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Unconventional trajectories on the Bloch Sphere: A closer look at the effects and consequences of the breakdown of the rotating wave approximation

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Synopsis

TRASE MRI uses rapid π -pulses of phase gradient fields, and in general requires as many as two distinct phase-gradient coils per encoding direction. This tends to restrict one to large amplitude, linear B_1 fields, which in low B_0 field leads to a breakdown of the rotating wave approximation. We have studied this regime both numerically and experimentally. Our results show a rich behavior involving a complex interplay of the Bloch-Siegert shift, the B_1 start and stop phase, and B_1 amplitude transients.

Introduction

TRansmit Array Spatial Encoding (TRASE) is a relatively new MRI method^{1,2} for which spatial encoding is achieved through the application of phase gradients of the B_1 field – rather than magnitude gradients of the B_0 field – and in general requires as many as two distinct phase-gradient coils per encoding direction. Moreover, traversal through k -space with TRASE requires a train of π -pulses generated by alternating phase-gradient coils. As a result, there is very strong motivation here to employ linear rather than rotating B_1 fields (lest the already large number of rf coils should further double) and to understand the full details of rapid π -pulse generation with such fields. This is particularly important for our ongoing evaluation^{3,4,5} of the benefits and limitations of TRASE at low field, where the magnitude of the linear B_1 field may not be negligibly small compared to B_0 leading to a breakdown of the rotating wave approximation (RWA). Here we explore the unconventional trajectories on the Bloch sphere arising from the breakdown of the RWA. Our work reveals a complex interplay of Bloch-Siegert shift,⁶ B_1 start or end phase,⁷ and B_1 amplitude transients⁸ that must be taken into account to achieve the expected trajectory terminus.

Methods

We studied the effects and consequences of the breakdown of the RWA through analytical and numerical solutions of the Bloch equations. For convenience, we express the magnitude of the B_1 field as the parameter $N_\pi = B_1/B_0$, which is the number of cycles of the oscillating field required to achieve a π -radian rotation. As such, the continuous wave Bloch-Siegert shift⁶ becomes $\Delta B_{cw} = B_0/(4 N_\pi)^2$. For all simulations presented here, we fixed the B_1 frequency to its nominal value ω_0 , applied rectangular pulses of linear field $B_1 \cos(\omega_0 t + \varphi)$ along the x -axis in the laboratory frame, and managed any de-tunings through a field shift δB away from B_0 . Experimental studies were performed in B_0 fields of a few mT or less, using both water and hyperpolarized ³He gas samples.

Results

Numerical simulations are shown in Figures 1 through 4; experimental results are in Figure 5. Figure 1 highlights the general effects of the breakdown of the RWA due to a strong counter-rotating B_1 field: the trajectory undergoes cycloid motion and a perfect π -pulse cannot be achieved without de-tuning the field. Every half-period, the trajectory without/with de-tuning lands on that due to a rotating B_1 field with/without de-tuning of the same magnitude. Figure 2 highlights the fact that the specific details of the cycloid trajectory, and in particular its terminus, depends strongly on the phase of the B_1 field. Starting and stopping pulses at the cusps in the trajectory (ie. zero field and zero coil current, occurring every half-period) is an important strategy for eliminating further complications due to B_1 amplitude transients in real coils. As shown in Figure 3, a perfect π -pulse can always be achieved by de-tuning the field by $\delta B = \beta \Delta B_{cw}$, where to lowest order the prefactor β depends only on the phase φ . In Figure 4, we show the effect of the breakdown of the RWA on a π -pulse intended to rotate transverse magnetization about the x' -axis in the rotating frame. Again, the appropriate de-tuning of the static field will achieve the desired rotation. In Figure 5, we present a small compilation of experimental results achieved to date. In particular, we show data that confirms the $1/N_\pi^2$ behavior of the Bloch-Siegert shift, as well as the magnitude and change of sign of the prefactor $\beta(\varphi)$. The Bloch-Siegert shift is determined experimentally as the de-tuning δB required to achieve a perfect π -pulse. We also present a comparison of the performance a composite π -pulse versus a simple rectangular π -pulse. Arbitrary pulse shapes and durations have also been investigated.

Discussion and conclusion

We have made extensive numerical and experimental studies of the breakdown of the RWA due to a strong counter-rotating B_1 field. Our results show a rich behavior involving the Bloch-Siegert shift, B_1 start and stop phase, and B_1 amplitude transient that is of fundamental interest in magnetic resonance. It is of great practical importance for low-field MR applications, in particular TRASE MRI where one is more or less restricted to using large amplitude, linear B_1 fields. Achieving the expected trajectory terminus in this regime requires an appropriate phase-dependent de-tuning of the field. Using pulse durations and sequence timings that are half-integer multiples of the B_1 period is also beneficial.

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Figures

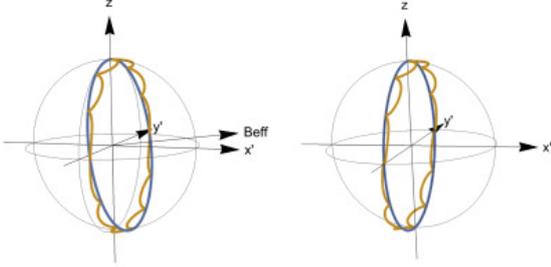


Figure 1: Illustration of the general consequence of the counter-rotating term on the trajectory: rotating field (blue) versus linear field (yellow). Simulations with $N_{\pi} = 3$. Left: Off-resonance rotating field ($B = B_0 + \delta B$) and on-resonance linear field ($B = B_0$). Right: On-resonance rotating field ($B = B_0$) and off-resonance linear field ($B = B_0 - \delta B$).

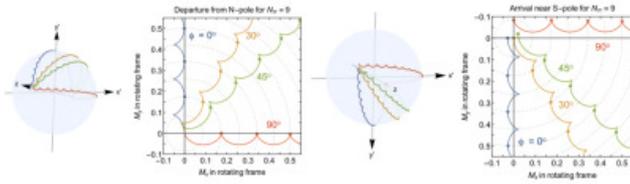


Figure 2: Trajectories near the beginning (left) and end (right) of a π -pulse with $N_{\pi} = 9$ and $\delta B = 0$. With no Bloch-Siegert shift, a perfect π -pulse can only be achieved with $\phi = 30^\circ$. The circles indicate time intervals equal to half-periods of the B_1 field from the start of the pulse. For $\phi = 90^\circ$ these occur at the cusps in the trajectory, which occur when the net B_1 field is zero.

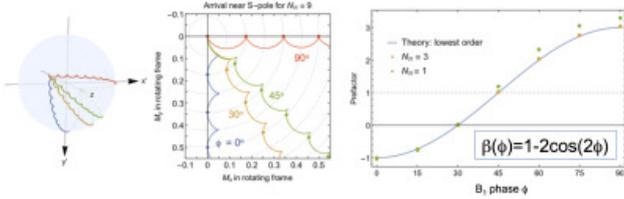


Figure 3: Trajectories near the end (left) of a π -pulse with $N_{\pi} = 9$ and $\delta B = \beta \Delta B_{CW}$. With the appropriate de-tuning, a perfect π -pulse can be achieved for any ϕ . Plot of the analytic form of β for the case where $N_{\pi} = n/2$, where n is an integer. Simulations for $N_{\pi} = 1$ and 3 reveal a higher order dependence of β on the magnitude of B_1 .

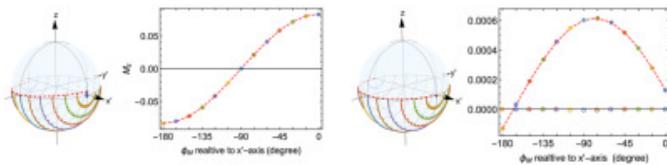


Figure 4: A π -pulse starting with unit magnetization in the transverse plane: $N_{\pi} = 9$ and $\phi = 0^\circ$. Left: On-resonance. The terminus overshoots or undershoots, depending on the original phase of the magnetization $\phi_M(0)$. Final M_z values, shown in the plot, are up to ± 0.08 . Right: Off-resonance ($B = B_0 - \delta B$, with $\delta B/B_0 = -1/(4N_{\pi})^2$). Final M_z values are reduced to below 1ppt for the nominal shift ($\beta = -1$, points, red dashed line). Using a more precise value of β to account for higher order effects reduces M_z to the ppm level (points).

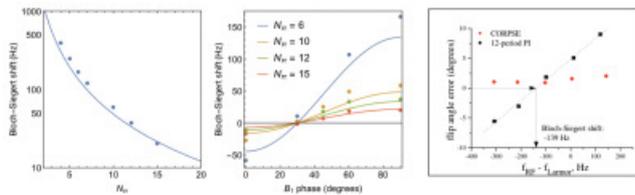


Figure 5: Some experimental results. Left: Bloch-Siegert shift versus N_{π} for $\phi = 90^\circ$ with data (points) and theory (line). Center: Bloch-Siegert shift versus ϕ for various N_{π} with data (points) and theory (lines). Right: Flip angle error (degrees from 180°) versus de-tuning for CORPSE composite pulse and an $N_{\pi} = 12$ rectangular pulse. The former remains insensitive to de-tuning despite the departure from the RWA.