MR Imaging of Intermolecular Double-quantum-filtered Zero-quantum Coherence

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Introduction

The CRAZED-based intermolecular zero-quantum coherence (iZQC) sequence has found limited application [1,2] since it is difficult to select signals from pure iZQCs due to the imperfect RF pulses and the presence of longitudinal magnetization during τ period, which gives rise to conventional single-quantum coherence (SQC) signals. Recently, we reported a three-pulse sequence with efficient phase-cycling for intermolecular multiple-quantum coherences [3]. In this abstract, a new three-pulse sequence with the selection of intermolecular double-quantum-filtered zero-quantum coherence and fast image acquisition was designed to choose the signals from pure iZQCs to avoid contamination from other coherences. Efficient phase-cycling scheme with optimal flip angles was proposed. Imaging experiments were performed to verify the theoretical predictions.

Methods

The desired pure iZQC signals were excited with a group of three RF pulses depicted in Fig. 1, which precedes a standard fast spin-echo (FSE) imaging sequence to form images. Three coherence selection gradients (CSGs) were applied with an area ratio of 1:0.5:2, where G and δ are the amplitude and duration of the first CSG. A rigorous analysis of the pulse sequence has been undertaken and the detected signals can be represented by:

$$M_{+}^{\mathrm{iZQC}} \approx \frac{3}{16}\gamma\mu_0(M_0)^2 t_2 \exp(i\Delta\omega t_2)(1-e^{-\Delta/T_1})^2 e^{-2\delta/T_2} e^{-2t_1/T_2} e^{-t_2/T_1} e^{-t_2/T_2} \times \sin^2\alpha \sin^2\beta \sin 2\theta \exp(-i2\Delta\omega\delta). \quad (1)$$

The optimal flip angles of the three RF pulses are α=β=90° and θ=45° for iZQCs. A phase cycling scheme (φ_1 = x, y, -x, -y) with the receiver phase (φ_{rec} = x, -x, x, -x) was applied to remove the unwanted residual coherence orders (±1, ±2). Theoretically, the maximal iZQC signal obtained herein is 3/4 time of that obtained from the original CRAZED sequence with n=0.

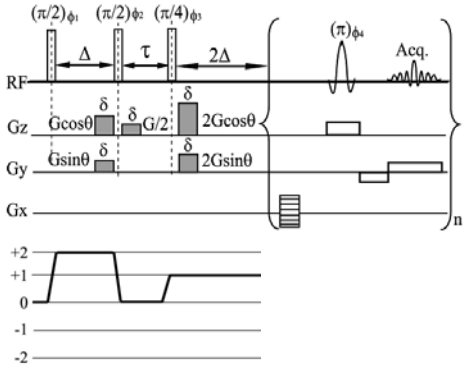

FIG. 1. Pulse sequence for pure iZQC images.

Results and Discussion

Imaging experiments were carried out on a Varian INOVA 600 NMR scanner. A phantom is made of two co-axial tubes with 2% and 3% (W/V) agarose gel in each tube respectively. The CSG amplitude is G = 60 mT/m and the duration δ = 1 ms. The field of view (FOV) = 6 mm × 6 mm, matrix size = 128 × 128, slice thickness = 1 mm, echo train length (ETL) = 4, and 16 signal averages were used.

Figs. 2(a)-(j) correspond to the slice profiles of the three-pulse iZQCs with varied flip angles. Figs. 2(a), (c), (e), (g) and (i) were acquired when all the three flip angles were 80%, 90%, 100%, 110%, and 120% of the setting flip angles of Fig. 1, respectively. The profiles of iZQCs are clean and not contaminated by the SQC or other unselected coherences. As predicted by theory, the iZQC signals shown in Figs. 2(b), (d), (f), (h) and (j) almost vanished when the CSGs were applied along the magic angle direction. It shows that the signals are originating from dipolar interactions. These results suggest that the three-pulse iZQCs are insensitive to the imperfection of RF pulses. Figs. 2(l)-(p) correspond to the slice profiles of the CRAZED-based iZQCs with the flip angles to be 80%, 90%, 100%, 110%, and 120% of the setting angles. The observed signals are composed of iZQC signal and residual conventional SQC signal due to imperfect flip angles and the recovered longitudinal magnetization during τ. Theoretically, two-step phase cycling of the second RF pulse with 45° and 135° can remove the residual conventional SQC signal whereas the signal from iZQC will add up. However, it is rather difficult to set exact flip angles (45° or 135°) in MRI due to the inhomogeneity in both RF fields and samples. Therefore, the residual conventional SQC signals cannot be effectively eliminated with the simple two-step phase cycling scheme for the CRAZED sequence.

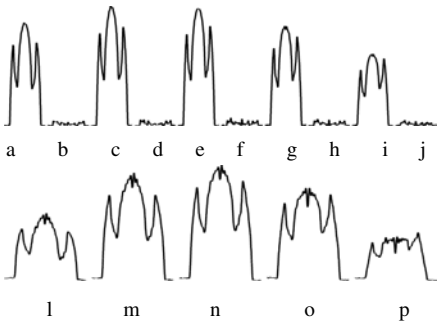

FIG. 2. The slice profiles of the iZQC images. (a-j) correspond to the three-pulse iZQC images; (l-p) correspond to the CRAZED iZQC ones.

Figure 3 are the images of an agarose-gel phantom obtained with varied CSGs. (a)-(c) correspond to the iZQC images acquired by the sequence in Fig. 1 with varied gradients of 15, 30, and 60 mT/m, respectively. Moreover, when the CSGs were applied along the magic angle direction, signals in the agarose-gel phantom almost vanished when the sequence in Fig. 1 were used with varied τ of 0, 10, and 20 ms respectively. The results show that the iZQC images are minimally contaminated by the conventional SQCs even with large evolution period τ. (d)-(f) correspond to conventional iZQC images acquired by the CRAZED sequence with varied gradients of 15, 30, and 60 mT/m, respectively. It is noted that the images of (d)-(f) have alternating bright and dark strips due to the RF tagging effect. This study suggests that the three-pulse iZQC sequence may provide an attractive alternative for feasible applications, and FSE is a viable technique for producing iZQC images quickly.

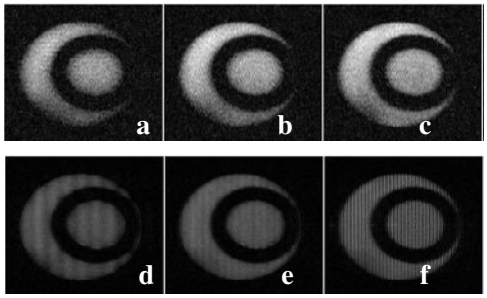

FIG. 3. Images of an agarose-gel phantom obtained with varied CSGs from the three-pulse iZQC sequence (a-c) and the CRAZED-based sequence (d-f), respectively.

Acknowledgments

This work was supported by the NNSF of China under Grants 10234070 and 20573084, and NIH under Grant NS41048.

References

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