current of the Techron 8607 gradient amplifiers driving the readout magnet. The feedback circuit was based on the design presented by Matter et al. [5].

The polarizing magnet is driven to 0.3 T, and ramps to zero-field in 33 ms, inducing a large emf in the readout magnet due to the mutual inductance between the two magnets. This induced emf causes decaying instabilities in the readout field. A delay of 50 ms is required before the readout field becomes stable. For a sample with T_1 of 250 ms, this delay causes less than a 20% decrease in signal.

To measure the stability of the readout magnetic field during a single free-induction-decay (fid), fids were acquired from a 7-cm diameter spherical sample with both a birdcage RF coil driven in quadrature and a double saddle RF coil. Long-time-scale field stability was investigated by measuring the phase of 128 consecutively acquired fids 1 ms into each acquisition. Fids were acquired 2.33 s apart, for a total scan-time of 5 min. In both studies, fids were acquired 100 ms after the ramp-down of the polarizing magnet.

The SNR of the signal was measured as a function of polarizing pulse duration and field strength. The signal was determined theoretically by numerically modeling the evolution of the magnetization over the given pulse sequences. The magnetic field, as well as the T_1 of the sample, is a function of magnetic field strength.

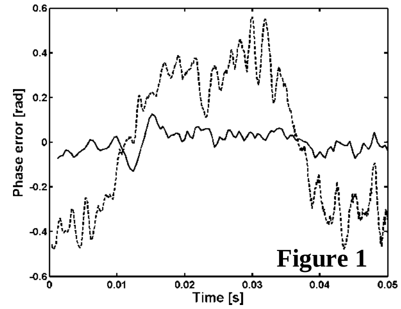
3d-FSE images were acquired of an onion and pepper (BW: 18 kHz; FOV: 10 x 10 x 4 cm; matrix: 192 x 128 x 10; N_{avg}: 10; TR/TE: 3160/21 ms; T_{scan}: 80 min; CPMG delay: 100 ms), to show the capabilities of the field-cycled MRI scanner and the effects of field stability.

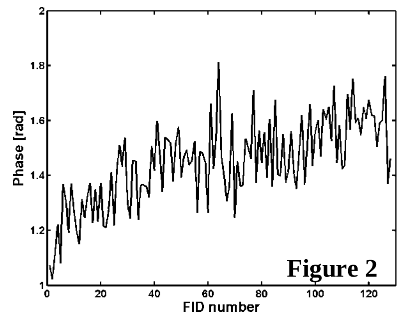
Results and Discussion: Fig. 1 shows the phase error during a single fid to be small. The larger phase error in the fid acquired with the birdcage RF coil (dashed line) is likely due to imperfect quadrature detection. Phase errors can cause ghosting and blurring artifacts in images, with artifacts being pulse sequence dependent. The small phase errors in Fig. 1 demonstrate the stability of the readout magnetic field, and do not cause visible image artifacts.

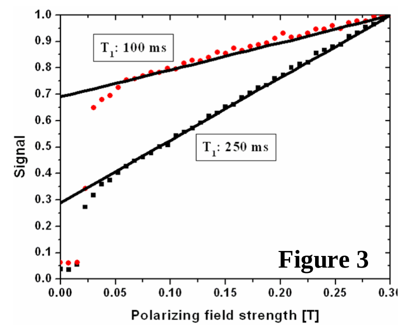
Large-scale changes in phase from fid-to-fid (Fig. 2) are due to center frequency drift caused by thermal heating of the readout magnet. However, long-time-scale changes in phase cause minor, correctable image artifacts, and can be reduced by allowing the scanner to reach thermal equilibrium prior to scanning. Large phase changes in adjacent fids are the greatest contributors to image artifacts in the phase-encode direction. Figure 2 shows phase errors in adjacent fids to be less than 0.4 rad.

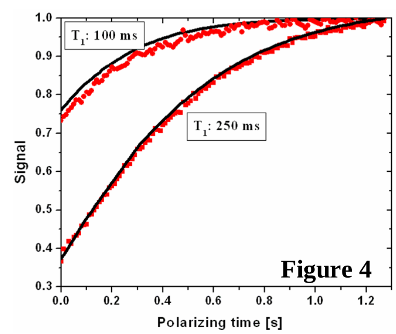
Figure 3 demonstrates the anticipated linear increase in signal with polarizing field strength, as predicted by Eq. 1. The theoretical predictions (solid lines) agree well with the experimental results. The increase in SNR with polarizing field strength is reduced due to the delay between the ramp-down of the polarizing magnet and the beginning of the CPMG sequence. Adding a correction to the feedback circuit can shorten this delay, and SNR will increase. Figure 4 shows good agreement between the experimental and theoretical signal as a function of polarizing time.

CPMG echo trains in FSE pulse sequences are highly sensitive to phase errors. The FSE images shown in Fig. 5 are high-resolution, acquired with a typical bandwidth, and do not show visible artifacts in the phase-encode (horizontal) direction, showing the stability of the readout field.









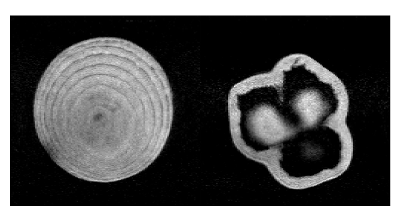


Figure 5

References:

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