Improved off-resonance phase behavior using a phase-inverted adiabatic half passage pulse for ^{13}C MRS in humans at 7T

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Introduction In vivo ^{13}C MRS is currently performed using surface coils in combination with adiabatic pulses for excitation. The high filling factor provided by surface coils results in good signal-to-noise ratio (SNR), while B_1 inhomogeneities are mitigated using adiabatic pulses [1]. However, the performance of adiabatic pulses degrades with off-resonance. The resonance offset must be taken into consideration when the sample contains nuclei with different Larmor frequencies, since the adiabatic condition is not necessarily satisfied simultaneously for all spins. In particular, the excitation bandwidth of adiabatic half passage (AHP) pulse is asymmetric relative to the carrier frequency, which could lead to asymmetric excitation of spectral lines relative to the centre of the spectrum. Therefore, the aim of this study was to implement a pulse-acquire sequence for adiabatic ^{13}C excitation with a symmetric bandwidth, utilizing a combination of two AHP pulses with inverted phases in alternate scans, and to test its feasibility for in vivo ^{13}C MRS at 7T by measuring natural abundance of ^{13}C signal intensities on the human muscle.

Methods A ^{13}C-linear/ ^{1}H-quadrature RF surface coil was built [2]. A pulse-acquire sequence with adiabatic half passage excitation (2050 µs) was implemented, combining an AHP pulse and a phase inverted Reverse-AHP (RAHP) in alternate scans (Figure 1). A Bloch simulator was implemented in Matlab to evaluate the off-resonance effects of AHP, RAHP, and AHP+RAHP sequences. MR experiments were performed on a 7T human scanner (Siemens Erlangen/Germany). A sphere (Ø = 7 mm) filled with 99% ^{13}C-enriched formic acid was placed in the centre of the ^{13}C coil as an external reference. The excitation bandwidth of AHP and AHP+RAHP sequences was measured in vitro by exciting formic acid at frequency offsets in a range of 2 kHz in 50 Hz steps (vector size 2048, TR = 10s, BW = 20 kHz, decoupling duration = 87 ms, 1 average (AHP) or 2 averages (AHP + RAHP)). In vivo non-localized ^{13}C MRS was performed on the human calf of 4 healthy volunteers who gave informed consent according to the procedure approved by the local ethics committee, to measure glycogen C_1 at the centre of the spectrum (decoupling duration = 20 ms, vector size = 2048, BW = 20 kHz, TR = 1 s and 256 averages). Both in vitro and in vivo results were compared with the simulated transversal magnetization (M_{xy}) at the required $\gamma B_1/2\pi$ for AHP.

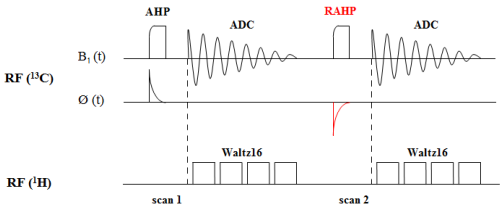

Figure1: Pulse-acquire sequence for symmetric ^{13}C adiabatic excitation, using an AHP pulse and a phase inverted RAHP pulse in alternate scans. Waltz16 scheme [3] was applied to achieve broadband ^{1}H decoupling.

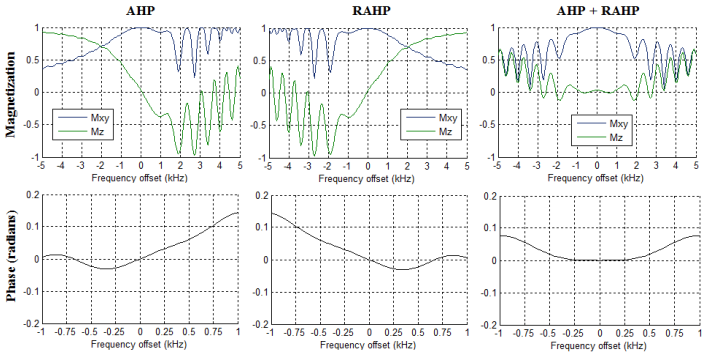

Figure2: Bloch simulations for each sequence, including magnetization and phase to resonance offset. The Bloch equations were programmed in Matlab, using 2050 µs pulse length and B_1 amplitude was normalized to 2 kHz.

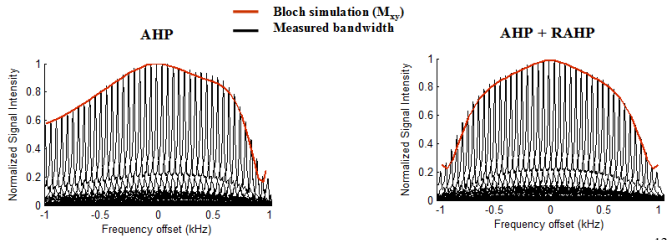

Figure3: Simulated transversal magnetization (M_{xy}) at 650 Hz (red) and ^{13}C excitation bandwidth measured in vitro on formic acid (black), using AHP pulse (left), and alternating AHP and RAHP pulses (right).

Conclusion It is feasible to apply two phase-inverted adiabatic half passage pulses for ^{13}C excitation to achieve a symmetric excitation bandwidth and a flatter phase-response to off-resonance, and this will allow further extension of this technique for ^{13}C MRS measurements such as in the human brain.

Results Bloch simulations show a proof-of-concept of symmetric excitation (M_{xy}), saturation (M_z), and phase (Ø) to off-resonance obtained with pulse-acquire when alternating AHP and RAHP (Figure 2). In vitro measurements on formic acid demonstrated a symmetrically excited bandwidth over 2 kHz using pulse-acquire when alternating, in agreement with Bloch simulations using the required $\gamma B_1/2\pi$ = 650 Hz for AHP (Figure 3). Natural abundance of glycogen C_1 (100.5 ppm) was detected in human muscle, as well as glycerol (62 and 69 ppm), fatty lipids (30 and 130 ppm), and methyl (15 ppm) peak (Figure 4). In particular, intensities of the lipids peaks are close to those theoretically predicted when using AHP+RAHP sequence, compared to those obtained with the AHP sequence.

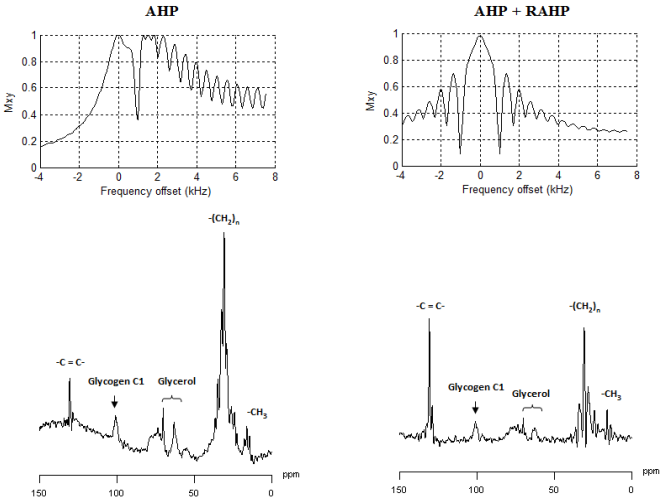

Figure4: Simulated transversal magnetization (M_{xy}) at 650 Hz (top) and in vivo ^{13}C NMR spectra of the calf muscle (bottom) using AHP (left), and alternating AHP and RAHP (right). Both spectra are with same vertical scale.

References [1] A. Tannús et al 1997; [2] G. Adriany et al 1997; [3] A. J. Shaka et al 1983

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