Improved Spatial Localization in 3D MRSI with a Sequence Combining PSF-Choice, EPSI and a Resolution Enhancement Algorithm

L.P. Panych\textsuperscript{1,3}, B. Madore\textsuperscript{1,3}, W.S. Hoge\textsuperscript{1,3}, R.V. Mulkern\textsuperscript{2,3}

\textsuperscript{1}Brigham and Women’s Hospital, Radiology Department, Boston, MA
\textsuperscript{2}Children’s Hospital, Radiology Department, Boston, MA
\textsuperscript{3}Harvard Medical School, Boston, MA

Presented at ISMRM 19\textsuperscript{th} Scientific Meeting and Exhibition, Montreal, 2011
Goals

• Improve spatial localization in MR spectroscopic imaging (MRSI) by eliminating truncation (or ringing) artifact.

• Increase speed by employing an echo-planar approach to encode one spatial dimension.

• Investigate the use in MRSI of a resolution enhancement method (super-resolution).
Enhancements to Standard MR Spectroscopic Imaging (MRSI)

- Implement PSF-Choice\(^1\) in 2 dimensions
- Implement Echo-Planar Spectroscopy\(^2\) in 3rd dimension.
- Acquire multiple low-resolution data sets and apply a resolution-enhancement algorithm (super-resolution\(^3\)).

Enhancements to Standard MR Spectroscopic Imaging (MRSI)

- Implement PSF-Choice$^1$ in 2 dimensions
- Implement Echo-Planar Spectroscopy$^2$ in 3rd dimension.
- Acquire multiple low-resolution data sets and apply a resolution-enhancement algorithm (super-resolution$^3$).

What is PSF-Choice?

A method that **improves** the point-spread-function (PSF) and **eliminates** ringing artifact.

1. PSF of standard phase encoding
2. PSF with PSF-Choice

Results in intra-voxel spectral contamination

FWHM (resolution) of both PSFs

Support of PSF 1

Support of PSF 2

How is PSF-Choice implemented?

1. Replace the standard $90^\circ$ RF excitation pulse with a train of RF sub-pulses.
2. Change amplitudes of the sub-pulses on each excitation according to a weighting scheme that determines the resultant PSF.
Example: 4x4 PSF-Choice Encoding

Each RF sub-pulse samples a different location in excitation k-space.

The standard RF excitation pulse is replaced with a train of 4 sub-pulses in our scheme. Amplitudes of the sub-pulses are changed on each excitation according to Gaussian k-space weighting.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
**Two-dimensional PSF-Choice Encoding**

With each excitation a new set of 4 points in excitation k-space is sampled.

- RF
- $G_x$
- $G_y$
- $K_x$ Encode: 2
- $K_y$ Encode: 3

Excitation k-space
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
Two-dimensional PSF-Choice Encoding

With each excitation a new set of 4 points in excitation k-space is sampled.
2D PSF-Choice Reconstruction

When combining the results from all excitations, the net effect is excitation of a Gaussian-shaped ‘virtual profile’ in the PSF-encoding directions, X and Y.
2D PSF-Choice Reconstruction

By applying a linear phase ramp to data from the different excitations, the virtual profile can be shifted within the field-of-view.
2D PSF-Choice Reconstruction

For a $N \times N$ PSF-Choice encoding, spectra from $N \times N$ different locations can be reconstructed. The effective PSF is determined by the shape of the virtual profile - e.g., a Gaussian PSF in our case.
PSF-Choice Encoding vs Fourier Encoding: Results in Phantom

- GE 3T Signa System (15M4).
- 3D MRSI acquisitions:
  - PSF-Choice encoding in $x$ and $y$
  - EPSI in $z$.
- GE Quadrature head coil.
- GE MRS phantom.
PSF-Choice Encoding vs Fourier Encoding

8 x 8 images of H$_2$O peak. *Selected volume is smaller than voxel size*
Excite a small volume and acquire multiple image sets
with 1/4-voxel shifts in each direction (4x4 shifts = 16 acquisitions)
Mapping the Point-Spread-Function

Excite a small volume and acquire multiple image sets with 1/4-voxel shifts in each direction (4x4 shifts = 16 acquisitions)
Mapping the Point-Spread-Function

Excite a small volume and acquire multiple image sets with 1/4-voxel shifts in each direction (4x4 shifts = 16 acquisitions)
Mapping the Point-Spread-Function

Excite a small volume and acquire multiple image sets with 1/4-voxel shifts in each direction (4x4 shifts = 16 acquisitions)
Mapping the Point-Spread-Function

Excite a small volume and acquire multiple image sets with 1/4-voxel shifts in each direction (4x4 shifts = 16 acquisitions)
Mapping the Point-Spread-Function

Excite a small volume and acquire multiple image sets with 1/4-voxel shifts in each direction (4x4 shifts = 16 acquisitions)
Data from the 16 image sets were interleaved (shifts of 1/4 pixel in two directions). Result forms high-density image of ‘point’ - PSF of the imaging method.
Enhancements to Standard MR Spectroscopic Imaging (MRSI)

- Implement PSF-Choice\(^1\) in 2 dimensions
- Implement Echo-Planar Spectroscopy\(^2\) in 3rd dimension.
- Acquire multiple low-resolution data sets and apply a resolution-enhancement algorithm (super-resolution\(^3\)).

Improved spatial localization in 3D MRSI with a sequence combining PSF-Choice, EPSI and a resolution enhancement algorithm

Echo-Planar Spectroscopic Imaging (EPSI)

A method that encodes 1 dimension in a single shot and increases speed significantly

**PRESS compared to EPSI with PSF-Choice**

**H₂O images**

- **FOV** = 24x12 cm
- **Acquisition Matrix**
  - PRESS:
    - 32x16x512 - 1 average
  - EPSI & PSF-Choice:
    - 32x16x512 - 32 averages
- **TE/TR** = 85/1000 msec
- **Total acquisition time:**
  - 32x16 shots X 1 sec = 8 minutes 32 seconds
  (for both methods)
Enhancements to Standard MR Spectroscopic Imaging (MRSI)

- Implement PSF-Choice\(^1\) in 2 dimensions
- Implement Echo-Planar Spectroscopy\(^2\) in 3rd dimension.
- Acquire multiple low-resolution data sets and apply a resolution-enhancement algorithm (super-resolution\(^3\)).

Resolution Enhancement
(or ‘super resolution’)

- Combine multiple low-resolution datasets with sub-pixel shifts to enhance resolution.
- PSF-Choice is suitable for resolution enhancement approaches because the PSF contains higher spatial frequency information.
- Standard Fourier encoded data contains no additional spatial frequency information.

Irani and Peleg. 10th Int Conf Pattern Recogn 1990; 2:115-120.
Resolution Enhancement: Algorithm

Initialize:
Set high-resolution estimate, Fe, equal to the interleaved low-resolution datasets.

Low resolution estimate, F, set equal to last high resolution estimate convolved with the assumed PSF.

Compute difference, Fd, between the measured low-resolution data and the low-resolution estimate.

Update high resolution estimate by adding the error, Fd, convolved with a back-projection kernel, BP.

\[ Fe_0 = Fl \]

\[ F = Fe_n \ast PSF \]

\[ Fd = Fl - F \]

\[ Fe_{n+1} = Fe_n + Fd \ast BP \]

Irani and Peleg. 10th Int Conf Pattern Recog 1990; 2:115-120.
Resolution Enhancement: Phantom Results

**Standard Phase Encoded MRSI datasets: H\textsubscript{2}O images.**

1 Acquisition | 4 Acquisitions | Enhanced

**PSF-Choice Encoded MRSI datasets: H\textsubscript{2}O images.**

1 Acquisition | 4 Acquisitions | Enhanced

Data was acquired using GE ‘resolution’ phantom.
Four acquisitions with 1/2 pixel shifts in x and y.
Resolution Enhancement: With noisy MRSI data

FOV = 80mm³
Press voxel = cube; 20mm³

Acquisition matrix = 8x8x8

Four acquisitions:
Half pixel shifts in two directions, reconstructed and combined using super-resolution algorithm.

Citrate image: 2.32 to 2.56 ppm.

Data acquired using ‘prostate’ phantom (choline, creatine and citrate solution).
Summary and Conclusions

- PSF-Choice encoding gives spectroscopic images free of truncation artifact.
- Use of EPSI to encode one direction reduces acquisition time: e.g., 24x12x8 matrix, 4 averages in 6min 24sec (TR=1sec).
- By repeating low resolution acquisitions with 1/2 pixel shifts in the PSF-Choice directions (in place of 4 simple averages), resolution enhancement methods can be applied.
- Low-resolution, averaged data is still available if high-resolution result is too noisy.
Acknowledgements

The authors wish to acknowledge the support of NIH R21/R33-CA110092 and NIH P41-RR019703.