Exotic Phase Cycling in ¹H MRS

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Introduction: Phase cycling is an indispensable coherence selection/suppression technique incorporated into most localized ¹H-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).

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 0° and 180°. 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: \( \phi_{FID3} = 90°, \phi_{Echo23} = 0° \), 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. A 16-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 \( \phi_{Echo23} = 2\phi_{23} - \phi_{2} = 315° - \phi_{2} \). Arbitrarily choosing 11°22.5°, or 247° as another 16-step cycle for \( \phi_{Echo23} \) yields \( \phi_{2} = 67.5° \). We are free to choose any value for the phase of the first RF pulse, \( \phi_{1} \). The obvious choices are either 0° or 180°. Although no residual signal is expected from FID1, there is no penalty for setting \( \phi_{1} \) = 180°. Thus, the final exotic phase cycle where Echo23 and FID3 are incremented sixteen times is: \( \phi_{1} = 180°, \phi_{2} = 67.5°, \phi_{3} = 157.5° \), and based on the phase equation for STEAM N (Table 1), \( \phi_{ADC} = 45° \). 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 diagonal projections. CLDs are 1-D representations of the 2-D non-averaged 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.

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.