Minimum-norm IDEAL spiral CSI for efficient hyperpolarized 13C metabolic imaging

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INTRODUCTION: Hyperpolarized [1-^{13}C]pyruvate has demonstrated significant potential for metabolic MR imaging [1]. In-vivo metabolism converts pyruvate into a limited number of ^{13}C detectable downstream metabolites (including lactate, alanine, bicarbonate) with singlet resonant peaks of known chemical shifts. With an in-vivo T_1 of ~30s, it provides MR detectable signal only for a very limited time span. The relevant information is spread over five dimensions including chemical-shift (CS), three spatial dimensions and time. In this work, echo time (T_E) shifted, single-shot spiral encoding is combined with spectrally-preconditioned, minimum-norm CS inversion to efficiently master this encoding challenge.

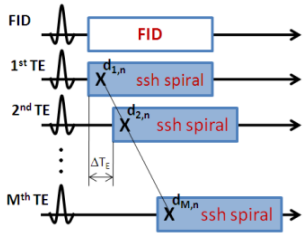

Fig.1: IDEAL spiral CSI.

MATERIALS and METHODS: Figure 1 illustrates the spectral-spatial IDEAL spiral CSI encoding scheme, starting with a FID and followed by M T_E-shifted, single-shot (ssh) spiral acquisitions. Multiple slices can be acquired in an interleaved manner and multiple time points are obtained via repetition of the main building block. The initial FID is used in the reconstruction as spectral prior knowledge to precondition the CS inversion.
Assuming equidistant echo-time spacing (ΔT_E=$T_{E,n+1}$-$T_{E,n}$=const), the signal for the mth echo time and the nth time point t_n (resp. k-space location k_n) can be written according to:

$$d_{m,n} \propto \sum_{l=1}^{\#\,\text{frequencies}} \int_{\text{volume}} d^3\mathbf{r}\, \rho_l(\mathbf{r}) e^{i\mathbf{k}_n\mathbf{r}} e^{i\omega_l m\Delta T_E} = \sum_{l=1}^{\#\,\text{frequencies}} e^{i\omega_l m\Delta T_E} \int_{\text{volume}} d^3\mathbf{r}\, \rho_l(\mathbf{r}) e^{i\mathbf{k}_n\mathbf{r}} = \sum_{l=1}^{\#\,\text{frequencies}} A_{m,l}\, \rho'_l(\mathbf{k}_n) \qquad [1]$$

with $\{\omega_l\}$ the CS frequencies, $A_{m,l} = exp(i\omega_l m\Delta T_E)$ the CS matrix, and $\rho_l(\boldsymbol{r})$ and $\rho_l'(\boldsymbol{k})$ the unknown metabolite concentration in spatial and k-space domain respectively. According to Eq. [1], the spectral-spatial reconstruction nicely separates into following two-step process: 1) a CS inversion $\boldsymbol{\rho}'(\boldsymbol{k_n}) = \boldsymbol{A}^{\dagger}\boldsymbol{d_n}$, with † denoting the Moore-Penrose pseudo-inverse, and 2) gridding reconstruction along the spiral trajectory $\rho_l(\boldsymbol{r}) = FFT\{Gridding(\rho_l'(\boldsymbol{k}))\}$. The noise amplification due to CS inversion, described by the condition number of **A**, is dependent on the CS frequencies and can be influenced via ΔT_E optimization.
The acquired FID spectra $s(\omega)$ can effectively be used as spectral prior knowledge for preconditioning the CS matrix **A** according to:

$$d_{m,n} = \sum_{l=1}^{\#\,\text{frequencies}} \tilde{A}_{m,l}\, \tilde{\rho}'_l(\mathbf{k}_n), \text{ with } \tilde{A}_{m,l} = s(\omega_l)\, A_{m,l}, \text{ and } \tilde{\rho}'_l(\mathbf{k}_n) = \rho'_l(\mathbf{k}_n)/s(\omega_l) \qquad [2]$$

Because $s(\omega)$ is incorporated in the encoding matrix the unknown conditioned spectral distribution $\tilde{\rho}'_l = \rho'_l/s(\omega_l)$ is expected to be relatively flat. Applying the Moore-Penrose pseudo-inverse provides the minimum norm solution (i.e. $||\tilde{\rho}'_l(\boldsymbol{k})||_2 \rightarrow minimum$). This in turn favors uniform distributions over peaked ones, which is also physically consistent with the expectation for $\tilde{\rho}'_l$. This provides accurate solutions also for the under-determined case and effectively allows resolving the full spectrum rather than the few most significant peaks.
The IDEAL spiral CSI concept was implemented into a multi-slice, pulse-and-acquire sequence. A constant echo time shift of ΔT_E=1.12ms was found to be optimal for the considered CS frequencies and M=7 IDEAL encoding steps. A single-shot spiral trajectory was designed for a FOV of 80mm, a sampling bandwidth of 62.5kHz and a matrix resolution of 38. The data was reconstructed using spectrally-preconditioned, minimum-norm CS inversion followed by gridding reconstruction. Sixty equidistant CS frequencies ([-100Hz…+800Hz]) were chosen covering the relevant metabolites of interest.
Experiments were performed using a 3T GE HDx scanner (GE Healthcare, Milwaukee, WI) equipped with a twin-speed gradient system. [1-^{13}C]pyruvate was hyperpolarized using a HyperSense DNP polarizer (Oxford Instruments, UK). RF excitation and signal reception was performed using a dual-tuned ^{13}C-^{1}H rat volume coil. Anesthetized in-vivo rat experiments were performed using 2% isoflurane in oxygen at a rate of ~1.5 l/min. A volume of 5ml/kg of 80mM, hyperpolarized [1-^{13}C]pyruvate was injected into the animals tail vein at an average injection rate of 0.17ml/s. During the experiment the animal's temperature, heart rate and breathing was monitored (SA Instruments, USA). Ethics approval was obtained from the regional governmental commission for animal protection.

RESULTS and DISCUSSION: IDEAL spiral CSI acquisition was performed for two axial slices through the animal's kidney and liver. The acquisition was started right before pyruvate injection and was triggered to the animals breathing signal. A full CSI dataset was obtained every second breathing cycle, resulting in an average time resolution of 2.16s. The first three rows in Fig. 2 show individual metabolite maps for the kidney slice at the 8th, 12th and 16th time step throughout the acquisition. In addition it shows the slice-selective FID spectra together with spectra obtained from the pre-conditioned, minimum-norm CS inversion for two selected spatial locations. Because of limited SNR the k-space data was smoothed with a Gaussian filter (FWHM = 12pts) prior to gridding reconstruction.

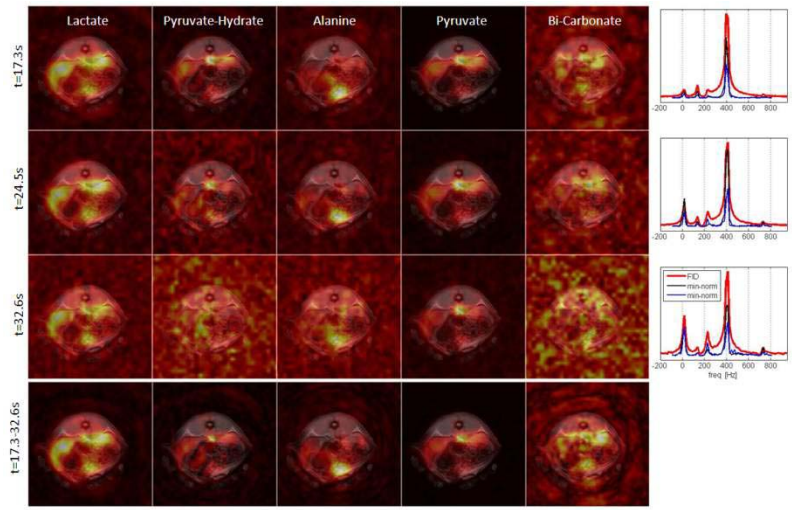

Fig. 2: Minimum-norm IDEAL spiral CSI metabolite maps and spectra.

The obtained images allow detailed study of the time-dependent arrival, distribution and conversion of the individual metabolites. For instance, they allow region-of-interest specific time-course analysis as required for kinetic modeling and metabolic activation studies.
The acquired data can also be time-averaged for the purpose of trading time resolution in favor of spatial resolution. The forth row in Fig. 2 illustrates higher resolution metabolite maps (FWHM of Gaussian k-space filter = 24pts) with averaging over nine time-steps around the bolus maxima. In this case, advantage is taken of the relatively high spatial encoding provided by the spiral trajectory (designed matrix resolution = 38pts).
In summary, the presented IDEAL spiral CSI sequence was found to be a highly robust and efficient acquisition scheme for time-resolved, multi-slice hyperpolarized ^{13}C CSI. In combination with pre-conditioned, minimum-norm CS inversion it allows extraction of the full spectral information for each spatial location.

ACKNOWLEDGMENTS: This work was partly funded by BMBF MobiTUM grant # 01EZ0827.
REFERENCES: [1] Golman, PNAS 103: 11270 (2006). [2] Brodsky, MRM 59: 1151 (2008). [3] Mayer, MRM 62: 557 (2009).