Role of Parallel Imaging in High Field Functional MRI

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Outline

• Background on Parallel Imaging
• Issues in Image Acquisition in High Field fMRI
• Spiral SENSE and fMRI
• Conclusions
“Standard” Fourier Encoding in MRI

• A fundamental property of nuclear spins says that the frequency at which they precess (or emit signals) is proportional to the magnetic field strength:

\[ \omega = \gamma B \]  - The Larmor Relationship

• Therefore, if we apply a gradient field, the precession frequency varies with spatial location.
Frequency Encoding

- Low Frequency
- High Frequency

B
Mag. Field Strength

x Position

Object

Low Frequency

High Frequency

x Position
Fourier Transforms

- Images are reconstructed through the use of the Fourier transform.

- The Fourier transform breaks down each MR signal into its frequency components.

- If we plot the strength of each frequency, it will form a representation (or image) of the object in one-dimension.
Fourier Image Reconstruction (1D)

- MR Signal
- Time
- Fourier Transform
- Object
- Low Frequency
- High Frequency
- 1D Image
- x Position
2D Imaging - 2D Fourier Transform

- Fourier encoding also works in 2 and 3 dimensions:
Localization in MR by Coil Sensitivity

• Coarse localization from parallel receiver channels attached to an array coil
• Sometimes used in MR spectroscopy
Combined Fourier and Coil Localization

- **SENSE** (SENSitivity Encoding)
- **SMASH** (SiMultaneous Acquisition of Spatial Harmonics)
- Basic idea: combining reduced Fourier encoding with coil sensitivity patterns produces artifact free images
  - Artifacts from reduced Fourier encoding are spatially distinct in manner similar to separation of the coil sensitivity patterns
SENSE Imaging – An Example

Full Fourier Encoding
Volume Coil

Pixel A
Pixel B

Unknown Pixel Values A & B

Known Sensitivity Info $S_{1A}$, $S_{1B}$, ...

Full Fourier Encoding
Array Coil

$S_{1A}$
$S_{1B}$
$S_{3A}$
$S_{3B}$

$S_{2A}$
$S_{2B}$
$S_{4A}$
$S_{4B}$
SENSE Imaging – An Example

Reduced Fourier – Speed-Up R=2
Volume Coil

Reduced Fourier – Speed-Up R=2
Array Coil

Insufficient Data
To Determine A & B

Extra Coil
Measurements
Allow Determination
of A & B
Solving this matrix equation leads to A & B and the unaliased image.
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Characteristics of fMRI Acquisitions

• T2*-weighting (gradient echoes)
• Slice-selective (2D), single-shot imaging
  – EPI, Spiral imaging are most common
  – Freezes head motion and physiological effects
• Temporal resolution – typically 2 s desired for event related studies
• High field desired for stronger BOLD effect
  – Susceptibility distortions are increased
Limits for Typical fMRI Acquisitions

- Susceptibility distortions from long acquisition readouts and high field strengths
- Limited spatial resolution (with single-shot imaging)
- Limited temporal resolution for whole-head scans
- Hardware limits
  - Gradient strength limited by peripheral nerve stimulation
  - Duty cycle limits
- Other susceptibility distortions
Susceptibility Distortions from Long Readouts

TE = 10 ms, Thickness = 4 mm, Spiral Acquisition
Limited Spatial Resolution

Resolution
3.1 mm
1.6 mm
1.0 mm

TE = 30 ms, Single-shot Spiral Acquisition

Signal Decays Before Sampling Is Complete (35 ms T2*)
Limits on Temporal Resolution

- Long readouts reduce number of slices

<table>
<thead>
<tr>
<th>In-plane Resolution</th>
<th>Number of Slices</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 mm</td>
<td>28</td>
</tr>
<tr>
<td>1.6 mm</td>
<td>19</td>
</tr>
<tr>
<td>1.0 mm</td>
<td>13</td>
</tr>
</tbody>
</table>

Single-shot spiral, TR = 2 s, TE = 30 ms
Parallel Imaging Solutions

- Reduced Readout Length
  - Reduced image distortions
  - Increased number of slices (indirectly, 15-20%)

- Increased Spatial Resolution
  - For a fixed readout length, in-plane pixel dimensions reduced by 30-50%

- Increased number of slices (3D)
  - Using SENSE in slice direction could lead to a direct doubling of number of slices
  - But 3D acquisitions are not commonly used in fMRI
Disadvantages of SENSE

• SNR penalty vs. array coil
  – Penalty more severe for large speed factors
  – However, SNR is often as good or better than head coil due to SNR advantages of array coil

• Raw data requirements are much larger

• Image reconstruction is more complicated
  – Also need to acquire coil sensitivity patterns

• Requires some special hardware
System Requirements

- Multiple (parallel) high-speed data acquisition channels
  - Many vendors have 4 to 16 channels
- Array coil with relatively *independent* coil patterns
  - 4 channel coil from Nova Medical
- SENSE reconstruction software
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Spiral Imaging and fMRI

- Single-shot fMRI Acquisition
  - Efficient use of gradient hardware
  - Reversed spiral acquisitions known to have excellent susceptibility properties
  - Image reconstruction more difficult and may include corrections for susceptibility distortions:

- Acquired K-Space Data
- K-Space Trajectory
- Sample Density
- Field Map (optional)
- Gridding
- FFT
- Estimated Image
Reduced Fourier Encoding

- Reduced Fourier encoding in spiral imaging leads to a more complicated artifact pattern than Cartesian sampled MRI, e.g.:

  - Full Fourier Data
  - Half Fourier Data
Image Reconstruction in Spiral SENSE

- Simple equations using coil images do not work
  - Iterative image reconstruction methods are needed
  - Fast methods based on the conjugate gradient algorithm and nonuniform-FFT (Sutton et al., *IEEE TMI* 2003; 22:178-188) are used here:
The k-space data for each coil are simulated:
- From the current estimate of the object
- Using prior information, and
- Using the MRI signal equation:

\[ y_k(t_i) = \sum_{n=0}^{N-1} S_{k,n} f_n e^{-i\omega_n t_i} e^{-i2\pi k(t_i) \cdot r_n} \]

Estimated Image is updated with each iteration
Spiral SENSE – An Example

Prior Information Needed for Image Reconstruction

Coil Sensitivity Maps (complex valued)

K-space Trajectory

Magnetic Field Maps (optional)
Spiral SENSE – An Example

Received Signal For Coil $k$

Iterative Image Reconstruction

Prior Information

Estimated Object

SENSE Recon

Half Fourier, Coil 1

Half Fourier, Coil 2

Half Fourier, Coil 1

Half Fourier, Coil 4
Spiral SENSE – Results

Head Coil

Single-shot spiral, TE = 25 ms, TR = 2 s
Readout = 20 ms – Full Fourier Acq

4-Channel SENSE Coil

Single-shot spiral, TE = 25 ms, TR = 2 s
Readout = 10 ms – Half Fourier Acq
Spiral SENSE – Results

Head Coil
Reduced Susceptibility Artifact

4-Channel SENSE Coil
Excellent Detail
Spiral SENSE – Activation Results

Head Coil

4-Channel SENSE

Bilateral finger tapping, 20s off/on
correlation threshold = 0.7

Time Courses
Spiral SENSE – Example

For this specific case, the use of SENSE technology allowed:

• Reduced susceptibility artifact
• A shorter readout that could be traded for
  – 17% reduced TR
  – 17% more slices/TR, or
  – 32% reduced pixel dimensions
• Comparable activation results to head coil
Conclusions

• Parallel imaging (e.g. SENSE) is an effective way to:
  – Reduce readout length for reduced artifacts
  – Reduce readout length for reduced TR or increased number of slices
  – Improve spatial resolution without extremely long acquisitions or multishot imaging

• SNR penalties are manageable

• Hardware/software requirements will become standard in the coming years