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Echo Planar Spectroscopic Imaging of Hyperpolarized ^{13}C in a Clinical System with Reduced Chemical Shift Artifacts

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Synopsis:

Fast and robust symmetric echo planar spectroscopic imaging sequence for hyperpolarized ^{13}C in clinical system is presented. The sequence employs a reconstruction algorithm that re-grids the sampled data in the spatio-temporal frequency space to compensate for the chemical shift artifacts and achieve an improved reconstruction within a limited bandwidth. The sequence was tested on a clinical 3 T whole body scanner using dedicated ^{13}C surface coils and was compared with the conventional chemical shift imaging. Good tradeoff between speed, efficiency and SNR was achieved and the reconstruction was superior compared to the commonly used FFT reconstruction.

Purpose:

Echo Planar Spectroscopic Imaging ^{1,2} (EPSI) is becoming a routine protocol to achieve dynamic imaging of metabolism in cancer ³ and cardiac ⁴ studies with hyperpolarized [1- ^{13}C]pyruvate. The image reconstruction in EPSI is often done using FFT, thus ignoring that the data in k-t space are not collected on a Cartesian grid. We implemented a fast and robust ^{13}C EPSI sequence with a reconstruction algorithm that reduces broadening from chemical shifts within a limited bandwidth. The presented sequence is compared with the conventional phase encoded chemical shift imaging.

Method:

The phantom experiment was performed in a mMR biograph scanner (Siemens Healthcare, Erlangen). The ^{13}C images were acquired using a 270 mm diameter birdcage ^{13}C head coil (RAPID Biomedical). A cylindrical ethylene glycol phantom with a diameter of 250 mm and height of 200 mm was used. It has three cylindrical compartments each with inner diameter of 19 mm filled with 1 M ^{13}C -bicarbonate, [1- ^{13}C]acetate, and ^{13}C -urea, respectively.

The CSI-FID reference data and the EPSI data were acquired with TR 1000 ms, acquisition delay 2.3 ms, field of view $100 \times 100 \text{ mm}^2$, spatial matrix size 16×16 , tip angle 90 degrees, and slice thickness of 100 mm. The CSI had a spectral bandwidth of 5000 Hz and 512 spectral points. The EPSI had a spectral bandwidth of 495 Hz and 64 spectral points. 16 averages were acquired for EPSI.

The EPSI data were reconstructed, Figure 1, by first applying re-gridding to compensate the uneven k-space sampling over the ramp. Then, the odd and even echoes were separated into two data arrays. Fourier transform was applied on the two data sets along time domain to obtain two k_x - k_y - f arrays. Before applying the spatial Fourier transform, a linear phase correction was introduced along k_x ⁵ to account for the time evolution when sampling along k_x which results in chemical shift displacement in the spatial domain, differing between even and odd numbered echoes. This

essentially regrids the data in the spectral-spatial domain. After introducing the phase correction, 2D Fourier transform was applied to obtain odd and even $x-y-f$ arrays. The data corresponding to odd and even echoes were finally summed to obtain a spectroscopic image.

Results:

Figure 2 shows the signal for the three substrates ^{13}C -Urea, ^{13}C -bicarbonate and $[1-^{13}\text{C}]$ Acetate obtained with CSI and EPSI and superimposed on the proton image. The relative SNR values obtained with EPSI-FID with respect to CSI were 0.89, 0.87, and 0.88, consistent with the ramp sampling related decrease in sampling efficiency⁶. SNR was measured from a regions of interest that encompass the cylindrical compartments.

Figure 3 shows the comparison between EPSI reconstruction algorithms. Direct FFT reconstruction, Figure 3-a, results in spatial blurring of the substrates in the ^{13}C image due to chemical shifts in opposite directions⁵. On the other hand, spectral-spatial regridding using the apparent frequency positions, Figure 3-b, results in narrower and more accurate spatial representation of ^{13}C -urea and ^{13}C -bicarbonate. Acetate, however, was outside of the critically sampled bandwidth and aliased which resulted in increased spatial broadening. When accounting for aliasing by using the actual frequency offset of the non-aliased peak, the chemical shift displacement of acetate was compensated as well, Figure 3-c.

Discussion:

The reconstruction⁵ employed in this work provides better accuracy compared to direct FFT. However, the bandwidth in EPSI is relatively small and aliasing may occur. Aliased metabolites cause an error in the spatial-spectral regridding. However, the ^{13}C spectrum in hyperpolarization experiments is often sparse and the metabolite frequencies known a priori. The problem can therefore be solved if peaks do not overlap in the aliased spectra by simply applying phase ramps corresponding to spatial shifts of non-aliased peak frequencies.

Conclusion:

An implementation of an EPSI sequence in a clinical system was presented with reconstruction that gives more accurate representation of the data. EPSI provided a good tradeoff between encoding speed and efficiency, and SNR.

Acknowledgements:

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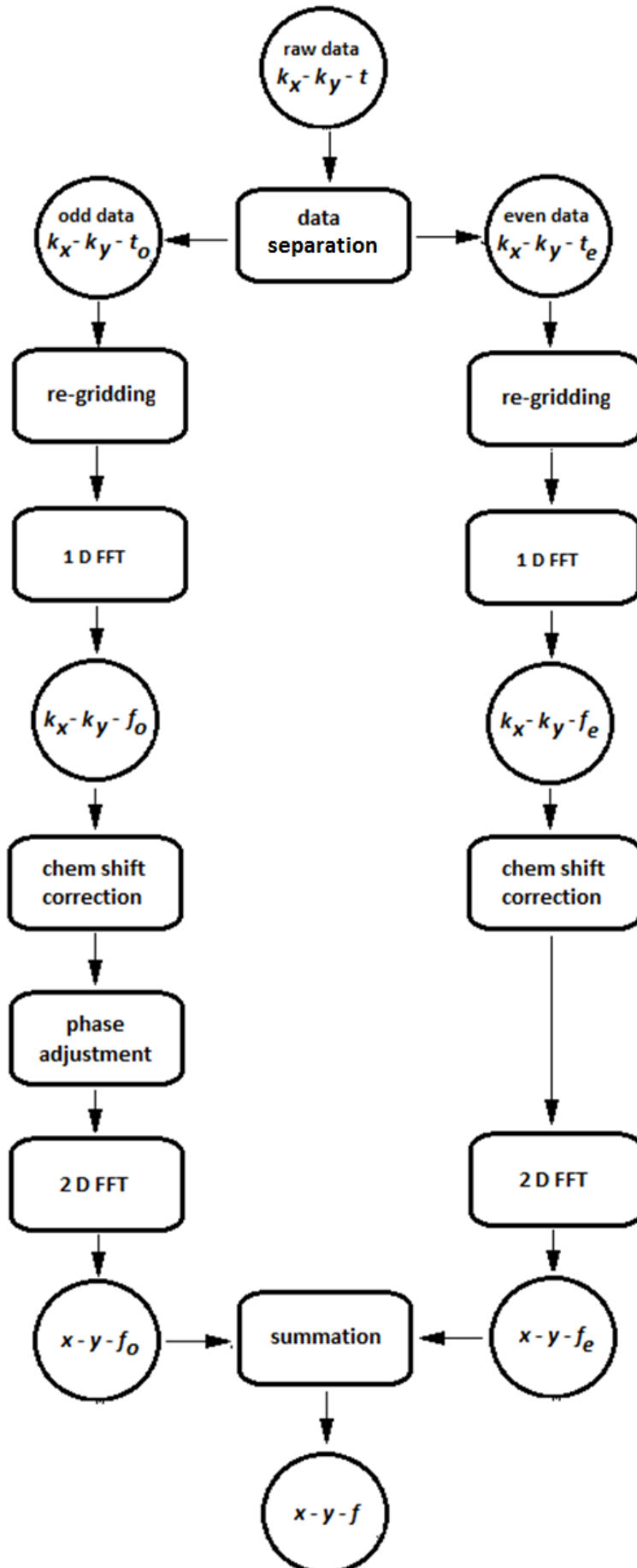


Figure 1: The pipeline used for the reconstruction of the raw data and the correction of the broadening due to chemical shifts in opposite directions in the odd and even data.

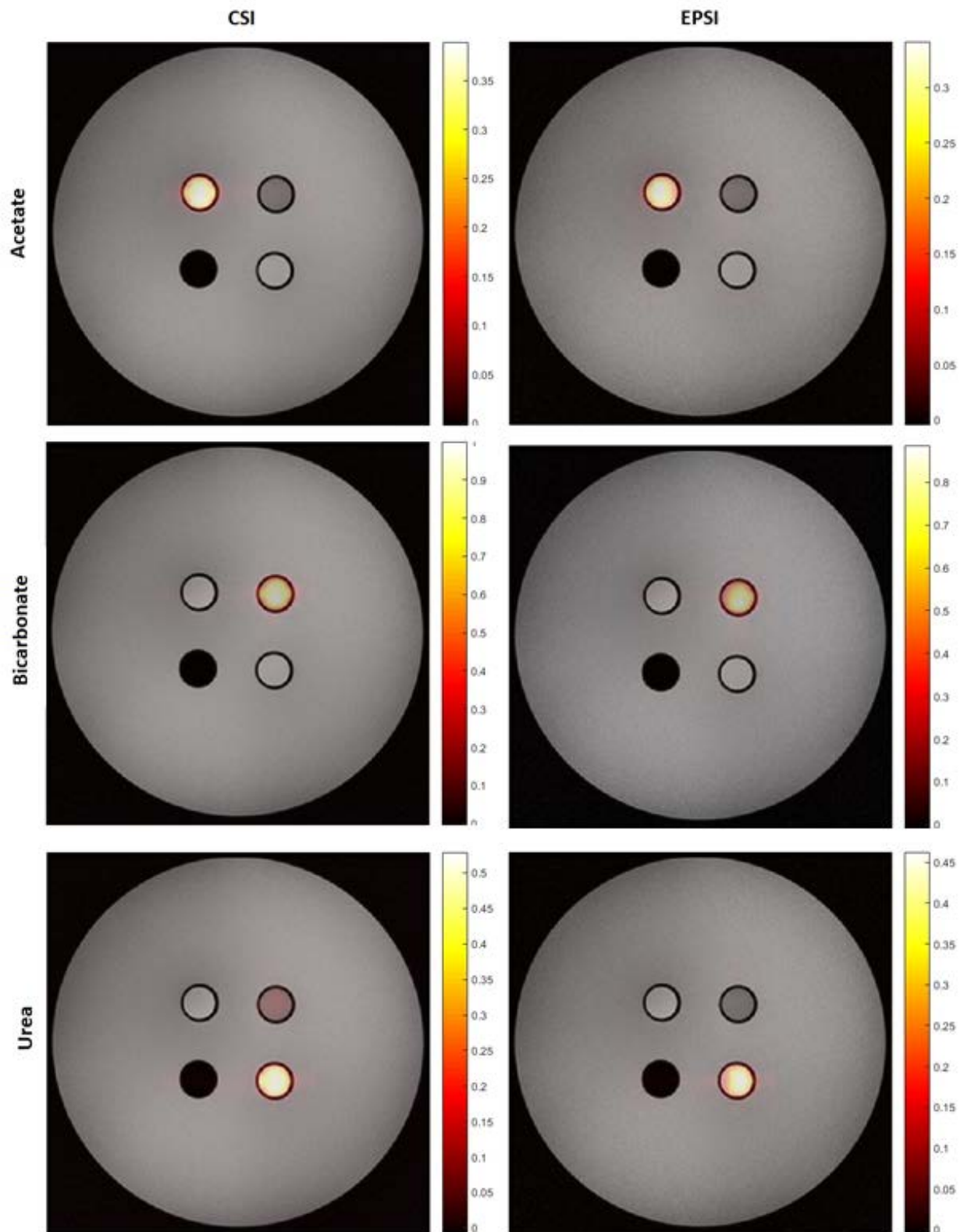


Figure 2: The $[1-^{13}\text{C}]$ acetate, ^{13}C -bicarbonate and ^{13}C -urea signals acquired by CSI and EPSI in color overlaid on proton images. The signal level is normalized with respect to the bicarbonate signal acquired with the CSI.

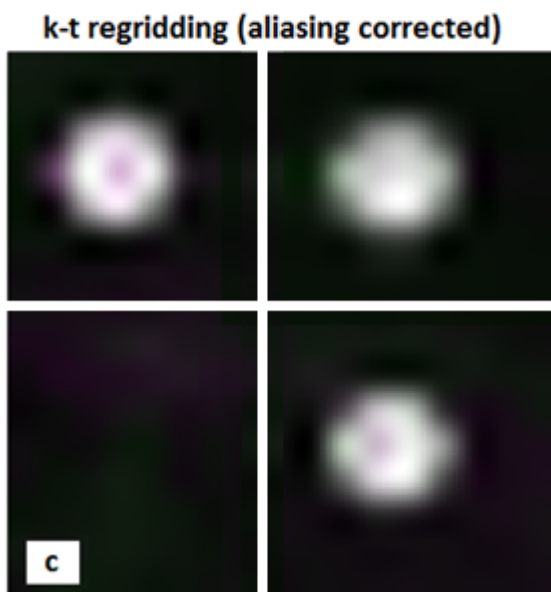
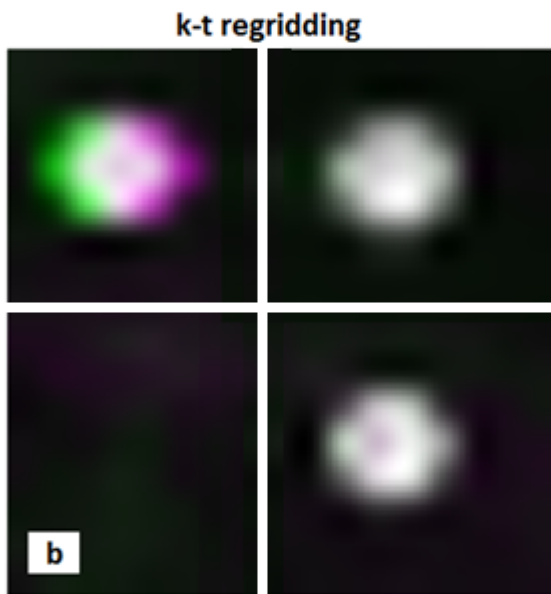
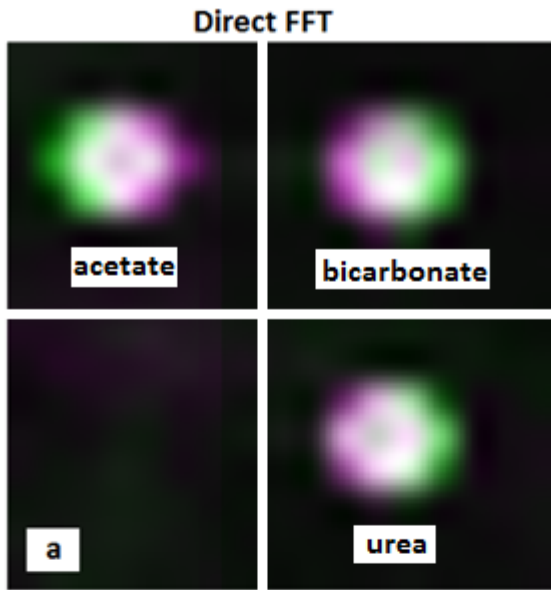


Figure 3: A comparison of chemical shift displacement with direct FFT reconstruction (a) and with reconstruction after spectral-spatial re-gridding (b,c). The Image from odd (green) and even (magenta) echoes were overlaid. The locations of overlap appear in white and the non-overlap locations appear colored. In (b) spectral-spatial regridding removes the chemical shift displacement of bicarbonate and urea, which are within the spectral bandwidth, but increases chemical shift displacement of acetate, which is aliased. In (c) the chemical shift displacement of the acetate peak was additionally corrected using its non-aliased frequency location.