Encoding chemical shift with Rabi modulated continuous wave excitation

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TARGET AUDIENCE Researchers with an interest in novel RF excitation methods and sequences

PURPOSE Continuous wave (CW) RF excitation, historically the primary form of MR excitation, was overshadowed by pulsed techniques due to a large efficiency gain when combined with the Fourier transform[1]. Recent work[2], inspired by quantum optics[3], has demonstrated that a spin system excited by a Rabi modulated CW achieves substantial *periodic steady-state* magnetization. The frequency components of this steady-state magnetization are restricted to harmonics of the excitation modulation frequency[4]. Here we report two experiments: the first confirms that these harmonics are affected by off-resonance effects, and therefore contain chemical shift information; the second, a proof of concept experiment, demonstrates that chemical shift information can be encoded in a series of CW excitations, and used to reconstruct a simple spectrum.

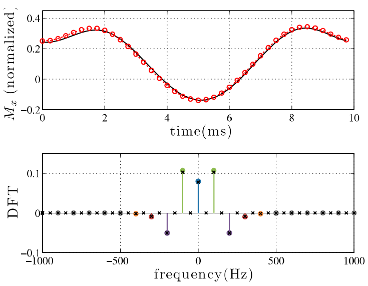

Fig.1 a) Measured (red) and theoretical (black) periodic steady-state magnetization waveform.
b) Measured (colored) and theoretical (black cross) harmonics of steady-state magnetization. See Fig.2 for color detail.

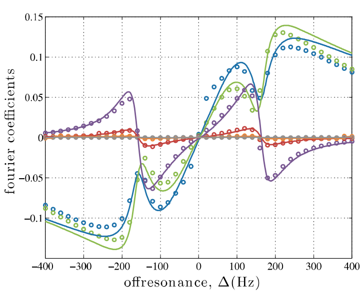

Fig. 2 Measured (circles) and theoretical (solid) frequency coefficients of steady state magnetization. DC component (blue), first (green), second (purple), third (red) fourth (orange) and fifth (grey) harmonics.

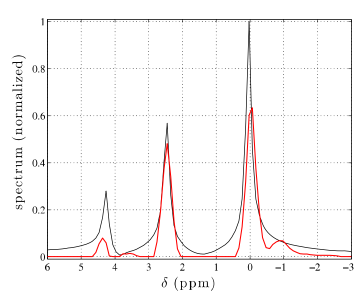

Fig. 3 Reconstructed (red) and measured reference (black) spectrum of an ethanol sample.

METHODS Two experiments were performed on a 4.7T Brüker BioSpec small bore MRI scanner. A Rabi modulated excitation envelope $\gamma B_1^e(t) = \omega_1(1 + \alpha\cos(\omega_1 t))$ was used, where ω_1 is the average Rabi frequency and α is the modulation frequency[3]. This excitation was applied for an initial duration of 1000ms to ensure the magnetization had reached a steady-state, after which the free induction decay (FID) was measured. A steady-state magnetization waveform (Fig.1a) can be acquired by selecting the first FID point, and repeating the process with an incremental increase to the excitation duration on each repetition[2]. Both experiments required B_0 and B_1 field maps.

Field mapping*:* The distribution of B_0 off-resonances was measured using the field-mapping sequence, MAPSHIM (Brüker Biospin). The distribution of ω_1 was measured with a B_1 mapping sequence[5]. Distributions were extracted using a histogram of non-background voxels.

Experiment 1: We investigated the effects of off-resonance, Δ, on the steady-state magnetization waveform. A spherical phantom of Gd-doped water (T_1=287ms, T_2=150ms) was selected for its narrow off-resonance distribution. Measurements for 41 off-resonance Δ values were taken between -400Hz to 400Hz with a 20Hz increment, with off-resonance Δ achieved by offsetting the excitation carrier frequency. The excitation envelope had parameters $\alpha = 1$ and $\omega_1 = 100$Hz. A discrete Fourier transform was applied to the measured steady-state magnetization waveform to extract its harmonic components. A theoretical curve was generated from a Fourier series approximation of the Bloch equation[4], numerically integrated over measured B_0 and B_1 (ω_1) distributions.

Experiment 2: A proof of concept experiment was undertaken to demonstrate the utility of chemical shift information encoded in the steady-state magnetization. Our objective was to reconstruct the spectrum of a spherical phantom of Gd-doped ethanol (T_1=197ms) from a series of CW excitations. Steady-state magnetization waveforms were acquired for 500 different CW excitation parameter pairs α and ω_1. Parameter pairs were selected using an optimization algorithm designed to minimize mean theoretical covariance. The DC component and first five harmonics were extracted from each steady-state magnetization and used to construct a measurement vector. The linear forward model matrix was constructed from a Fourier series approximation of the Bloch equation, numerically integrated over the measured ω_1 distribution. The reconstructed spectrum was solved by least squares optimization with a nonnegative and smoothness constraint. A reference spectrum from a single 2048-point FID was acquired with a dwell time of 100µs.

RESULTS Fig. 1a shows the measured (red) and theoretical (black) steady-state magnetization waveform from Experiment 1 for $\Delta = 180$Hz. The spectrum of this steady-state magnetization (Fig. 1b) shows information is restricted to harmonics of the Rabi frequency, $\omega_1 = 100$Hz. The variation in these harmonics is shown, over a range of off-resonances, in Fig. 2. The experimental results (circles) agree with the theoretical curves (solid) and show that the relative strengths of the harmonic components are influenced by off-resonance effects such as chemical shift, δ. Fig. 3 shows the reconstructed (red) and measured reference (black) spectrum from an ethanol spectrum. The zero ppm reference represents the system frequency. The reconstruction demonstrates that under Rabi modulated CW excitation, chemical shift information can be encoded in the steady-state magnetization.

CONCLUSION Rabi modulated CW excitation allows the measurement of a periodic steady-state magnetization. The steady-state magnetization is influenced by off-resonance effects, two of which are chemical shift and field gradients. Our work demonstrates a proof-of-principle of the encoding of chemical shift information under CW excitation. Future work will aim to encode gradient localization information to achieve image reconstruction. Furthermore, we are constructing hardware to enable isolated detection of the steady-state magnetization from the transmit CW signal, which will greatly increase the efficiency of experimentation.

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