Selective adiabatic population inversion at low rf peak amplitude

L. K. Mitschang[1], H. Rinneberg[1]
[1]Medical physics and metrological information technology, Physikalisch-Technische Bundesanstalt, Berlin, Germany

Introduction

Adiabatic pulses are frequently used in MRI to invert spins over a specified range of transition frequencies robustly when subjected to a nonuniform rf amplitude. While principally any amplitude/frequency modulation scheme – if slowed down sufficiently – could be used to induce adiabatic following, an arsenal of dedicated pulse shapes are in use. The reasons are limitations which exist in pratice for the execution time because relaxation losses occur concomitantly, for the absorbed energy because the sample heating can be a hazard, particularly in human applications, and for the rf peak amplitude because high power loads can provoke probe arcing. In addition, spectral selectivity is pivotal in many applications, e.g. for a slice selective approach. In this work, a novel adiabatic pulse is derived which resembles the well known sech/tanh pulse in performance, but at a significantly reduced rf peak amplitude.

Methods

A linear frequency sweep at constant pulse amplitude – if it extends infinitely – is ideal to affect all isochromats equally and independently of their transition frequency [1]. If the sweep is restriced to a specified bandwidth (BW), however, the rf amplitude must be quenched properly to achieve selectivity [2]. Restricting the discussion to one half of the symmetric pulse shape, the end point of the linear sweep with amplitude ω_{1max} and offset BW/2 relative to the center of the specified band must be connected to a point of vanishing amplitude outside the band, say with offset (BW+b)/2, by a smooth curve (see Fig. 1). Consider adiabatic following of the boundary isochromat, the isolated spin with resonance offset BW/2 with respect to the center of the frequency band. For apodization we choose a quarter ellipse with half axes b/2 and ω_{1max} which blends – as required – smoothly into the linear sweep region. In addition, the effective field is removed very cautiously from the z-axis, as the slope of the trajectory vanishes initially. The boundary isochromat obeys adiabatic following, i. e. follows the effective field, as long as the adiabatic approximation, expressed in terms of the adiabaticity parameter $k(t) = \omega(t)/d\theta(t)/dt$ as k(t)>>1, is valid. The length of the effective field, $\omega(t)$, and its polar angle, $\theta(t)$, refer to the frequency frame [1]. To minimize relaxation losses, we require most rapid adiabatic following of the boundary isochromat, i. e. with constant, the smallest yet tolerable value of the adiabaticity parameter, k_0. The modulation schemes must then satisfy the expression $d\theta(t)/dt = k_0\omega(t) = k_0 b/2\mathrm{Sqrt}[1+\varepsilon^2 \sin^2\theta]$ where ε is the eccentricity of the ellipse. The solution $\theta(t)$ determines the effective field $\omega(t)$ and, thus, the pulse shape during the apodization uniquely. For the linear frequency sweep at constant field amplitude adiabaticity is most crucially affected for a particular isochromat when the resonance condition is traversed [1]. That point in time coincides in case of the boundary isochromat with the discharge of the elliptical path into the linear sweep. To avoid any discontinuities in adiabatic tracking of the boundary isochromat, we maintain the adiabaticity parameter at the constant value k_0 at the blend point. In consequence, the rate for the linear sweep becomes $k_0\omega_1^2$. Thus, by proper choice of k_0, the pulse allows for inversion of the boundary isochromat by adiabatic tracking along the complete trajectory. But also all isochromats within the specified band are adiabatically inverted in this case. For each one of them obeys adiabatic following at least to the same degree as the boundary isochromat because their adiabaticity parameter never drops below k_0 (k_0 is probed only once, when the linear sweep traverses the resonance). On the other hand, our choice of the magnitude of the adiabaticity parameter to just make adiabatic following of the boundary isochromat along the elliptical path possible, implies failure to do that in case of isochromats with a smaller adiabaticity parameter. For resonance offsets in the range BW/2 to b+BW/2 the effective field and the adiabaticity parameter are initially smaller than for the boundary isochromat, because the trajectory starts with zero slope. Thus, the transition region inverted/non-inverted magnetization has a width on the order of b.

Results and Discussion

Numerical calculation of inversion in dependence of rf peak amplitude and resonance offset is displayed in Fig. 2 for the new adiabatic pulse, as well as for the sech/tanh pulse [3]. Both pulses are calibrated to a bandwidth of 8 kHz and a length of 9 ms which is matched by the settings $k_0 = 3.3$, $b/2\pi = 835\,\mathrm{Hz}$ and $\omega_{1max}/2\pi = 800\,\mathrm{Hz}$ for the new pulse. The sech/tanh pulse requires a 94% higher field amplitude than the new pulse to achieve 95% homogeneous population inversion over the specified bandwidth. Both pulses have a similiar energy and width of the transition region at the threshold value of the field amplitude for 95% inversion (the ratio of these quantities for sech/tanh to those for the new pulse are 0.94 and 0.89, respectively). For the new pulse, however, the transition region increases modestly with rf field strength. Thus, in comparison to the sech/tanh pulse the new pulse can achieve selective inversion at almost half the rf peak amplitude on cost of a slight increase in energy deposition in the sample and profile sharpness. Recently, Rosenfeld el al. have presented an adiabatic inversion pulse which shares, despite significant differences in design and actual shape, some features with the new pulse, particularly, a linear frequency sweep region and an emphasis of the boundary isochromat [4]. The ratio of rf peak amplitude, energy, and width of the transition region at the threshold rf peak amplitude for 95% inversion of their pulse (8 kHz bandwidth, 9 ms length) to those quantities of the new pulse are 1.07, 1.2, and 1.2, respectively.

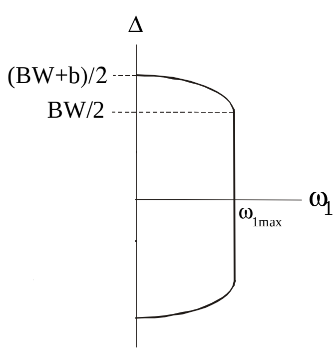

Fig. 1: Pulse trajectory, offset $\Delta(t)$ vs. amplitude $\omega_1(t)$, in frequency frame with respect to the isochromat at the center of the specified bandwidth.

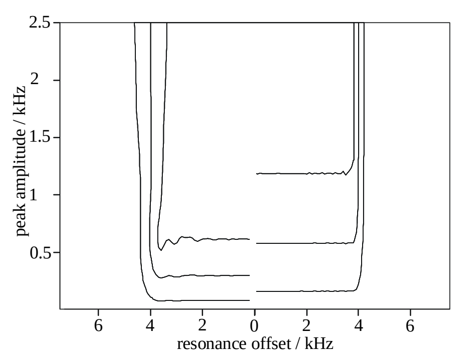

Fig. 2: Contours of longitudinal magnetization at the end of the new (lhs) and sech/tanh pulse (rhs). Inner, middle, outer line are 95%, 50%, 5% inversion.

References

[1] Garwood M, et al., J. Magn. Reson. 2001; 153:155-177. [2] Kupce E, et al., J. Magn. Reson. A 1995; 117:246-256. [3] Silver M S, et al., Phys. Rev. 1985; A31:2753-2755. [4] Rosenfeld D, et al., Magn. Reson. Med 1996; 36:124-136.