Intermolecular zero-quantum coherence imaging in structured samples

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Introduction

Previous studies have shown that intermolecular multiple-quantum coherence (iMQC) MR imaging sequences provide a fundamentally different contrast mechanism to conventional MRI [1]. iMQC signal arises from the interaction between spins on other molecules, via long range dipolar fields. The direct dipole-dipole interaction between intermolecular spins mainly arise from a distance of half a helix pitch generated by a polarising gradient [1]; thus structural information can be elucidated at definable distance scales (usually order of tens µm), which are much finer than conventional MRI. Previously, a double-quantum iMQC sequence has been adapted to include frequency selectivity and used for imaging coherences between two different spin species in a structured phantom [2]. Theoretical analysis and numerical studies of **zero-quantum** coherence imaging (iZQC) have shown that the real part of the signal is *inherently* sensitive to frequency differences between spins separated by the selected correlation distance. Specifically the signal follows a 1-cos[$\tau_{zq}(\Delta\omega_I-\Delta\omega_S)$] dependence, where τ_{zq} is the evolution time, and $\Delta\omega_I$ - $\Delta\omega_S$ is the difference in resonant frequency between the two spin species [3]. iZQC sequences therefore potentially offer sensitivity in applications where susceptibility differences are present on a distance scale of 10s to 100s of microns, e.g. fMRI or studies involving contrast agents.

iZQC sequences are particularly sensitive to contamination from other coherence orders due to the lack of a second coherence selection gradient (CSG) after the β pulse (see Figure 1). In this study, iZQC imaging sequences have been implemented, with particular emphasis on minimising signal from other coherence orders, and verified against theory. The sequences were then tested in structured phantoms with local susceptibility gradients.

Methods

A 4.7T Bruker vertical MR system temporarily equipped with a Siemens AC44 gradient set (40mT/m, 200µs) was used. An iZQC sequence was developed (Figure 1), consisting of non-slice-selective α and β pulses separated by evolution time τ_{zq}, with a polarising iZQC CSG within τ_{zq}. A slice selective single spin echo sequence was then used for imaging. A 4-step phase cycle (α: x, -x, y, –y) was used to eliminate signals from residual single-, double-, and triple-quantum coherences; signal from higher coherence orders being relatively low [4, 5].

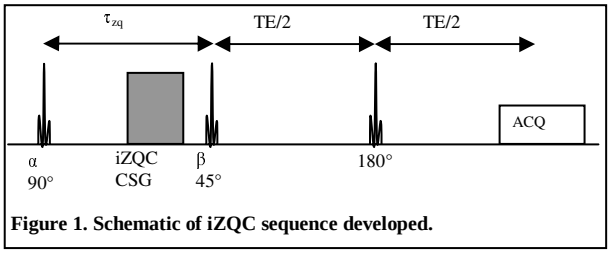


Figure 1. Schematic of iZQC sequence developed.

Verification of iZQC signal formation was performed on a 26mm spherical silicone oil (polydimethyl siloxane) phantom using a 15cm inner diameter birdcage coil. The experimental relationship between signal and TE, iZQC CSG angle and strength, and τ_{zq} were compared with theory.

Structural investigations were performed on a phantom consisting of two coaxial NMR tubes (inner tube, inner diameter 4mm with ~400µm walls; outer tube, inner diameter 8mm) filled with silicone oil using a custom built Alderman-Grant resonator (50mm long, 38mm diameter) for greater sensitivity. TE was set to 500ms (approximately the peak signal as determined in the verification experiments, see below), τ_{zq} = 23.5 ms, the iZQC CSG was set to 2mT/m & 29.4mT/m for 10ms (distance scale = 587µm & 40 µm respectively).

Results

Results from the verification experiments showed excellent agreement with theory [6]: the relationship between image intensity and iZQC CSG angle demonstrated dipolar properties, fitting well to the $3\cos^2\theta$-1 form (Figure 2). The relationship between signal and TE was observed to follow the expected 1st order Bessel function and demonstrated a peak intensity of iZQC signal at TE~500ms which is consistent with previous measurements (data not shown). These results give a strong indication that iZQC are observed and signal from other coherence orders are minimal.

Figure 3 shows a conventional image of the structured phantom (a), iZQC images with correlation gradient applied in y (b) and z (c) demonstrating the theoretical 1:2 signal ratio. The subtraction image in Figure 3d shows contrast in areas where there are susceptibility gradients tuned to a distance >2pixels. Identical scans tuned to 40µm (<<1pixel) did not show any contrast (Figure 3e).

Conclusion

We have developed and verified an iZQC imaging sequence. Studies involving structured phantoms with susceptibility gradients suggest that iZQC image contrast can be tuned to be sensitive over specific and user-defined distance scales. Potential applications include tracking of labelled cells and mechanistic studies in fMRI.

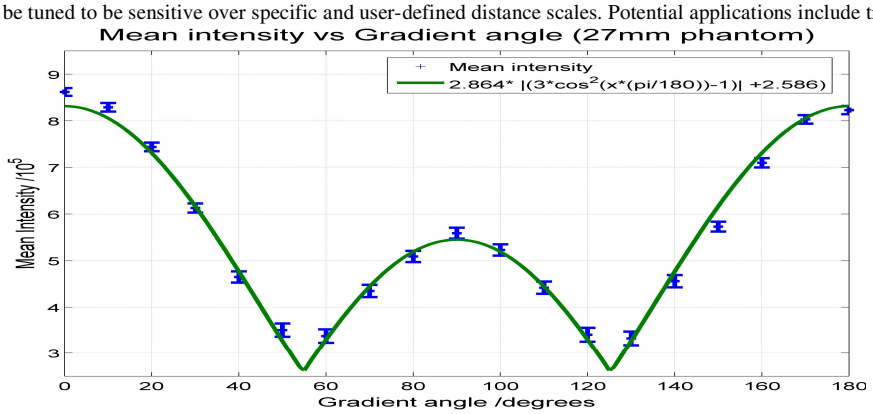
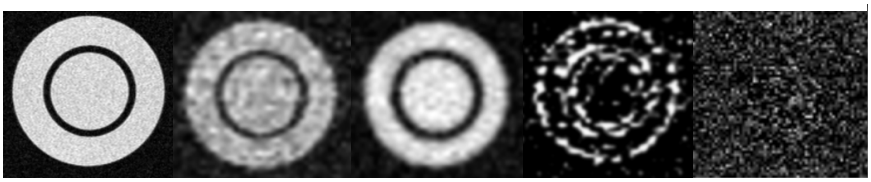


Figure 2. iZQC gradient angle vs. mean intensity.



a b c d e

Figure 3. Structured phantom scans: (a) conventional spin echo image, (b) y-gradient iZQC, (c) z-gradient iZQC, (d) Twice y-grad image minus z-grad image at 587µm, (e) Twice y-grad image minus z-grad image at 40µm. (b), (c), (d), (e) have 250µm resolution. All are 2mm thick axial slices.

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