A New k-Space Sampling Strategy for RARE Based Fast Spectroscopic Imaging

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Introduction: Various fast spectroscopic imaging (SI) methods have been proposed [1-6], each having specific advantages and drawbacks. In this study, we have considered the properties of spectroscopic RARE where all data points of a k_x-k_y-plane are sampled by a train of spin echoes and the chemical shift (cs) is encoded in a series of excitations [6]. This method allows improved signal separation and yields high SNR values if $T_2^* << T_2$. However, it has also inherent disadvantages. As the minimum total measurement time (T_{min}) is given by the number of encoding steps in k_ω (typ. 64-96), T_{min} is longer than for fast SI methods where T_{min} is given by the number of spatial encodings (typ. 16-32). Furthermore, localization problems in phase encoding direction occur if the J modulation is not broken in the spin echo train [7], i.e., if the inverse interecho delay ΔTE is not longer than the coupling constant J and the cs difference between coupled spins. Thus J-modulation of a signal may be misinterpreted as spatial phase encoding. This is a particular problem for weakly coupled spins (e.g., lactate or alanine) which increases with increasing B_0 [8]. In the following, a modified k-space sampling strategy is described which overcomes these problems and also opens the way to "J-scaling" [9,10].

Method: Fig.1 shows a 2D variant of the new RARE based pulse sequence for fast SI. Note that preceding standard parts for water, lipid and/or outer volume suppression are not shown. RF excitation is performed by a cs selective composite pulse supporting water and lipid suppression. A volume of interest may be selected by three spatially selective 180° refocusing pulses. Then a train of rectangular 180° pulses (a xyxy phase cycle suppresses off-resonance artifacts [11]) creates a train of spin echoes which are detected under a read gradient. Different to spectroscopic RARE [6], spatial phase encoding is not performed within the echo train but in a series of N_{pe} experiments. Additional delays are inserted between the 180° pulses to encode the chemical shift. Thus the echo trains acquire data from k_{read}-k_ω-planes at different points k_{pe}. Although the spectral linewidth will be broadened by $(2*\Delta TE)/\Delta t_{cs}*(1/(\pi T_2)$, this drawback is acceptable at high B_0 *in vivo* as $T_2^* << T_2$ and is compensated for by the improved spatial resolution.

Two variations to sample the k-space are displayed in schemes b,c of Fig.1. The first scheme (Fig.1b) corresponds to the pulse sequence of Fig.1a, where each echo acquires data at a different k_ω-position, so that all data of a k_{read}-k_ω-plane may be sampled by one echo train. Analogous to standard spectroscopic RARE, this variant requires a high B_1 homogeneity and precise gradient adjustment to avoid artifact signals [12]. Data processing may use two separate data sets ("FID mode") with either $k_\omega \geq 0$ or $k_\omega \leq 0$, or one data set combining all sampled data ("echo mode"). The second sampling scheme (Fig.1c) is more robust against B_1 inhomogeneities and offset effects. It uses groups of four echoes uniformly phase encoded and inserts an additional delay only after the 5th, 9th, 13th etc. 180° pulse. However, to achieve a sufficiently large spectral width (SW), N_{int} interleaves may be required (e.g., 2 or 4) by adding appropriate delays prior to the train of rectangular 180° pulses. Of course, interleaves may also be used for the first sampling scheme to increase SW.

Experimental: *NMR Hardware:* All experiments were performed on a 4.7T/40cm Biospec system (Bruker, Germany). A saddle-type resonator (98mm i.d.) was used for RF transmission and signal reception. Phantom experiments were performed on spheres or tubes filled with aqueous solutions of N-acetyl aspartate (NAA), myo-inositol (Ins) and/or lactate (Lac). *Pulse sequence: W*ater suppression by three consecutive 15ms Gaussian saturation pulses; 1-2τ-5.4-τ-5.4-2τ-1 composite pulse (τ=1.25ms, 80°); three 2.5ms optimized sinc-like 180° pulses; train of 140µs rectangular 180° pulses; interecho delay = 3.35-4.35ms; SW=1000 Hz (additional delay 1ms); The first of 129 echoes (1.6ms, 32 data points) was acquired at TE=15ms (slice selective) or TE=24ms (3D zoom); 32 phase encoding steps; FOV: 48*48mm^2; 3mm slice; TR=2s; two accumulations; no interleaves. *Data processing* used IDL (Bolder, USA) for data reordering in k-space, zero filing in k_ω, apodization, 3D FFT and magnitude calculation (echo mode) or phase correction (FID mode). Metabolic images were calculated by peak area integration in each voxel.

Results and Discussion: Fig.2 shows spectra measured by the proposed SI sequence with the k-space sampling scheme of Fig.1b. As the data were acquired in the echo mode along k_ω, magnitude spectra show no additional line broadening as compared to phase corrected spectra. Fig.2a displays a SI spectrum from a solution of 50mM NAA and 50mM Ins. Both the singlet signal of NAA and the signals of coupled spins of Ins and NAA are detected with good spectral resolution and high SNR (considering the nominal voxel size of only 6.5 µl and the short total measurement time of 2.1 minutes). Fig.1b shows the FLASH water image of this spherical phantom and Fig.2c a NAA map demonstrating the applied zoom technique (on a rectangular region within the FOV) and the good spatial resolution. Fig 2d shows a SI spectrum of a lactate phantom (100 mM). The lower SNR is primarily due to the used composite pulse. Note the 59 Hz line separation of the Lac doublet, although the coupling constant is J=6.9 Hz. This so-called "J-scaling" is a well known tool widely used in analytical 2D and heteronuclear 1D NMR spectroscopy [9,10]. The splitting of 59 Hz agrees well with the sequence parameter $((2*\Delta TE+\Delta t_{cs})/\Delta t_{cs}*J=60$ Hz) and depends on the ΔTE used in the sequence.

Conclusion: A new k-space sampling strategy for RARE based fast SI is proposed to acquire all data of a k_{read}-k_ω-plane by a train of RF refocused echoes. By this means, T_{min} can be shortened compared to former variants of spectroscopic RARE. Furthermore, the localization in phase encoding direction is improved, in particular for weakly coupled spin systems for which the J-modulation is not broken by the train of 180° pulses. J-scaling can be imposed for these signals to improve peak assignment and signal separation in *in vivo* spectra.

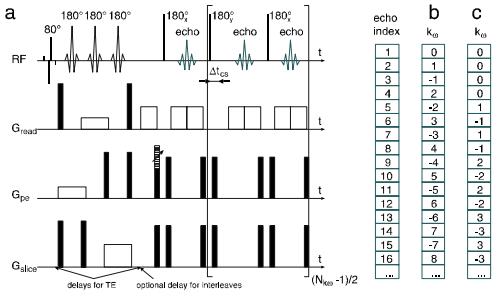

Fig.1: (a) Pulse sequence for the new RARE based SI method with (b,c) two k-space sampling schemes (see text).

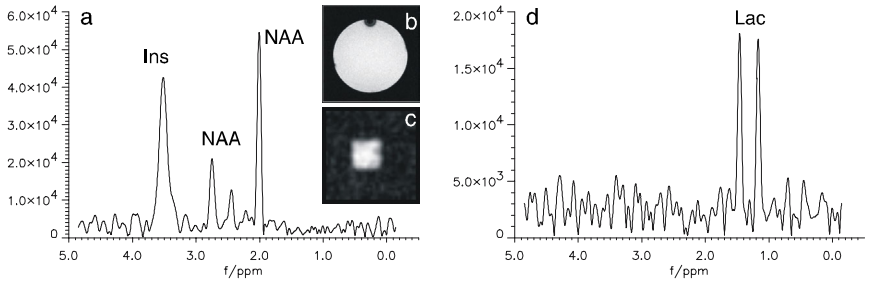

Fig.2: Results of phantom measurements on aqueous solutions (a-c) 50mM NAA, 50mM Ins
(a) spectrum from one voxel, (b) water image, (c) NAA image (using zoom to a VOI),
(d) spectrum from one voxel of a 100 mM solution of Lac.

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