A bandwidth-modulated adiabatic RF pulse for highly selective saturation and inversion (BASSI)

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Introduction Applications such as outer volume suppression or pulsed arterial spin labeling require RF inversion and saturation pulses with extremely high spatial selectivity. It has been shown that, at fixed peak RF amplitude, the selectivity of adiabatic RF pulses can be further improved using a variable slice-select gradient [1,2]. We present here a *b*andwidth modulated *a*diabatic highly *s*elective *s*aturation and *i*nversion RF pulse (BASSI). The corresponding amplitude modulation was derived from an analytical calibration equation for hyperbolic secant (HS) pulses [4]. The current scheme is compared to previous approaches.

Methods The amplitude and frequency modulation functions and the gradient amplitude of the HS pulse can be written as:

$$AM(t) = \frac{a}{\pi}\frac{2\beta}{T_p}\frac{1}{2\pi\gamma}\operatorname{sech}\left(\frac{2\beta}{T_p}t\right),\ FM(t) = \frac{b}{\pi}\frac{2\beta}{T_p}\tanh\left(\frac{2\beta}{T_p}t\right),\ G(t) = \frac{b}{\pi}\frac{2\beta}{T_p}\frac{1}{\pi\gamma\Delta x}$$

with amplitude, bandwidth and cutoff parameters a, b and β, width of the inverted slab Δx, pulse duration T_p, time $t \in [-T_p/2; T_p/2]$ and gyromagnetic ratio γ. Starting from these conventional equations, we introduce a time-varying bandwidth parameter $b(t) = f(t)\, b_0$, so that the bandwidth of the pulse can be increased during its beginning and end when the transition bands are inverted, leading to increased selectivity. At the same time the RF amplitude in the central part of the pulse can be limited. The corresponding amplitude parameter $a(t) = 2\sqrt{L}\sqrt{b(t) - L}$, with $L = \ln\left((1-P_e)^{-\frac{1}{2}}\right)$, depends on the desired population inversion $P_e = (M_0 - M_z)/(2M_0) = \frac{1}{2}(1 - cos(\alpha))$, α being the equivalent flip angle [4]. This amplitude modulation corresponding to the instantaneous bandwidth parameter is derived from an analytical solution of the Bloch equations and ensures homogeneous population inversion. We chose a smooth modulation function f that affords close to constant RF amplitude in the central part of the pulse and that increases the bandwidth (and thus the gradient strength) by a maximal factor of f_0 at the borders (Figure 1):

$$f(t) = \left(\left(\cosh^2\left(\frac{2\beta}{T_p}t\right)\left(1 - \frac{L}{b_0}\right) + \frac{L}{b_0}\right)^{-2} + f_0^{-2}\right)^{-\frac{1}{2}}.$$

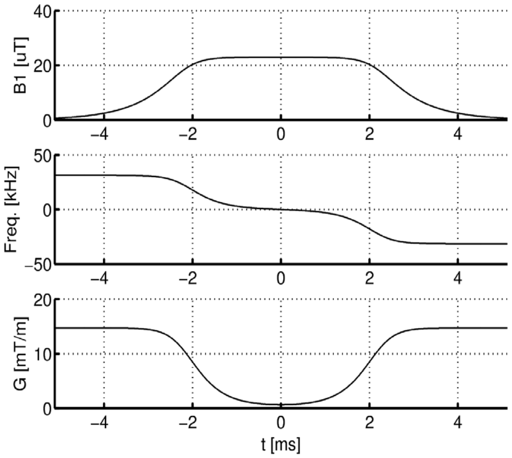

Figure 1: Pulse shape of the BASSI pulse with $\alpha = 175°$, $T_p = 10.24\,\text{ms}$, $\beta = 6.3$, $b_0 = 22.8$, $f_0 = 22$.

This pulse is conceptually similar to the C-shape FOCI pulse [2], but uses an analytically derived relation between amplitude and bandwidth modulation ensuring homogeneous inversion across the entire bandwidth, and a smooth modulation function rendering the pulse more robust to slight offsets between RF and gradient waveforms due to hardware imperfections.

Using numerical simulations of the Bloch equations, we compared the BASSI pulse presented here to: (1) a conventional HS pulse, (2) the GOIA pulse derived from the BASSI amplitude and gradient modulation functions [3], (3) the C-shape FOCI pulse [2] and (4) a VERSE version of the HS pulse [1]. Criteria for the comparison were the selectivity (width of the transition region from 5% to 95% of the target inversion), the homogeneity of the inversion (rms deviation from the target population inversion of the inversion profile inside the pass band) and the total pulse energy. Each of the pulses was parameterized for saturation and inversion (target flip angles of 90° and 175°, respectively) within typical hardware limits of 1.5T MR scanners (maximum RF and gradient amplitudes of $23\,\mu\text{T}$ and $26\,\frac{\text{mT}}{\text{m}}$, respectively). To retain acceptable selectivity, the HS inversion pulse used a reduced flip angle of 170°. Common pulse parameters were a slab width of 100 mm as well as pulse durations of 8.1 ms and 10.24 ms for saturation and inversion pulses, respectively. To suppress ringing in the profile due to the cutoff of the amplitude modulation function, the pulses were apodized using a quaterwave sine during the first and last 4% of the pulse.

Results and Discussion Table 1 shows the pulse parameters used and the results obtained with each of the pulses. The HS pulse achieves excellent homogeneity, but only limited selectivity, especially for inversion. The BASSI pulse is highly selective and homogeneous for both saturation and inversion while using the lowest pulse energy among the alternatives to the HS pulse tested here. This pulse cannot be improved by re-calculating the frequency sweep using the GOIA approach. The C-shape FOCI pulse suffers from the overestimation of the pulse amplitude, leading to high pulse energy, extreme heterogeneity of the saturation profile, and degradation of the inversion selectivity. The VERSE pulse performs very well for saturation, albeit requiring higher energy than the BASSI pulse. For inversion, bandwidth (and thus selectivity) is limited by the gradient amplitude at the borders of the pulse. The excellent performance of the BASSI pulse is confirmed experimentally, Figure 2 showing a pulse profile obtained in an agar phantom using two successive BASSI saturation pulses parameterized as shown in Table 1.

Conclusion The bandwidth modulated RF pulse presented here achieves extremely high selectivity and uniformity at a moderate increase of pulse energy with respect to a HS pulse. It is applicable to inversion as well as saturation of longitudinal magnetization. Preliminary findings suggest that a QUIPPSII PASL sequence using BASSI saturation and inversion pulses can operate at label gaps as low as 2 mm without detectable influence of the label pulse on static spins in the imaging region.

	α=90°, T_p=8.1 ms						α=175°, T_p=10.24 ms					
Pulse	β	b_0	f_0	tw	hom	E	β	B_0	f_0	tw	hom	E
HS	5.3	157	N/A	1.83	0.37%	1	5.3	37.7	N/A	8.5	0.13%	1
BASSI	5.3	167	3	0.61	0.40%	1.26	6.3	22.8	22	0.68	0.07%	1.59
GOIA	5.3	167	3	0.61	0.42%	1.26	6.3	22.8	22	0.68	0.56%	1.59
FOCI	5.3	167	3.2	0.42	30%	1.53	6.3	22.8	22	1.14	0.43%	1.91
VERSE	5.3	228	2.2	0.63	0.35%	1.51	5.3	80.4	11	1.68	0.05%	2.09

Table 1: Comparison of the BASSI pulse to other pulses described in the literature. The transition width (tw) between 5% and 95% of the target inversion is measured in mm; the homogeneity (hom) is expressed as relative rms deviation from the target inversion; and the pulse energy (E) is normalized to the energy of the HS pulse. The VERSE pulse cannot be described in terms of a bandwidth modulation. The parameters b_0 and f_0 cited for that pulse are purely descriptive of the gradient waveform used.

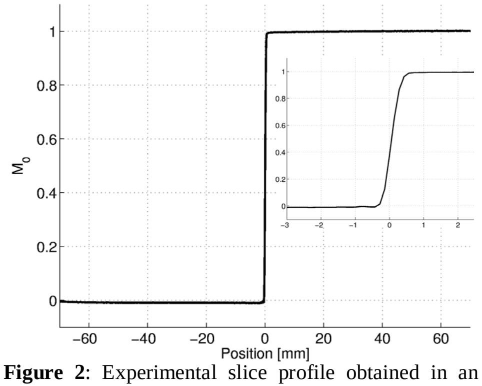

Figure 2: Experimental slice profile obtained in an agar phantom (T_1=2700 ms, T_2=70 ms) following two BASSI saturation pulses. The profile was acquired using a high resolution (140 µm) spin-echo sequence with the readout oriented in the troughplane direction of the saturation pulses.

References

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