# Improvements in Spectral Resolution in in vivo-Hyperpolarized 13C-CSI on Pigs Using Spectroscopic GRASE

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**Introduction:**.There has been some discussion about the possibility to increase the resolution of MR images by application of superresolution algorithms which are commonly used in optical imaging (1). Superresolution reconstruction is based on combining several images acquired with sub-pixel shifts. The rationale of this approach has been correctly questioned in a comment to this paper (2), where it was pointed out, that sub-pixel shifts are generated by digital filtering and shifting of identical oversampled datasets. It appears to be intuitively clear, that data manipulation, which does not add additional information is unable to introduce high resolution information, which is not already visible in the original image and that therefore any apparent improvement in image quality is more cosmetic than real. The purpose of this abstract is to demonstrate, that both positions are correct: Appropriate reconstruction using frequency shifted data does not add additional information, but it reveals information, which is hidden by partial volume effects in directly transformed data.

**Methods:** The spectral resolution df after Fourier Transformation(FT) of a discrete dataset of np complex datapoints sampled at a distance dk is given by df=1/(np * dk). The points spread function is a sinc-function determined by the finite length np*dk of the sampling window. The spectrum S(f) generated after FT represents the values of the sinc-function at the position of the grid points of the discrete spectrum. Spectra of lines, which are shifted by a fraction ddf of df therefore show partial volume effects and ringing (Fig.1A). These partial volume effects introduce position depend fluctuations of the signal amplitude by up to 32%. It has been know from the CSI-literature, where such 'spectral bleed' can be prominent due to the large size of spectral compartments, that this bleed can be avoided by frequency shifting prior to FT (3). This requires, however prior knowledge about the position of the expected spectrum or iterative reconstruction algorithms, which become unfeasible for datasets with more than a few points. Frequency sweep reconstruction (FSR) is based on repetitive FT of incrementally shifted k-space data I(k) by frequencies $df/n_{res}$:

$$I_m(k) = I(k)*\exp(-\, i\, 2\pi m\; df/n_{res})$$

with $m=1\ldots n_{res}$.(Fig.1B) After FT the nres spectra are recombined to a new spectrum with a nominally higher spectral resolution of $df/n_{res}$. As shown in Fig.1C this procedures dies not introduce an improvement of the spectral resolution (a sinc remains a sinc). It does however considerably reduce partial volume effects.

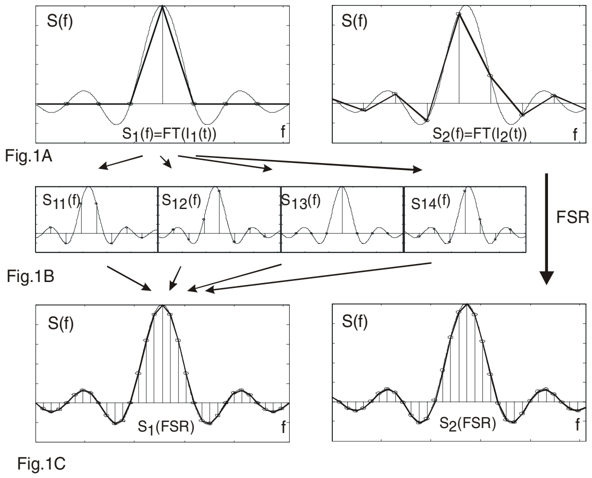


**Fig.1. Priciple of FSR-reconstruction:** Partial volume effects shown in S2 are removed by combination of data after shifting in k-space.

**Results:** FSR-reconstruction was applied to 13C-CSI-data generated with a multi-echo spectroscopic RARE(GRASE)(4) sequence implemented on a Siemens Sonata 1.5 T scanner based on similar principles as a previously used bSSFP-sequence (5). 13 echoes were acquired within one TR interval, and all phase-encoding steps were completed after a single 90° pulse. TR and matrix size were 19 ms and 64×86, resulting in scan times of ~0.6 s. $^{13}$C-pyruvate was hyperpolarized to ~20% with Dynamic Nuclear Polarization (DNP) (6). Images were acquired of the head of a pig (13 echoes, TR=19 ms).

Fig. 2 shows results of spectra from different pixels. Spectra show lactate(lac, 106ppm) (ala, 0ppm), pyruvate (pyr, -92 ppm). It is demonstrated, that the signal amplitude in the FSR-spectra is consistently higher and the spectral separation of adjacent peaks (in particular ala and pyr) are improved compared to direct reconstruction.

**Discussion:** FSR improves partial volume effects and is therefore well suited in cases, where the line width of the observed signals is in the order of the spectral resolution. As shown in Fig.2 this is the case for EPSI-type CSI-acquisition, where frequency encoding is performed in the 2[nd] dimension and df is constrained by the limited number of data points in the spectral dimension. For MR imaging FSR can also be demonstrated to improve resolution and is expected to be suitable especially for imaging of small discrete structures like in MR angiography.

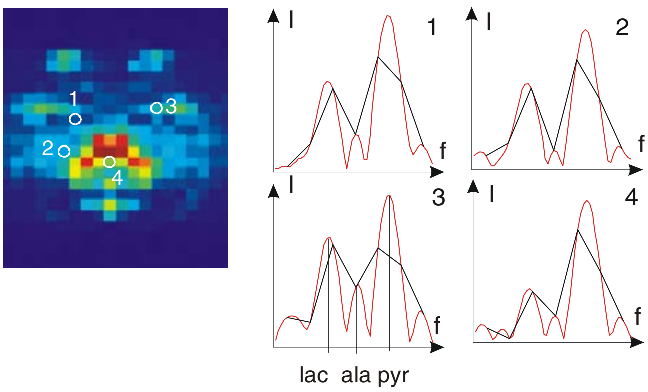


**Fig.2 .** Separation of $^{13}$C metabolites in the head of a pig. Metabolite intensities **I** vs. frequency **f**: lactate = 106 Hz, pyruvate hydrate = 40 Hz, alanine = 0 Hz, pyruvate = –92 Hz. The lactate image (left) was used as reference for spectrum selection.

**Conclusion:** It should be noted, that FSR-reconstruction is performed on the original data. It is therefore different from conventional superresolution algorithms (1), which use magnitude image data. Applying FSR to data generated from inverse FT of magnitude images will not lead to any improvement. In a nutshell it can be concluded, that FSR does not introduce additional spectral information, but it transforms the full information content contained in the complex k-space data into the f-domain and avoids partial volume effects caused by accidental misplacement of spectral lines with respect to the spectral grid. It should be pointed out, that this approach is not fundamentally new: As illustrated by Fig.1, FSR is equivalent to sinc-interpolation, which is commonly used in MRI and MRS. The really surprising result with respect to the application to 13C-MRS is the fact, that sinc-interpolation with zero-filling by a factor of 8-16 leads to a quite significant improvement in spectral quality compared the commonly used filling factors of 2-4.

The considerable improved peak definition of FSR-spectra allows to calculate field maps directly from the spectra, which may be used to correct the frequency offset in each pixel and thus lead to further improvement of metabolite maps.

**References:**

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