Spectroscopic imaging with volume selection by unpaired adiabatic π pulses: Theory and application

J. Valette[1], J-Y. Park[1], O. Gröhn[1], K. Ugurbil[1], M. Garwood[1], and P-G. Henry[1]

[1]CMRR, University of Minnesota, Minneapolis, MN, United States

Spectroscopic imaging (SI) of the brain combined with prelocalization allows minimization of spectral contamination by lipid signal from the scalp. Prelocalization can be achieved using adiabatic pulses, leading to excellent insensitivity to B_1 inhomogeneity and to reduced chemical shift displacement error due to the high achievable bandwidth (BW) of adiabatic pulses [1]. An example of fully adiabatic localization sequence is the LASER sequence [1], which can be used for SI prelocalization [2,3]. In LASER, after a non-selective excitation, volume selection along the three spatial dimensions is achieved by three pairs of adiabatic full-passage (AFP) pulses (π rotation) in conjunction with B_0 gradients. AFP pulses are used in pairs because the π rotation induced by a single AFP pulse generates a spatially non-linear phase which must be refocused by the second AFP in order to restore full signal. The present work explores the feasibility of SI using only one AFP pulse per dimension, in order to reduce the number of pulses and the echo-time (TE). Theoretical considerations are developed, and adequate spatial and spectral post-processing is presented. A new adiabatic sequence allowing selection with unpaired AFP pulses, named Pseudo-LASER, is then used for 2D-SI in the rat brain at 9.4 T.

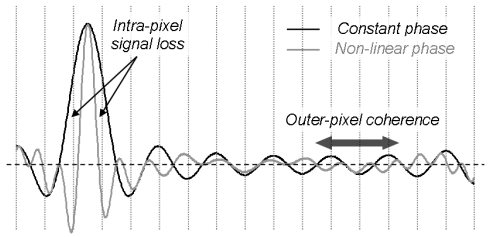

Fig. 1: SRF of the 3rd pixel for a uniform k-space (N=16) with Φ=0 (black) or a non-linear phase (gray).

Theory

Modulation of the SRF by the non-linear phase profile: Fig. 1 illustrates how a non-linear phase Φ modulates the spatial response function (SRF): *i)* within the considered pixel, the signal dephasing results in a narrower main peak and hence in a reduced intra-pixel signal; *ii)* outside the pixel, the secondary lobes can be coherently modulated by the phase so that they do not average to zero over large regions, yielding a large outer-pixel contamination. Integration of the SRF allows the derivation of a unique condition (the C_N condition) to simultaneously keep intra-pixel signal loss smaller than 5% for each dimension localized with unpaired AFP, and to keep outer-pixel contamination equivalent to the case where the phase is constant. This C_N condition is: $|\partial\Phi/\partial x| \leq 0.3k_{max}$ (where the *k*-space is uniformly sampled between $-k_{max}$ and k_{max}). For the phase profile induced by an unpaired hyperbolic secant (HS) pulse, the C_N condition is expressed as: $N \geq 1.75 \times R \times FOV/THK$ (*N*: number of encodings; *R*=product of BW in Hz by the pulse duration T_p in s; *FOV*: field of view; *THK*: thickness of the slab).

Spatial apodization by a sliding window: Spatial apodization is usually performed on SI data in order to minimize secondary lobes of the SRF. The associated increased pixel size may lead to a dramatic intra-pixel signal loss on the edges of the image when using unpaired AFP pulses. However, for any given pixel in x_p, a window centered on $(\partial\Phi/\partial x)(x_p)$ restores full signal, in analogy to the sliding window described by Park *et al.* [4]. Indeed, a shift of the window by an amount $-(\partial\Phi/\partial x)(x_p)$ in the *k*-space is equivalent to a spatial linear phase $-(\partial\Phi/\partial x)(x_p) \times x$ in the image, which compensates for the intrapixel phase dispersion. For a Hanning window with width $2k_{max}$, shifts such as $0.4\text{-}0.5k_{max}$ still yield a relatively unaltered SRF, despite the truncation of the shifted window on one side. This allows a greater flexibility on the minimal number of encodings compared to the C_N condition for a uniform *k*-space.

Echo-time shifting: When using adiabatic frequency-swept pulses, spins are inverted when their resonance frequency matches the frequency of the pulse. Since this moment essentially depends of the position in the B_0 gradient, the spectroscopic echo (time when all chemical shifts are in phase) depends on the position. In particular, the earliest echo occurs before the nominal TE. Hence the acquisition has to start before the nominal TE in order to collect the earliest echo. Then, after spatial reconstruction, for each pixel, a number of points corresponding to the delay between the acquisition start and the local spectroscopic echo has to be removed at the beginning of the FID.

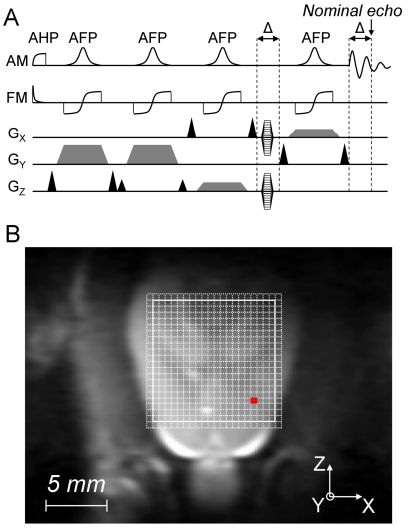

Fig. 2: A) The Pseudo-LASER sequence. B) The VOI localized by Pseudo-LASER (continuous lines), and the 22×22 SI matrix (dashed lines).

Methods

Experiments were conducted on a horizontal 9.4 T/31 cm Varian system. A surface quadrature coil was used for RF transmission and reception in the rat brain. A new sequence named Pseudo-LASER (fig. 2A), derived from LASER [1], was used to select a 10×3×10 mm^3 axial slab (fig. 2B). A pair of HS pulses (R=25, T_p=1.5 ms) was used for slab selection along Y. Then, two unpaired HS pulses (R=15, duration 1.5 ms) were used for selection along X and Z. A SI gradient in the X and Z directions was included just before the last AFP pulse. The acquisition started 10.7 ms after the excitation pulse (time of the earliest spectroscopic echo). The nominal TE (echo at the center of the VOI) was 12.5 ms, and the latest echo occurred 14.3 ms after the excitation. The SI FOV was 11×11 mm^2 spanned by 22×22 encodings, resulting in a nominal 0.5×0.5 mm^2 in-plane resolution. Total acquisition time was 97 min. The sequence and acquisition parameters corresponded to $|\partial\Phi/\partial x| \leq 0.4k_{max}$, compatible with a sliding Hanning window. The whole reconstruction procedure (sliding Hanning window + echo-time shift) was performed with Matlab.

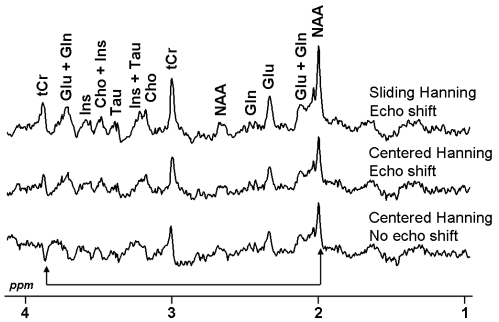

Fig. 3: Effect of the sliding reconstruction for a pixel near the edge of the VOI (in red on fig 2B).

Results

The impact of the sliding reconstruction on spectral quality is exemplified on fig. 3, for a pixel close to the edge of the VOI (in red on fig. 2B). Standard apodization by a centered Hanning window, and FID starting at the nominal TE, result in phase variation over the metabolite ppm range (bottom spectrum). Correcting for the echo-shift allows restoring a homogeneous phase (fig. 3, middle spectrum). Finally, the sliding Hanning window yields an increased SNR (+40% for the considered pixel, fig. 3, top spectrum). When the full sliding reconstruction was performed, spectra were equivalent to what could be obtained with SI localized with a conventional LASER sequence (not shown here).

Conclusion

In this work, conditions on the minimal number of pixels and adequate reconstruction procedures have been derived for SI localized with unpaired AFP pulses. These new insights have been applied to design a sequence, dubbed Pseudo-LASER, which was used in the rat brain. The main drawback of Pseudo-LASER is the high spatial resolution required. Advantages include a shorter TE and lower power deposition compared to regular LASER SI. Therefore this localization method may become more beneficial at higher magnetic field, when T_2 become shorter and power deposition increases. In particular, reducing the TE and the number of pulses may prove very beneficial when performing SI in the human brain at high field.

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[1] Garwood M and DelaBarre L, *JMR* 153, p.155 (2001); [2] McNab JA and Bartha R, *NMRBiomed* 19, p. 999 (2006); [3] Valette J et al., *Proc ISMRM Berlin*, p. 1248 (2007); [4] Park JY et al., *MRM* 55, p. 848 (2006).