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The Suppressing of MR Image Artifacts using Phase Cycling in Fast SE Sequence

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Abstract: The correction of image artifacts due to misadjustment in tuning of RF coils (tip angle) and in the RF single sideband spectrometer was investigated using phase cycling of the $\pi/2$ and π pulses in spin-echo sequences. A general procedure was developed for the systematic design of phase cycles that select desirable coherence-transfer pathways. To analyze a phase cycling sequence, changes in the coherence level and phase factor for each RF pulse in the spin-echo cycle must be determined. Four different phase cycling schemes (FIXED, ALTERNATE, FORWARD, REVERSED) to suppress unwanted signal components such as mirror and ghost images were evaluated using two signal acquisitions. When the receiver phase factor is cycled counter-clockwise (REVERSED), these artifacts are completely removed.

INTRODUCTION

Nuclear Magnetic Resonance (NMR) radio frequency (RF) pulse sequences are in many cases described simply in terms of pulse *flip angles* and *delays*. However, another important aspect of pulse NMR experiments is the *phase* of the RF pulses and the way in which these phases are systematically varied. Phase cycling allows suppression of artificial peaks which may arise from the imperfect pulses, irrespective of whether the imperfections are due to errors in the calibration or inhomogeneity of the RF field.

Phase cycling is also employed to reduce artificial image peaks which are present to some extent in quadrature detection. Quadrature detection involves the use of two phase sensitive detectors fixed at the same frequencies but at a phase 90° apart from each other. The signals are digitized separately and treated as real and imaginary parts of a complex spectrum which subsequently undergoes Fourier transformation. If the signals received by the two detectors are not of exactly the same amplitude or if the phase difference is not exactly 90°, then *quad images* will be produced. These quad images have reduced magnitude and can be recognized by their difference in phase and spatial position with respect to the main signal. These system artifacts are a nuisance when weak signals are being studied in the presence of strong ones. Such unwanted signals are usually suppressed by signal averaging using different settings of the RF phases and the receiver phases.[1] The acquired signals are added together and the unwanted "spectral" features, such as *ghosts* and *phantoms*[2] are canceled out.

NMR pulse experiments are described in terms of pathways through various orders of coherence. A general procedure has been described for the systematic design of phase cycles that select desirable coherence-transfer pathways.[3,4] A.D. Bain presented a simple way of calculating the effect of phase cycling in connection with quadrature detection and heteronuclear coherence transfer.[5] In another study, G. Bodenhausen *et al.*[3] demonstrated the utility of phase cycling in homonuclear experiments involving several coherence-transfer steps.

This paper presents theoretical considerations and experimental methods for phase cycling in RF spin-echo(SE) pulse sequences. In these experiments, changes in the quadrature detection system, gain imbalance and dc-offset in the two phase channels were evaluated. Different phase cycling schemes which suppressed unwanted signal components at the completion of every cycle were used to compare theory with experimental results.

METHOD AND EXPERIMENTAL

Coherence Pathways

NMR signals are, in the simplest case, the magnetization of the system, but more generally they are the elements of a density matrix.[6] The signals represent a quantum-mechanical coherence between two spin states and the magnitude of coherence in each spin system is governed by the *coherence level*. Coherence may be associated with a transition probability between two spin states, and this transition normally involves a number of radiation quanta[7] which will show both positive and negative multiple quantum coherence. A spin level is altered by the absorption of energy from an RF pulse. The spin coherence that starts off as z-magnetization at equilibrium will be transferred to some other level by several ensuing RF pulses until it reaches the receiver. The sequence of coherence levels that the signal passes through during the pulse sequence constitutes the coherence pathway. Once the pathway is defined for the coherence which reach the receiver, it is a simple matter to calculate which signals are added together and which are canceled in a phase-cycling procedure.

Phase Cycling in SE Sequence

The SE sequence[8] is the most often used NMR imaging technique due to its clinical utility. The spin echo is sensitive to T_1 and T_2 relaxation times, as well as to hydrogen density and flow, and this sensitivity can be easily "tuned" over a wide range of tissue relaxation times. The SE has a wide dynamic range, and each *tuning range* provides image contrast for the set of acquisition parameters which provides a different image contrast biological tissues.

The signal from the spin echo depends on hydrogen density, T_1 and T_2 relaxation times, and flow. Strong T_1 discrimination is provided by acquiring at short pulse repetition time (TR) and echo delay time (TE), and can be calculated from two successive scans at the same TE and different TR's. T_2 discrimination is provided by acquiring at a long TE and TR, and can be calculated by varying the TE at a fixed TR. The initial, maximal strength of the spin echo (immediately after the $\pi/2$ pulse) is determined by the T_1 of the tissue and by the programmable repetition interval TR. The rate at which the signal decreases after a $\pi/2$ pulse is determined by the T_2 of the substance. The free induction decay (FID), following a $\pi/2$ pulse, decays quickly due to loss of coherence resulting from inhomogenity in the external magnetic field. The effect of a π pulse is to restore this coherence so that the strength of the signal subsequently acquired depends less on field inhomogenity than on the T_2 and on internal fields of the substance.

The phase shift in RF pulses determines the rotation axis and its direction. These RF pulses are referred to as the $\pi/2$ and π pulse, respectively, to avoid confusion with the phase angle. A right hand coordinate system is assumed. Phase angle 0° is assumed to be along the $+x$ axis direction, and the angular increment is in the counter-clockwise direction. Sixteen different combinations of phase shift are possible in a SE sequence. In general phase cycling is needed for both the transmitter and receiver. The most typical phase cycling methods in SE sequences have been CP,[9] CPMG,[10] CYCLOPS,[11] and EXORCYCLE.[12]

For an example of the SE sequence, we chose the COSY technique.[5] The first pulse creates coherence with coherence levels of +1 and -1 and leaves some z-magnetization in coherence level 0. It is clear that coherence can reach the receiver after the second pulse via three pathways; it can leave the +1 coherence level in the same level, it can promote the z-magnetization from coherence level 0 to +1 (selection of P-type peak), or it can transfer the coherence from -1 to +1 (selection of N-type peak). All possible phase factors for two-pulses are given in Table 1 for the selection of N-type peaks only, as can be seen by multiplying the phase factors together for each pulse and summing over the phase cycling sequence. If the second pulse has a flip angle of 180°, all the P-type peaks vanish because of flip angle effects, as is observed in the *J*-resolved experiment. However, in general, all two-pulse experiments are fundamentally similar.

Experiments

Our spin echo sequence is based on an improvement of CPMG[10] phase cycling. The phase cycling scheme is a selectable 4 phase roll, FIXED, ALTERNATE, FORWARD, REVERSED. The acquired data is added or subtracted depending on the phase of $\pi/2$ at the buffer level before the next sequence data are acquired. In addition, the complimentary phase is used for the two successive averaging sequences in order to include as many phases as possible. For example, if two averages per sequence is used, then the number of phase

Table 1. Phase Factors for the COSY Experiment

π /2 PULSE		π PULSE		RECEIVER	
Phase	Factor	Phase	Factor	Phase	Factor
0	+ 1	0	+ 1	0	+ 1
180	− 1	90	− 1	0	+ 1
180	− 1	180	+ 1	180	− 1
0	+ 1	270	− 1	180	− 1
90	− *i*	90	− 1	90	− *I*
270	+ *i*	180	+ 1	90	− *I*
270	+ *i*	270	− 1	270	+ *I*
90	− *i*	0	+ 1	270	+ *I*
0	+ 1	180	+ 1	0	+ 1
180	− 1	270	− 1	0	+ 1
180	− 1	0	+ 1	180	− 1
0	+ 1	90	− 1	180	− 1
90	− *i*	270	− 1	90	− *i*
270	+ *i*	0	+ 1	90	− *i*
270	+ *i*	90	− 1	270	+ *i*
90	− *i*	180	+ 1	270	+ *i*

cycle modes is four. The complete phase cycling of two averages per sequence for phase roll mode is listed in Table 2. Imbalance in the quadrature detector is created by varying the gain in each channel, and imperfect tip angles for the π /2 and π pulses are also used. Two tubes of different diameters (13 and 22 mm) and relaxation times (T_1, T_2 ; water doped with manganese sulfate) were employed as test phantoms. The phase roll mode was varied in each scan (TR=250 ms, TE=33 ms, slice thickness=5 mm).

All experiments were performed on a horizontal 2.0T (superconducting magnet) 31-cm small-bore NMR system. Computer programming and data analysis were performed on a PDP 11/84 computer system.

RESULTS AND DISCUSSION

When there was gain imbalance in the two channels and imperfect tip angles of RF pulses in the SE sequence were used, a quadrature glitch and a ghost image for the first sequence (NSQ=1) appeared for all phase rolls.

Fig.1 is axial images of the water tubes acquired using different phase cycles and twoTable 2. Phase Factors in Complimented Phase Cycling of Spin-Echo Sequence for Two Times Averages per Sequences averages per sequence (NSQ=2). Fig.1(a) is a FIXED phase

Phase Cycling	π /2 PULSE		π PULSE		RECEIVER	
	Phase	Factor	Phase	Factor	Phase	Factor
(a) FIXED	0	+ 1	90	− 1	180	− 1
	0	+ 1	90	− 1	180	− 1
	180	− 1	90	− 1	0	+ 1
	180	− 1	90	− 1	0	+ 1
(b) ALTERNATE	0	+ 1	90	− 1	180	− 1
	180	− 1	90	− 1	0	+ 1
	180	− 1	90	− 1	0	+ 1
	0	+ 1	90	− 1	180	− 1
(c) FORWARD	0	+ 1	90	− 1	180	− 1
	90	− *i*	180	+ 1	270	+ *i*
	180	− 1	90	− 1	0	+ 1
	270	+ *i*	180	+ 1	90	− *i*
(d) REVERSED	0	+ 1	90	− 1	180	− 1
	270	+ *i*	180	+ 1	90	− *i*
	180	− 1	90	− 1	0	+ 1
	90	− *i*	180	+ 1	270	+ *i*

roll image, where the receiver phase factor is alternated (-1,-1,+1,+1), as shown in Table 2. This produced a inverted mirror-image with respect to the center of the spectrum and also a ghost-image offset in the y-direction. Fig.1(b) is an ALTERNATE phase roll image, produced by a receiver phase factor alternation of (-1,+1,-1,+1). The ghost-image is completely removed but the mirror-image remains. Fig.1(c) is a FORWARD phase roll image, where the receiver phase factor is cycled clockwise (-1,+*i*,+1,-*i*).

The mirror-image is completely removed but the ghost-image remains. Fig.1(d) is a REVERSED phase roll image, where the receiver phase factor is cycled counterclockwise (-1,-*i*,+1,+*i*). Both the mirror-image and ghost-image are completely removed.

Fig.2 is an axial image of a QA phantom using the same SE sequence as above. When the ALT phase roll is used under the same tuning conditions, a mirror-image, comparable to Fig. 1(b), appears as shown in Fig 2.(a). When the gain balance is adjusted and the correct tip angle is used, the mirror-image disappears completely as seen from Fig.2(b). The same results are obtained for all types of phase roll and are independent of transmitter/receiver coil tuning.

Normally one assumes that quadrature detection is perfect; however, in practice, imperfections exist, which result in the formation of an image peak on the other side of the carrier. Certain quadrature detection schemes employ two phase-sensitive detectors instead of one, and this introduces additional practical problems. One is that the two *channels* may

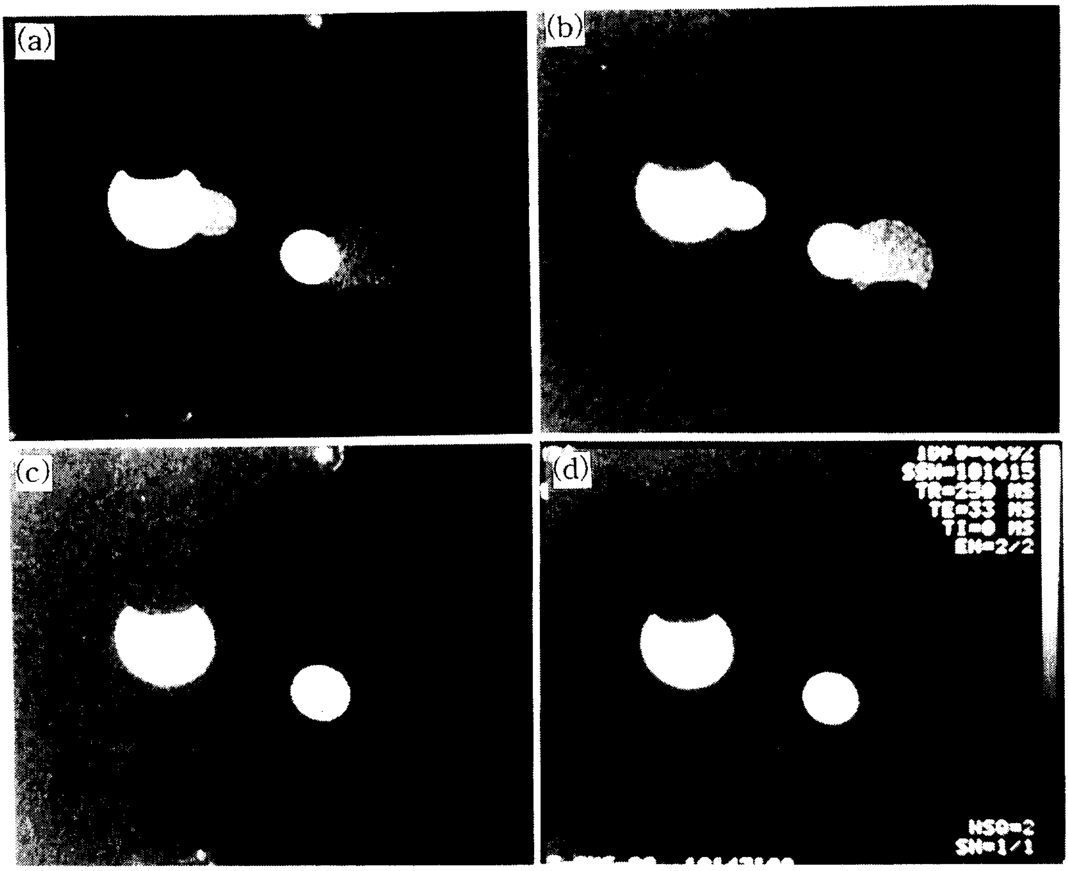

Fig. 1. Phase-Roll Image for Gain Imbalance and Imperfect Tip Angle
(a) FIXED (b) ALTERNATE (c) FORWARD (d) REVERSED

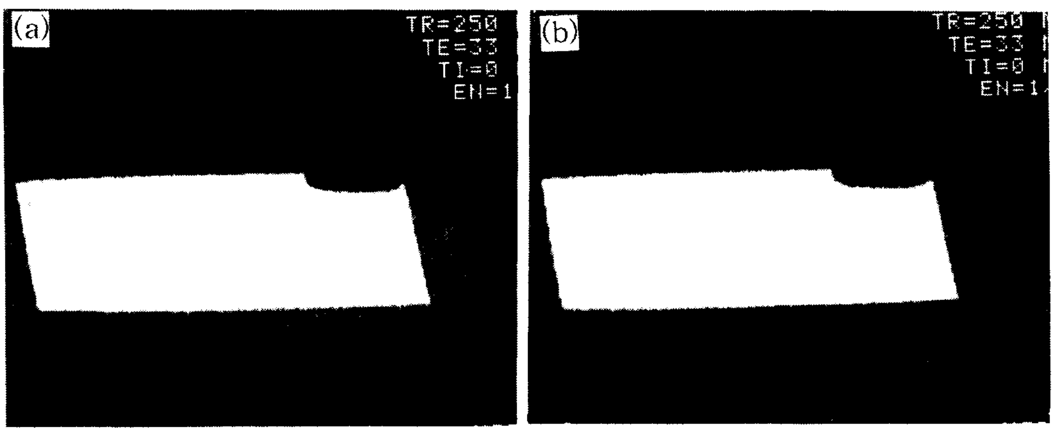

Fig. 2. QA Phantom Image in ALTERNATE Phase-Roll
(a) Gain Imbalance Imperfect Tip Angle
(b) Balanced Gain and Correct Tip Angle

not be properly matched in gain, which leads to weak spurious responses at mirror-image frequencies with respect to the center of the spectrum (zero frequency). The second is that the baseline level of the free induction decay acquired in one channel may not be exactly balanced with respect to that in the other channel. This gives rise to an anomalous response in the center of the spectrum, usually known as the *quadrature glitch*.

CONCLUSIONS

In general, the signal at the receiver from each coherence pathway depends on the product of the pulse phase factor (which depends on the RF phase) and the receiver phase factor (which depends on the data routing). To analyze a phase cycling sequence, one has to calculate the change in coherence level and the phase factor for each pulse in the cycle, including the phase of the receiver. All the phase factors are multiplied together, and the results are co-added over the cycle.

As fast NMR imaging techniques develop, the emphasis on using only one or two signal acquisitions may introduce spurious image artifacts. Once recognized by appropriate quality assurance methods, these can be eliminated by proper sequencing of the phase of the pulses in the standard spin-echo sequence, or by proper tuning of the imaging system.

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