Correction for Off-resonance-induced Displacement in Spectrally Undersampled Hyperpolarized 13C Echo-planar Spectroscopic Imaging

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INTRODUCTION: The typically low bandwidth of the echo planar spectroscopic imaging (EPSI) requires the under-sampling of the sparse hyperpolarized ^{13}C spectrum [1-3]. However, at high field, the large frequency differences between ^{13}C pyruvate and metabolites can cause pronounced spatial displacements along the EPSI readout direction. For the spectrally oversampled EPSI, this off-resonance-induced displacement can be corrected in k-t space implicitly by interpolating the EPSI sampling points onto a Cartesian grid [4], but the same algorithm cannot efficiently correct the spectrally undersampled EPSI. Notably, the correction for the off-resonance-induced blurring in the spectrally undersampled spiral CSI was reported previously [5]. Inspired by these previous studies, this study aims to characterize the off-resonance-induced displacement in the spectrally undersampled flyback EPSI. The analytical result is further utilized to correct the displacements in both phantom and *in vivo* experiments at 7 and 3T.

THEORY: The signal from an object containing multiple spectral components ($f_1 f_2 \dots f_m$) is

$$s(t) = \sum_{m=1}^{components} \int \rho(f_m, x) e^{i2\pi[f_m t - k_x(t)x]} dx \quad [1]$$

where x the spatial dimension, t the time, $\rho(f_m, x)$ the density of the mth spectral component, and $k_x(t)$ is the k-space trajectory. For one frequency component f_m the off-resonance ($e^{i2\pi f_m t}$ term) can cause phase difference between the rectilinear grid and the oblique EPSI trajectory in $k_x - t$ space (e.g. between *red* and *blue* points in Fig. 1):

$$\Delta\varphi(k_x, f_m) = 2\pi f_m \Delta\tau \cdot FOV \cdot k_x, \quad [2]$$

where $\Delta\tau$ the dwelling time and FOV is the field of view. Such linear phase along k_x causes the displacement:

$$\Delta x_m = f_m \Delta\tau \cdot FOV. \quad [3]$$

Then two conditions are assumed: 1) $|f_m|$ is greater than half of EPSI bandwidth, $|f_m| > BW/2$, resulting in aliased frequency $f_{m,alias} = f_m - c_m BW$, where $c_m$is the aliased times (of the Nyquist band), and 2) sampling points are interpolated onto rectilinear grids in $k_x - t$ space [4]. Such interpolation can be considered as subtracting $2\pi f_{m,alias}\Delta\tau \cdot FOV \cdot k_x$ from the linear phase in Eq. 2. Finally, the residual displacement is

$$\Delta x_{m,res} = (f_m - f_{m,alias})\Delta\tau \cdot FOV = c_m BW \Delta\tau \cdot FOV \quad [4]$$

Note that precise frequency (f_m) is not needed for the correction of the residual displacement. In addition, the first order phase due to the delays (defined in Fig. 1 *bottom*) is given by $2\pi f_0[t_d + \Delta\tau\,(N-1)/2]$, and can be corrected as well.

METHODS: Phantom: A ^{13}C phantom with four cylinder chambers containing 85mg/mL bicarbonate (at 163.5ppm), 113.06mg/mL lactate (at 185ppm), 90.09mg/mL alanine (at 178ppm), and 85mg/mL formate (at 172.5 and 166.5ppm) was imaged at ^{13}C natural abundance. **Animal:** A transgenic mouse model of prostate cancer was imaged immediately after a 350µl injection over 12s of 80mM hyperpolarized [1-^{13}C] pyruvic acid and 80mM ^{13}C urea (prepared in HyperSense DNP) [3]. **MRI Protocols:** Phantom experiment was preformed on a 7T GE scanner. A 2D (A-P: phase encoding and L-R: EPSI readout) flyback EPSI protocol was used, with TE/TR=170/2000ms, voxel size=3.33X5.4X20mm^3, matrix size=12X16, and transceiver frequency=74.96324MHz. In vivo experiment was performed on a 3T GE scanner. A 3D (A-P and L-R: compressed-sensing-accelerated phase encodings and slice: EPSI readout) flyback EPSI was used [3], with TE/TR=150/250ms, slice thickness = 5.4mm, voxel size=3.33X3.33X5.4mm^3, matrix size=12X12X16, and transceiver frequency=32.138496MHz. For two experiments, a double refocused spin echo sequence with full echo acquisition was used [2]. **EPSI parameters:** Same EPSI parameters were used for two experiments: BW=580Hz, FOV=86.5mm, equivalent number of phase encoding N=16, and dwelling time $\Delta\tau$ =40µs. **Correction for Displacement:** Two steps are 1) spectral segmentation according to the frequencies of metabolites in EPSI spectra and 2) removal of the linear phase in k-t space based on Eq. 4. **Data Analysis:** Spectral analysis was performed using the SIVIC software package. Spectral apodization and zero padding were performed for *in vivo* experiment. No spatial smoothing filter was used. Magnitude spectra were plotted since the full echo acquisition was used.

RESULTS: As seen in Fig. 2 the frequency offset of lactate was 1146Hz, which caused 4mm displacement (by Eq. 4). Meanwhile, in Fig.3, *in vivo* result shows improved registration of spectra with anatomical images after the correction of 2mm displacements of lacate and urea (by Eq. 4).

CONCLUSION: We observed 2 and 4mm off-resonance-induced displacements in the spectrally undersampled flyback EPSI at 3 and 7T. Such displacement in EPSI can be efficiently corrected, improving registration with anatomical ^{1}H images. Although demonstrated on flyback EPSI, this approach potentially can be extended to symmetric EPSI as well.

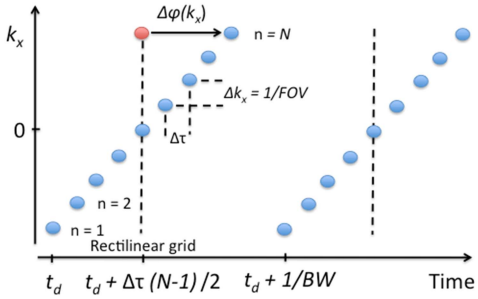

Fig. 1 In $k_x - t$ space, first 2N sampling points on the flyback EPSI trajectory. The oblique trajectory and off-resonance together can cause a spatial displacement.

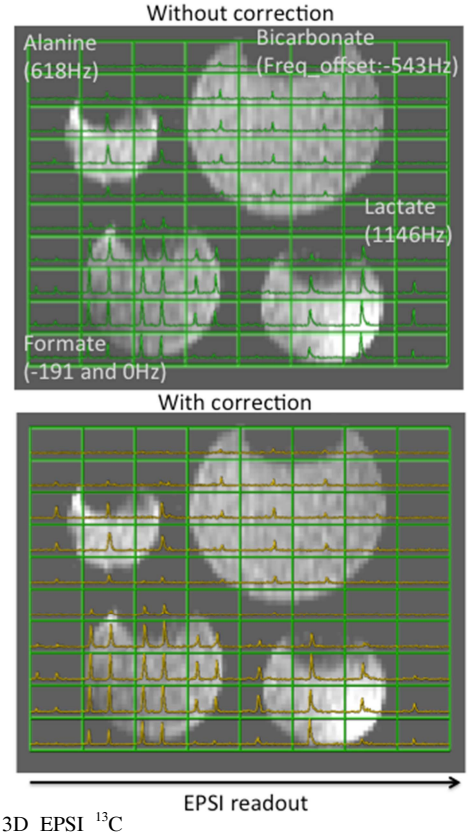

Fig. 2 The 2D EPSI ^{13}C spectra without or with correction of the off-resonance-induced displacements. Spectral displacements (lactate: 4mm, alanine: 2mm, formate: 0mm, and bicarbonate: -2mm) are along EPSI readout direction.

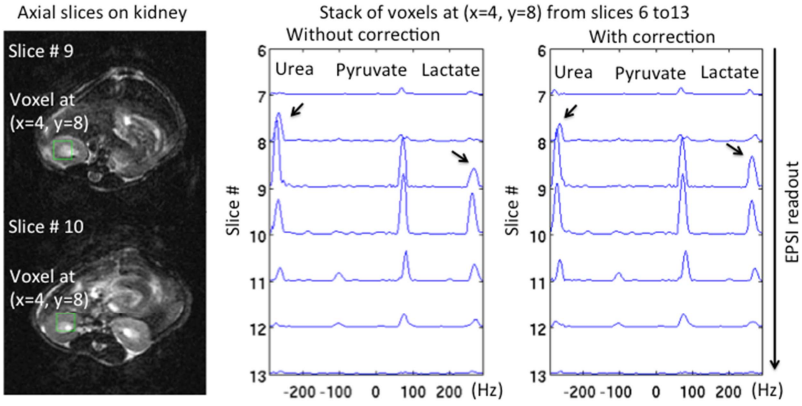

Fig. 3 In *vivo* 3D EPSI ^{13}C spectra without or with correction. Only two MRSI slices were positioned on kidney (#9 and #10). Arrows indicate re-positioned peaks after correction of the displacements (lactate: 2mm, urea: -2mm), consisting with the geometry.

REFERENCES: 1. Ramirez M. S., MRM 2014; **2.** Larson P. E., J Magn Reson 2008; **3.** Larson P. E., MRM 2011; **4.** Cunningham C. H., MRM 2005; **5.** Mayer D., MRM 2006.