Highly efficient localized distant dipolar field and its application in MRI

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Introduction

Intermolecular multiple quantum coherences (iMQCs) originated from distant dipolar field (DDF) possess numerous interesting properties, including their immunity to magnetic susceptibility variations and sensitivity to local microstructures [1]. They have been utilized for many important applications in NMR spectroscopy [2] and MRI [3]. However, a more wide-spread utilization of iMQCs is hindered by the poor signal-to-noise ratio (SNR) inherent to current methodologies [4]. This problem is exacerbated in clinical MRI, which is often operated at relatively low field. Our theoretical analysis shows that the DDF strength in a thin slice of sample will be more than two folds enhanced if the magnetization modulation within the slice is inverted relative to the remainder, while it will be close to zero outside the inverted slice, as shown in Fig. 1. To tailor such a localized and efficient DDF, an adiabatic inversion pulse was introduced into the conventional CRAZED (Cosy Revamped with Asymmetric Z-gradient Echo Detection) sequence. Experimental results demonstrate that the resulting iMQC signals are greatly enhanced as expected with this kind of DDF. We name this variant of CRAZED sequence Localized and Enhanced DDF (LED) sequence.

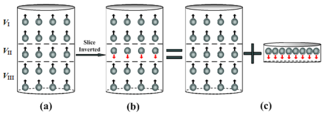

Fig. 1 Sketch of localized DDF model for a column sample. (a) Equilibrium magnetization before inversion pulse, (b) single slice inversion magnetization at the center of the sample, and (c) equivalent model of (b) taken as a sum of the original sample with equilibrium magnetization and two flat pancake samples with inversion magnetization.

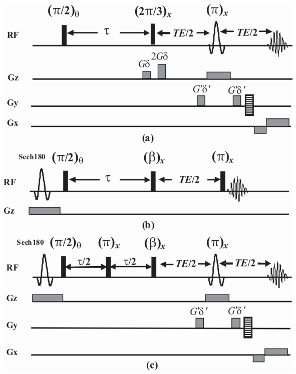

Fig. 2 Pulse sequences used to detect iDQC signal. (a) Original CRAZED imaging sequence, (b) LED spectroscopic sequence, and (c) LED imaging sequence.

THEORY

When the magnetization modulation is along the Z direction, the effective dipolar field inside the inversion slice for a sample with arbitrary shape will be $B_d = \xi\mu_0 M_z$, where ξ=p+2 is referred as DDF amplification factor. p can be taken as a shape factor (p≈0 for a whole lemon). The signal intensity from the LED sequence can then be deduced to be $M_+ = iM_0 \dfrac{4\tau_d}{\xi t_2} J_2(\xi t_2 / \tau_d) e^{i(\omega_0 t_2 + \gamma \Delta B t_2)}$, where $\tau_d = (\gamma\mu_0 M_0)^{-1}$ is the dipolar demagnetization time, J_2 is the 2nd order Bessel function. When β=2π/3, the strongest +iDQC signal is obtained as $M_+ = M_0 \dfrac{3\sqrt{3}}{2}\dfrac{\tau_d}{t_2} J_2(t_2/\tau_d) e^{i[\omega_0 t_2 + \gamma\Delta B t_2]}$. To achieve pure iDQC signal, a four-step phase cycling with the phases of the first RF pulse (x, -x, y, -y) and the receiver (x, x, -x, -x) should be employed.

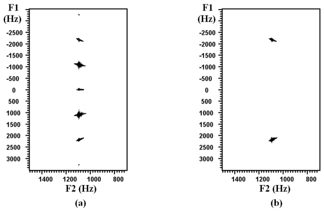

Fig. 3 2D iMQC spectra of a lemon sample from the LED sequence. (a) Without phase cycling, and (b) with a four-step phase cycling.

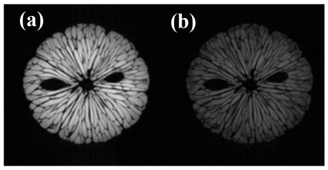

Fig. 4 MR images of a lemon sample with an imaging slice thickness of 0.2 mm. (a) From the LED sequence, and (b) from the CRAZED sequence.

Experiments and results

The pulse sequences are shown in Fig. 2. The experiments for Figs. 3 and 4 were performed at 298 K on a 7.0 T Varian MRI system with a horizontal-bore Magnex magnet, equipped with 10 cm bore imaging gradients (40 G/cm). Fig. 3 shows the 2D spectra of a whole lemon sample to demonstrate the effects of LED sequence. The pulse sequence used is shown in Fig. 2(b). All major iMQC orders appear at the expected frequency sites. To distinguish the signals from different iMQC orders in the 2D spectra, the ^{1}H frequency offset was set to about 1090 Hz. The MR images of a whole lemon sample are shown in Fig. 4. The experimental parameters were: 6.5 cm field-of-view, 128×128 matrix, TR = 8 s, and 0.2 mm slice thickness. The TE was optimized for maximal signal intensity: 200 ms for the LED sequence and 250 ms for the CRAZED sequence.

Discussion

It can be seen that all the ±iDQC, ±iSQC and iZQC signals appear when no phase cycling is applied (Fig. 3(a)). When the four-step phase cycling is applied, only iDQC signals remain (Fig. 3(b)). These results indicate that the LED sequence combined with the four-step phase cycling scheme effectively select pure iDQC signal with +2 and -2 coherence orders. Fig. 4 displays the MR imaging of the lemon sample. The signal amplification ratio from the LED sequence relative to the CRAZED sequence in Fig. 4 is about 2.4. For a whole lemon sample, we have ξ≈2. According to the above signal expression, the theoretical signal amplification ratio is about 2.3. So the experiment result agrees well with the theoretical prediction. Note that the diffusion effect was ignored in the theoretical calculation, while the conventional CRAZED sequence has a much stronger diffusion effect because of the magnetization modulation mode.

Acknowledgment

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References

[1] Galiana G, et al. *Science*, 322 (2008) 421-424.
[2] Chen Z, et al. *J Am Chem Soc*, 126 (2004) 446-447.
[3] Schäfer A, et al. *Magn Reson Med*, 60 (2008) 1306-1312.
[4] Cai CB, et al. *Magn Reson Med*, 64 (2010) 1128-1134.