Exotic Phase Cycling in ^{1}H MRS

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Introduction: Phase cycling is an indispensable coherence selection/suppression technique incorporated into most localized ^{1}H-MRS sequences, especially *in vivo* applications at super-short echo times. While there exists a variety of phase cycles, specific methods for generating, comparing, and evaluating different phase cycles has yet to be presented. In this work, we present a general concept of phase cycling, focusing on its potential application in a super-short TE stimulated echo localization sequence (STEAM).

Signal	RF1	RF2	RF3	Phase
FID1	90°	0°	0°	Φ_1
FID2	0°	90°	0°	Φ_2
FID3	0°	0°	90°	Φ_3
Echo12	90°	90°	0°	$2\Phi_2- \Phi_1$
Echo13	90°	0°	90°	$2\Phi_3- \Phi_1$
Echo23	0°	90°	90°	$2\Phi_3- \Phi_2$
STEAM N	90°	90°	90°	$\Phi_3+ \Phi_2-\Phi_1$
Double Echo	90°	90°	90°	$2\Phi_3-2\Phi_2+\Phi_1$

Background: Phase cycling techniques vary from a simple 2-step to the 4-step EXORCYCLE to the more robust 8-step commonly employed in STEAM (1). Current implementations of phase cycling generally focus on alternating the phases of the RF pulses between values of 0º and 180º. In some cases, the values of 90° and 270° are also included in the cycling scheme. The ADC phase is modulated such that only the STEAM N coherence is selected (Table 1). While the ultimate efficacy of a phase cycle is measured by its selectivity, in simulations, only the phase shift and phase dispersion can be measured, where the latter is a measure of the density of the sampling over 360°. By moving away from the typical binary or quad phase selections, additional phase cycling schemes become apparent; what we call "exotic phase cycles" refers to utilizing more complex phase cycling schemes to eliminate signals from unwanted coherence pathways (Table 1). In exotic phase cycling, the scheme is designed not around the binary oscillation of STEAM N, but rather a more densely sampled cycle applied to the problematic coherences: FID3 and Echo23. By increasing the number of phase cycles applied, exotic phase cycles provide a greater phase dispersion that has two advantages: 1) it increases the likelihood of coherence cancellation when the data are averaged and 2) if the coherences should reform, there is a much greater likelihood that the intensity of the coherences will be reduced.

Theory: Recent data suggest that in super-short TE STEAM sequences, not only is the residual signal from FID3 problematic, but also the residual signal from Echo23. Utilizing the phase equations for problematic coherences: $\varphi_{FID3} = \varphi_3$ and $\varphi_{Echo23} = 2\varphi_3 - \varphi_2$, an exotic phase cycle can be designed to provide greater phase dispersion than the standard phase cycles. Just as in typical phase cycling, the phase of the ADC is incremented to match the phase of the stimulated echo so that each acquisition is coherent for STEAM N. A16-step exotic phase cycle is generated by any odd integer multiple of 360°/16, i.e., 22.5°* 1, 3, 5, . . 15. If FID3 and Echo23 are incremented by one of these eight possible values, then each will experience a 16-step phase cycle. For example, if FID3 is set to 7*22.5°, 157.5°, then we calculate $\varphi_{Echo23} = 2\varphi_3 - \varphi_2 = 315° - \varphi_2$. Arbitrarily choosing 11*22.5°, or 247.5° - another 16-step cycle - for φ_{Echo23} yields $\varphi_2 = 67.5°$. We are free to choose any value for the phase of the first RF pulse, φ_1. The obvious choices are either 0° or 180°. Although no residual signal is expected from FID1, there is no penalty for setting $\varphi_1 = 180°$. Thus, the final exotic phase cycle where Echo23 and FID3 are incremented sixteen times is: $\varphi_1 = 180°$, $\varphi_2 = 67.5°$, $\varphi_3 = 157.5°$, and based on the phase equation for STEAM N (Table I), $\varphi_{ADC} = 45°$.
Perhaps the best method for assessing these exotic phase cycles, outside of actual experiments, is through a coherence location diagram (CLD). The CLD is generated by examining the 1-D projection of the 2-D non-averaged data after FFT. A CLD shows the position (phase shift) of a particular coherence by normalizing 360° to the number of averages. The position of each coherence is determined by the coherence shift = $\frac{\varphi * N}{360°}$ where N is the number of averages and φ is the phase of the coherence of interest.

Results: Comparison of the CLDs for an exotic phase cycle and a 8-step phase cycle demonstrate how the exotic phase cycle provides better separation of the coherence of interest (stimulated echo) from FID3 and Echo23 than the standard 8-step cycle. In addition, the exotic phase cycle completely separates all eight coherences, such that through appropriate selection of the ADC phase, each coherence can be examined for its contribution independent of the other coherences. This provides an ideal method for assessing the effectiveness of gradient spoiling on each coherence. However, it is not necessary that all coherences are separated, just that the same coherence does not show up on multiple lines.

Discussion: The phase scheme described above is just one example of the many possible exotic phase cycles. In this particular case, we are not concerned with multiple-quantum coherences or anti-echoes as these are completely destroyed with the appropriate gradient scheme. Nonetheless, their phase equation could be included in the analysis such that an exotic phase is to designed for their possible signal contributions.

References: 1) Bodenhausen G et al. J Magn Reson 1977; 27:511-4.

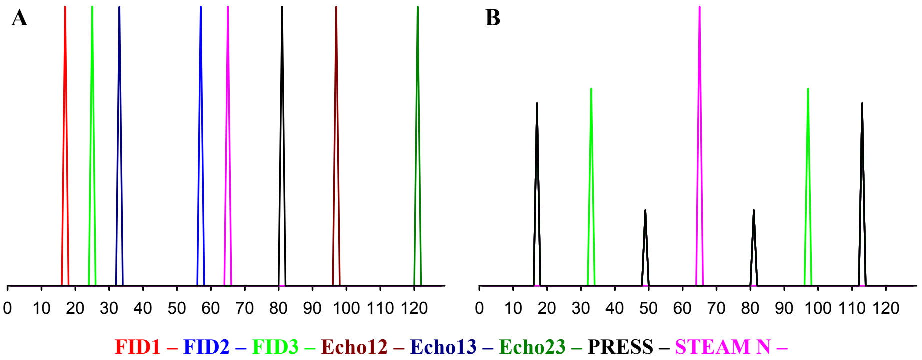

Figure 1. Simulated coherence location diagrams for 128 acquisitions for phase cycling schemes of φ_1=180º, φ_2=67.5º, φ_3=157.5º (A) and a standard 8-step using 0º and 180º increments (B). These diagrams are 1-D representations of the 2-D non-averaged phase cycling data set after FFT with the frequency information removed. Thus, the presence of a peak identifies the location of a specific coherence. Both (A) and (B) contain all eight coherences with STEAM N in the center: in (B), FID1, FID2, Echo12, Echo13, Echo23, and PRESS have the same location; while in (A), each coherence occurs on a separate line.