Fast Sequence Optimization for Superior Signal Suppression with Multiple Hyperbolic Secant Pulses

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INTRODUCTION: Most water suppression sequences for MRS by executing a series of chemical shift selective excitation pulses, each followed by crushers. Many sequences have been proposed to reduce the sensitivity flip angle errors. Optimizing the nominal flip angles of each of the pulses can render the sequence somewhat insensitive to B1 field inhomogeneity, but, the frequency response profile of selective non-adiabatic pulses often changes with flip angle. Thus, a pulse with an ideal flat suppression band and narrow transitions can exhibit a far less ideal profile at flip angles other than the design flip angle deteriorating the response away from the centre of the suppression band and rendering the sequence susceptible to errors from combined B1 and B0 inhomogeneity. These are the problems that most plague 1H-MRS in high field magnets and they can be overcome by the use of selective adiabatic pulses for solvent suppression sequences. Adiabatic pulses have been used for water suppression in 1H-MRS, but either the side band was used (1,2), giving a non-ideal suppression profile, or an inordinately high number of pulse was used (3), restricting use due to SAR limits. Simple substitution of non-adiabatic pulses by adiabatic pulses in optimized water suppression sequences will lead to disappointing results because adiabatic pulses have a fundamentally different relation between B1 and flip-angles. A method for fast optimization of sequences with sech pulses is presented and illustrated with the optimization of water suppression sequence.

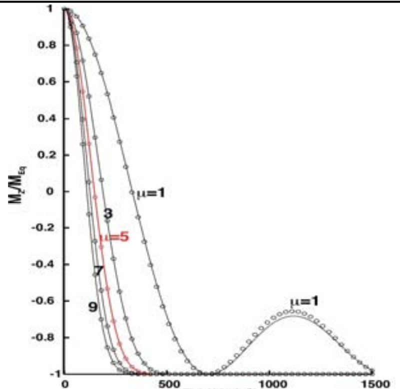

***Figure 1**. Comparison of Eq 1 (lines) and numerical simulation (circles) BW=1kHz with quality factor, μ, varied from 1 to 9.*

THEORY: An analytical expression for the on-resonance residual longitudinal magnetization, M_z/M_{Eq}, for a hyperbolic secant (sech) adiabatic pulse can easily be derived from Eq 17 in reference (4) by setting the off-resonance terms to zero:

$$\frac{M_Z}{M_{Eq}} = \frac{1-\cosh(-\pi\cdot\mu)+2\cos\left[\pi\cdot\mu\sqrt{\left(\frac{\gamma\cdot B1}{BW\cdot\pi}\right)^2-1}\right]}{1+\cosh(-\pi\cdot\mu)} \qquad [1]$$

With the cosine of imaginary numbers calculated as: $\cos(z)=\frac{e^{iz}+e^{-iz}}{2}$ [2],

where μ = quality factor, BW: bandwidth [Hz], B1 in μT and γ: gyro-magnetic ratio in rad*s^{-1} /μT . Comparison of Eq. 1 and numerical simulation is shown in Fig. 1 for various values of μ. Because with Eq. 1 the resulting M_z/M_{Eq} can be calculated much faster than a numerical simulation of the Bloch equations, the cumulative effect of a number of sech pulses can be optimized with any stable optimization algorithm. The VAPOR water suppression sequence(5), which uses seven pulses with optimized delays and amplitudes, does not yield a good result with adiabatic pulses (see Fig. 2B). Eq. 1 was used to optimize the relative RF amplitudes for this sequence to work with adiabatic the sech pulses.

METHODS: All calculations were performed in *Matlab* (Mathworks, Natick, MA). M_z/M_{Eq} was calculated as a function of B1 and offset for the VAPOR suppression scheme using a 52ms hamming windowed seven-lobe sinc pulse and a 47ms sech pulse, μ=4, both with BW=250 Hz. The T1=1s and inter-pulse delays and pulse amplitudes were taken from (5), normalized to the B1 for a 90º flip (sinc required 40% more peak RF power). VAPOR delays and amplitudes (Table 1) were used as start values for an optimization of the amplitudes with the Levenberg-Marquardt algorithm for best suppression for the interval $20<\gamma B1/2\pi<140$ Hz. The error function values, E=abs(M_z/M_{Eq} (B1)), were multiplied by $w=\exp(-pa^p)$, $-1<a<1$, p = 24 to de-emphasize the errors at edges of the interval.

RESULTS: Fig. 1 shows an excellent agreement between numerical simulation and analytical solution using Eq 1, except for low μ and high B1 probably because the pulse shape used for numerical simulation was truncated at 1%. The response for VAPOR with a high definition sinc pulse (Fig 2A,E black) is much better than VAPOR with sech pulses (Fig 2B,E --) but after the optimization (fig 2D) of relative pulse amplitudes VAPOR with sech pulses shows a very good response (Fig. 2C,E red), extending the range of B1 independent suppression and with more consistent suppression off-centre.

CONCLUSION: This optimization method will allow the substitution of adiabatic pulses into many selective signal suppression schemes and this can yield superior performance on and off-resonance for 1H-MRS.

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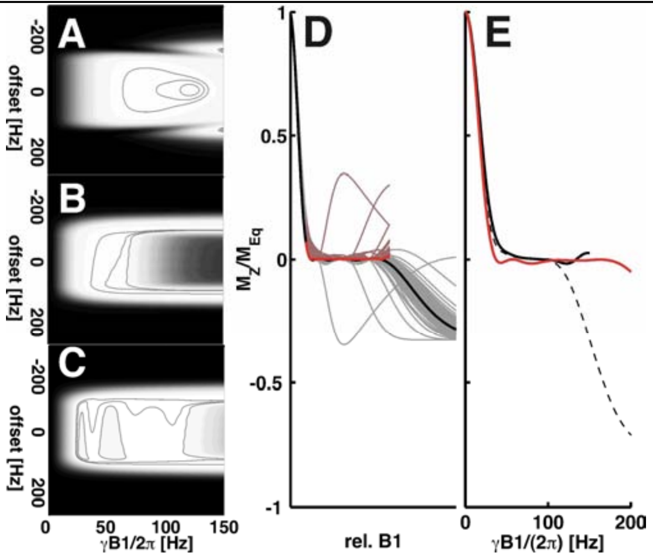

***Figure 2.**A-C: Intensity plots of $|M_z/M_{Eq}|$ after VAPOR suppression. $|M_z/M_{Eq}|$ =0 is white and contours are drawn at 0 and ±1% levels. A) VAPOR water suppression scheme with sinc pulse B)VAPOR with sech pulse C) VAPOR optimized for sech pulses (Table 1). D) Optimization of pulse amplitudes for sech pulses. Red trace is the error function and black trace is the Mz/Meq intermediate steps are shown in lighter shades. E) On resonance responses taken from plots A (black thick line), B (dashed line) and C (red line).*

Table 1.Optimized VAPOR pulse amplitudes

for sinc:	0.75	0.75	1.33	0.75	1.33	0.75	1.33
for sech:	0.71	0.56	1.10	0.52	1.54	0.42	2.15