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

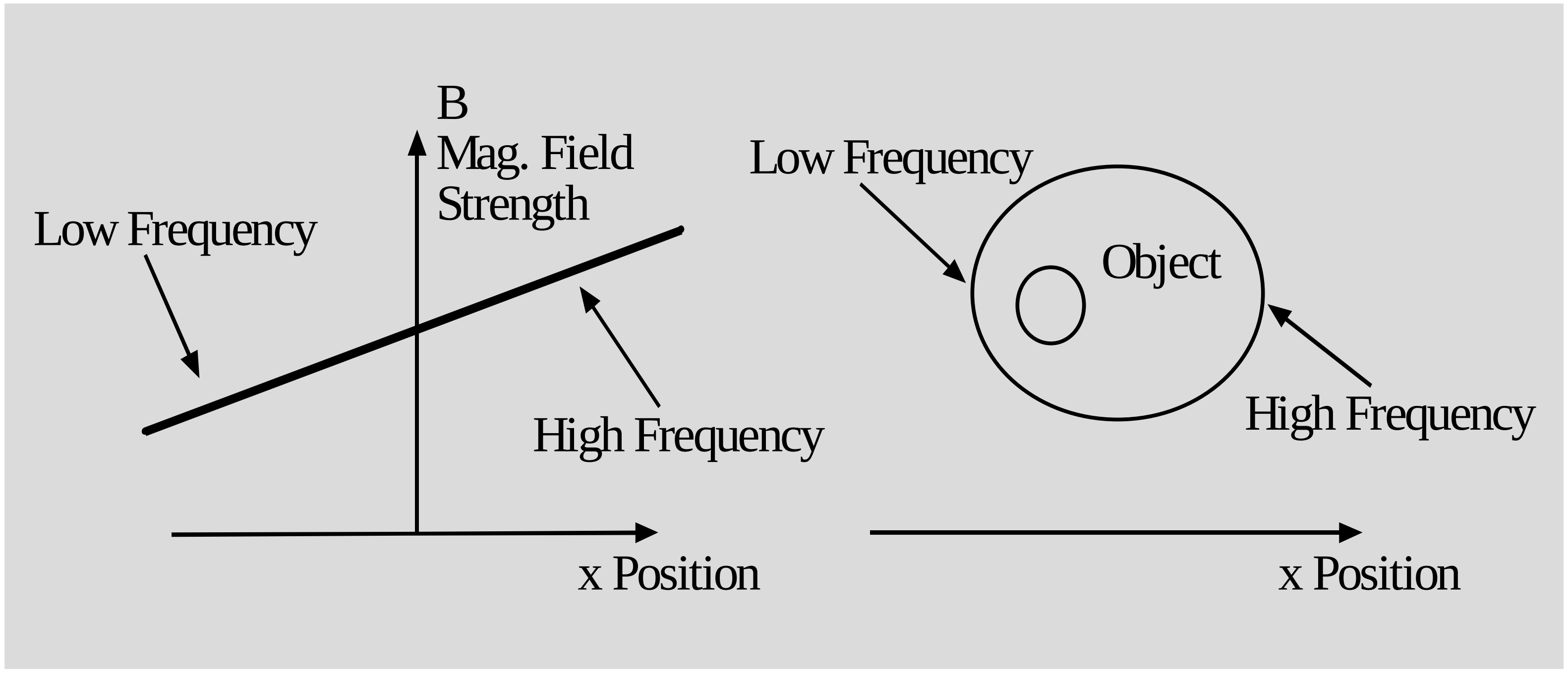
- A fundamental property of nuclear spins says that the frequency at which they precess (or emit signals) is proportional to the magnetic field strength:

$$\omega = \gamma B$$

- The Larmor Relationship

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

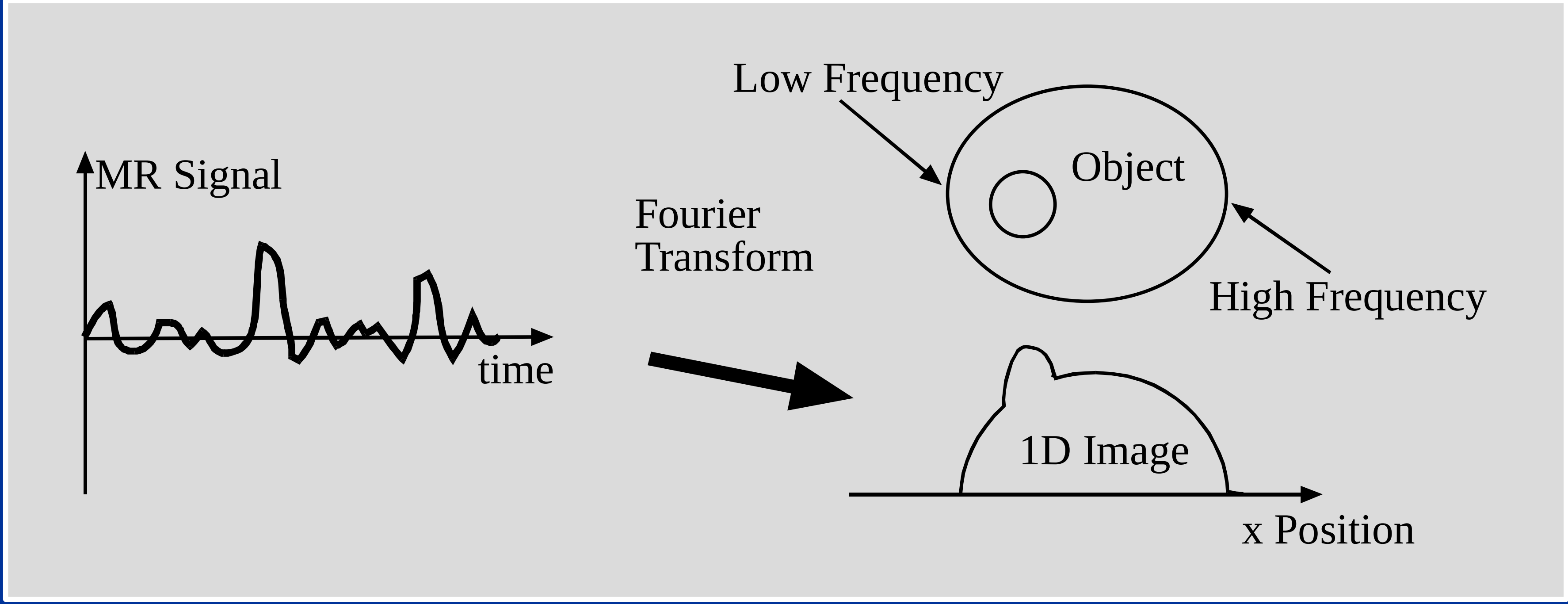
Frequency Encoding



Fourier Transforms

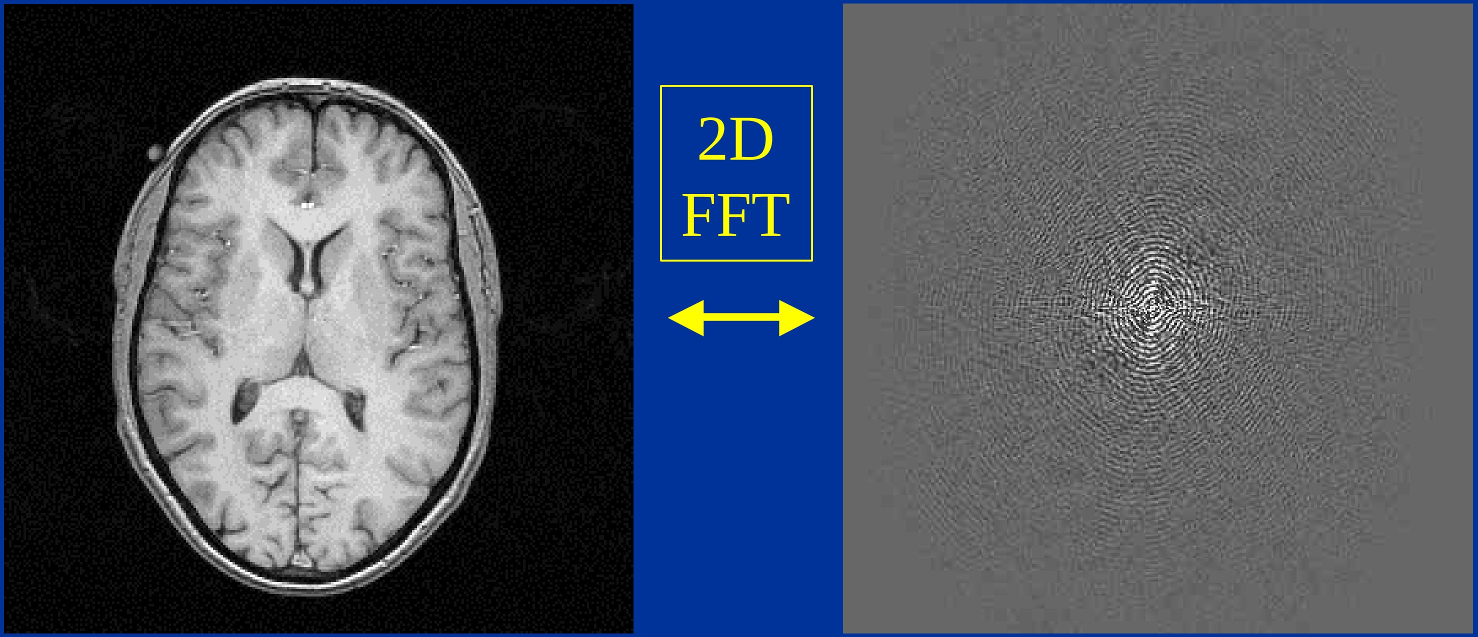
- Images are reconstructed through the use of the Fourier transform.
- The Fourier transform breaks down each MR signal into its frequency components.
- If we plot the strength of each frequency, it will form a representation (or image) of the object in one-dimension.

Fourier Image Reconstruction (1D)



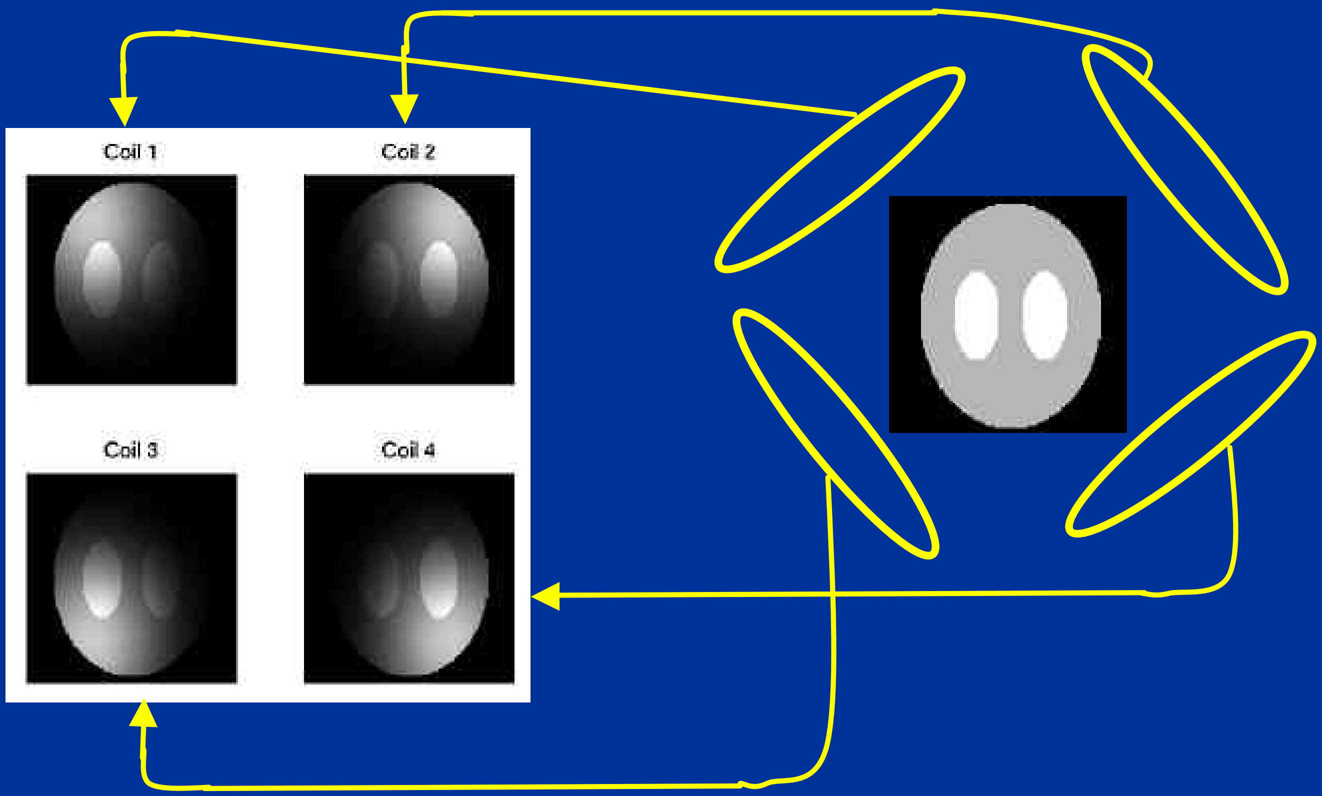
2D Imaging - 2D Fourier Transform

- 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

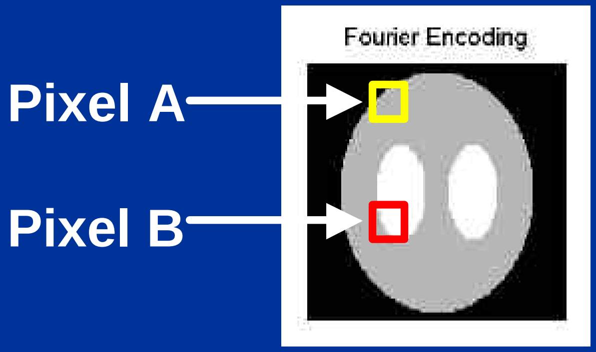


Combined Fourier and Coil Localization

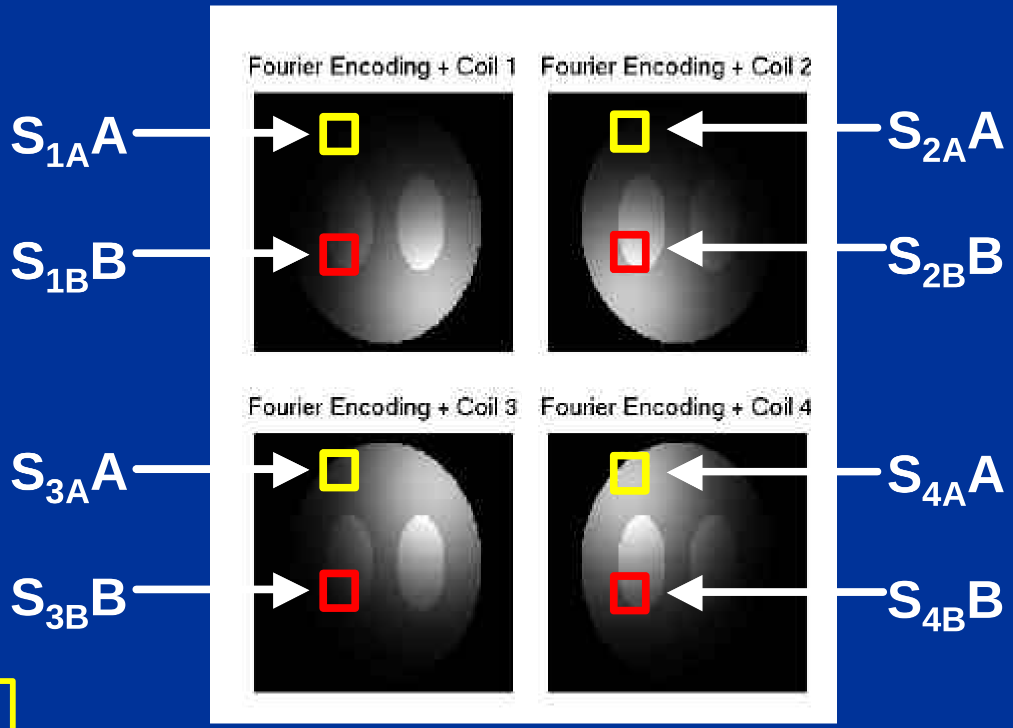
- SENSE (SENSitivity Encoding)
  - Pruessmann, et al. *Magn. Reson. Med.* 1999; **42**: 952-962.
- SMASH (SiMultaneous Acquisition of Spatial Harmonics)
  - Sodikson, Manning. *Magn. Reson. Med.* 1997; **38**: 591-603.
- Basic idea: combining reduced Fourier encoding with coil sensitivity patterns produces 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



Full Fourier Encoding
Array Coil



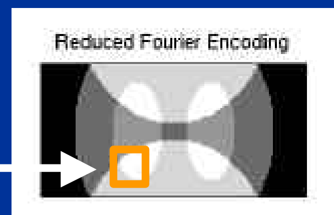
Unknown Pixel Values **A** & **B**

Known Sensitivity Info $\mathbf{S_{1A}}$, $\mathbf{S_{1B}}$,…

SENSE Imaging – An Example

Reduced Fourier – Speed-Up R=2
Volume Coil

A+B

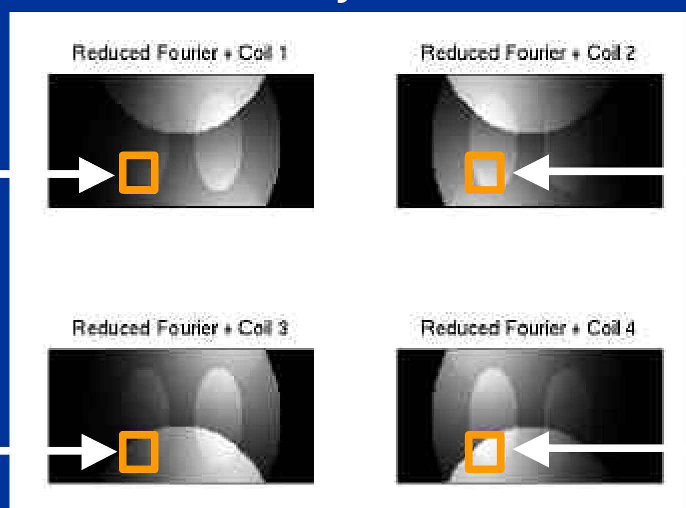


Insufficient Data To Determine A & B

Reduced Fourier – Speed-Up R=2
Array Coil

$S_{1A}A+S_{1B}B$

$S_{2A}A+S_{2B}B$

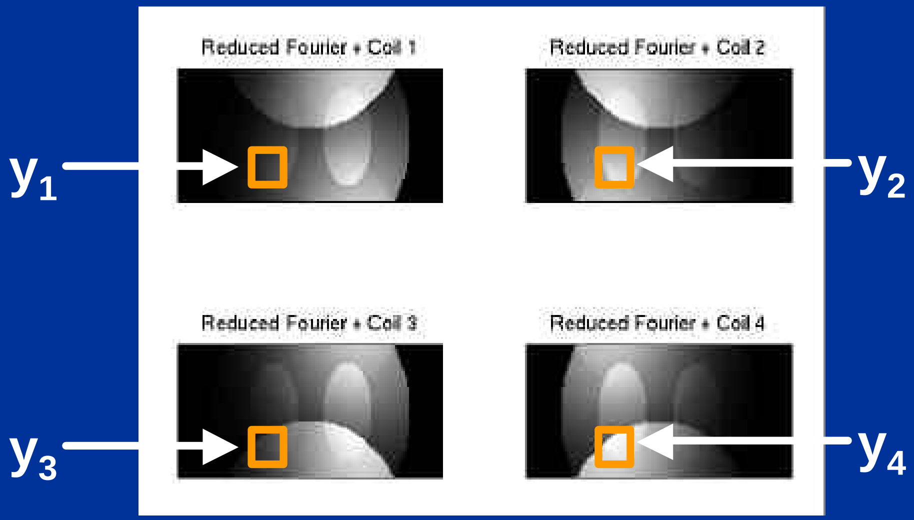


$S_{3A}A+S_{3B}B$

$S_{4A}A+S_{4B}B$

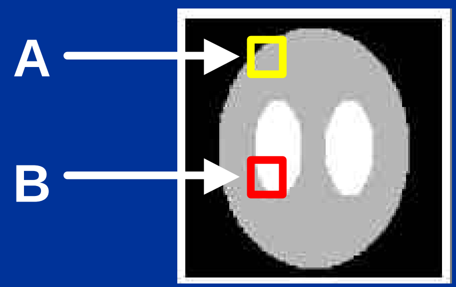
Extra Coil Measurements Allow Determination of A & B

SENSE Imaging – An Example



$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ y_4 \end{bmatrix} = \begin{bmatrix} S_{1A} & S_{1B} \\ S_{2A} & S_{2B} \\ S_{3A} & S_{3B} \\ S_{4A} & S_{4B} \end{bmatrix} \begin{bmatrix} A \\ B \end{bmatrix}$$

Solving this matrix equation leads to A & B and the unaliased image



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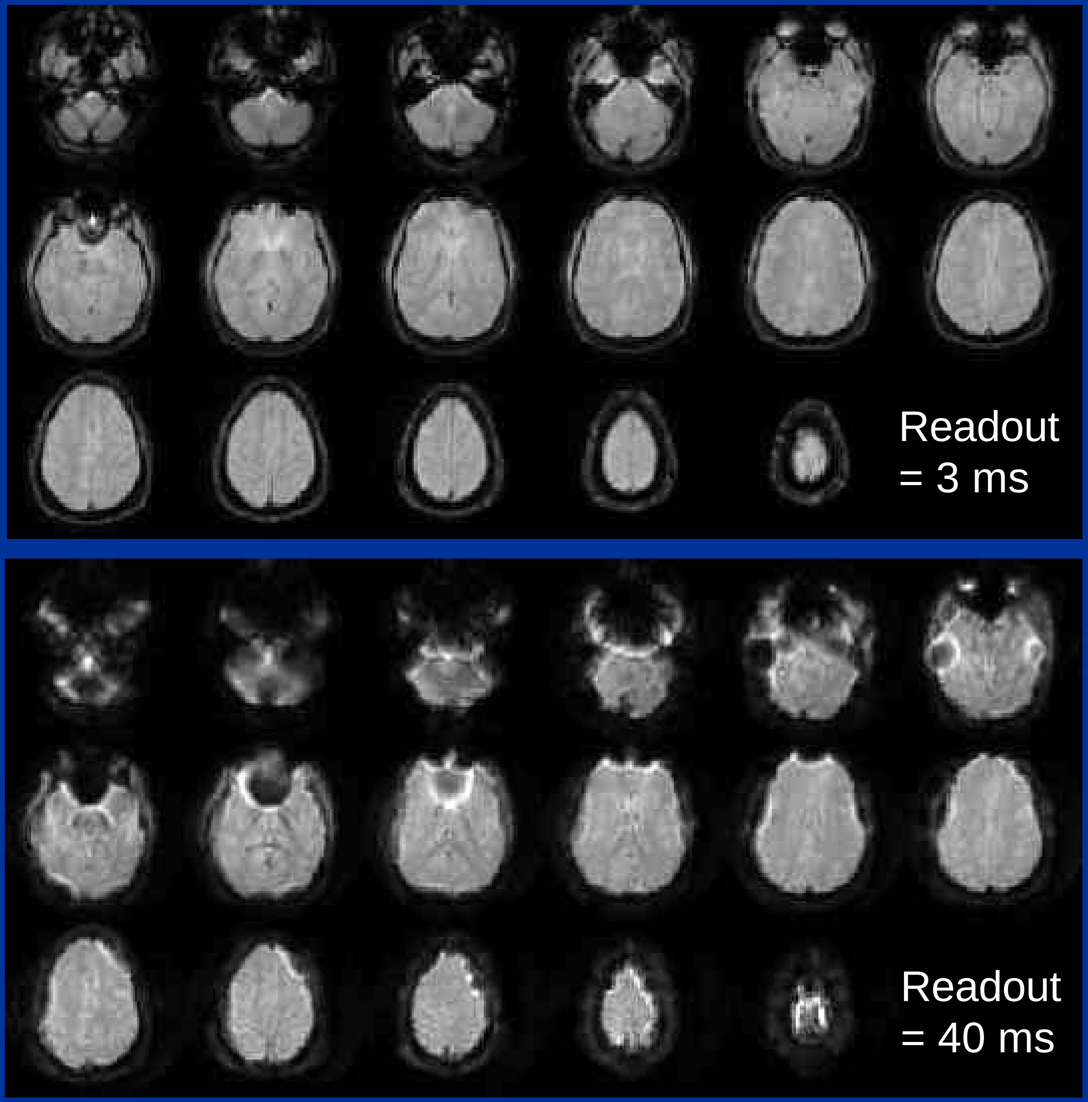
Characteristics of fMRI Acquisitions

- 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

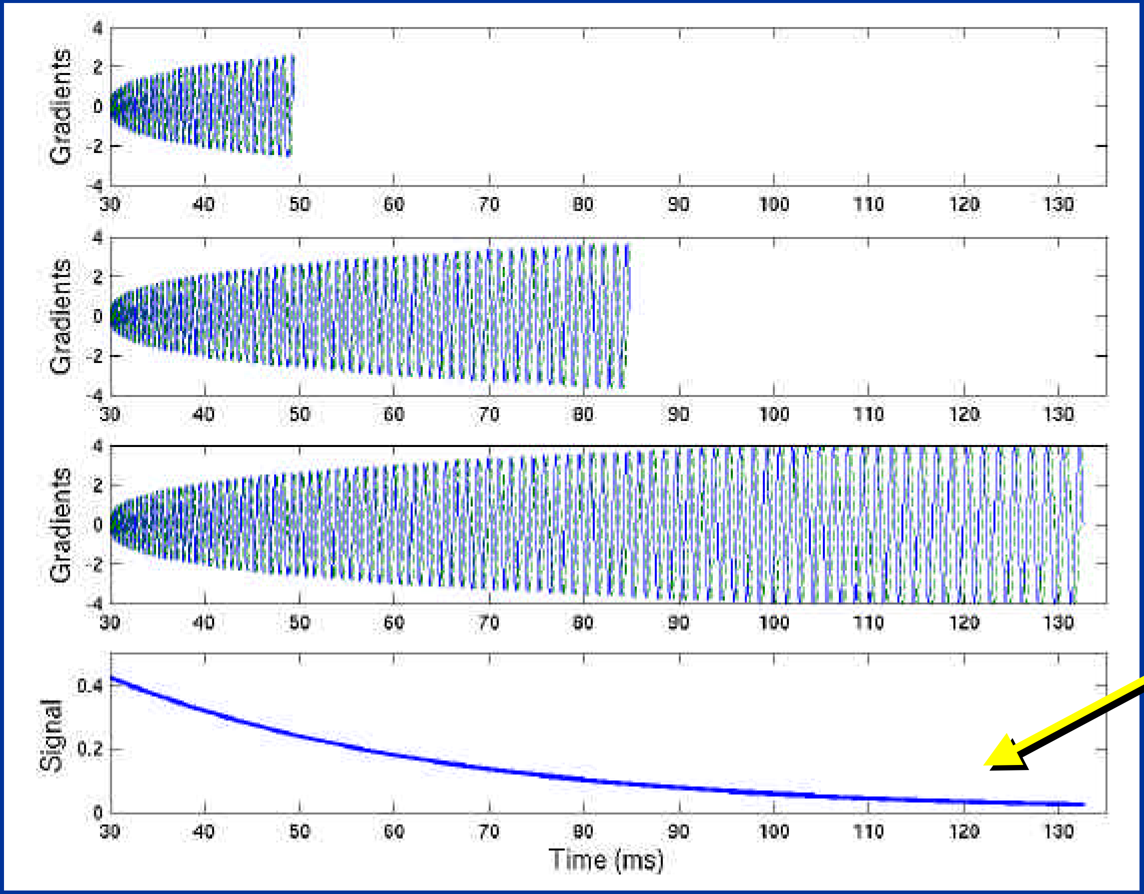
Susceptibility Distortions from Long Readouts



TE = 10 ms, Thickness = 4 mm, Spiral Acquisition

Limited Spatial Resolution

Resolution
3.1 mm
1.6 mm
1.0 mm



Signal Decays Before Sampling Is Complete (35 ms T2*)

TE = 30 ms, Single-shot Spiral Acquisition

Limits on Temporal Resolution

- Long readouts reduce number of slices

In-plane Resolution	Number of Slices
3.1 mm	28
1.6 mm	19
1.0 mm	13

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

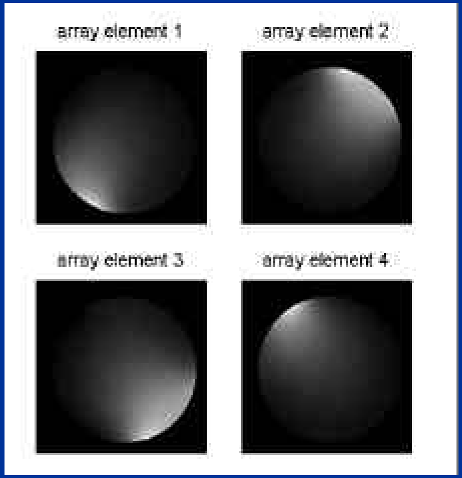
Disadvantages of SENSE

- 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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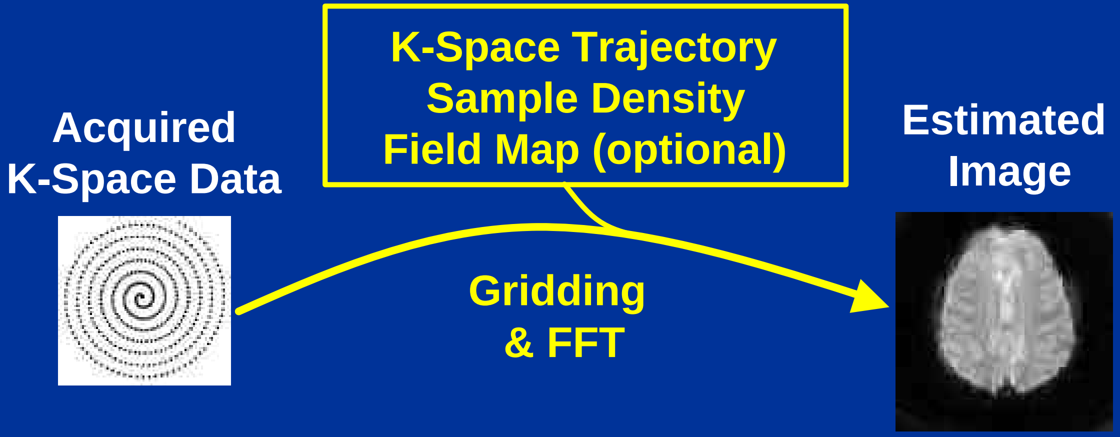
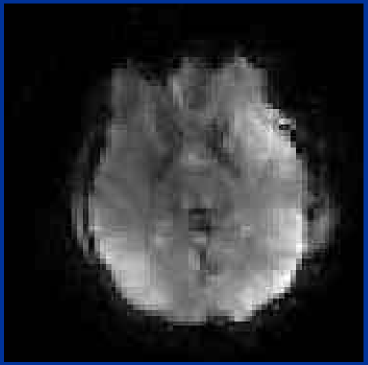
Spiral Imaging and fMRI

- 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:

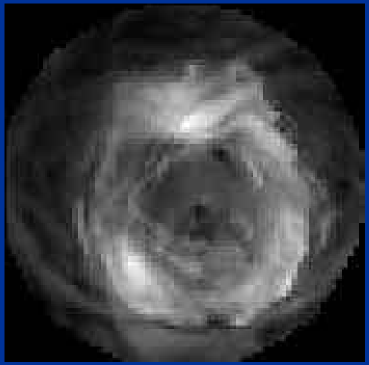


Reduced Fourier Encoding

- 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:

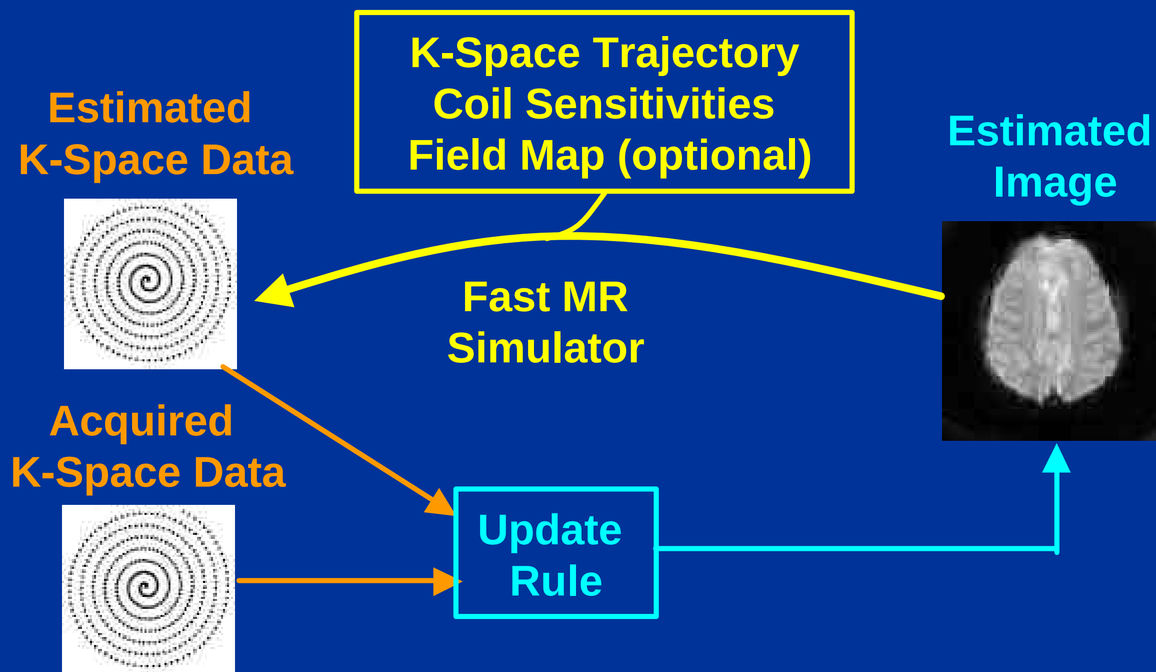


Image Reconstruction in Spiral SENSE

- 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:

$$y_k(t_i) = \sum_{n=0}^{N-1} S_{k,n}\, \mathrm{f}_n\, e^{-iw_n t_i}\, e^{-i2p\, \mathbf{k}(t_i)\cdot \mathbf{r}_n}$$

Measured and Predicted Signal For Coil *k*

Sensitivity Pattern for Coil *k*

Estimated Object

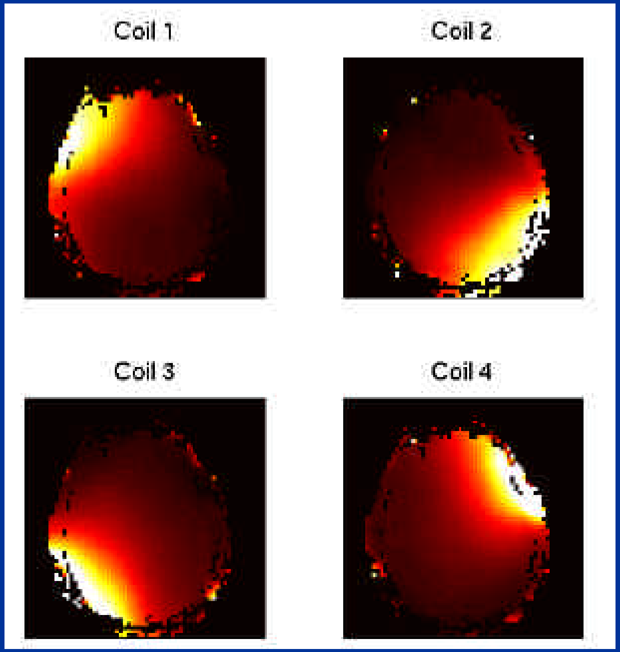
Magnetic Field Map

K-Space Trajectory

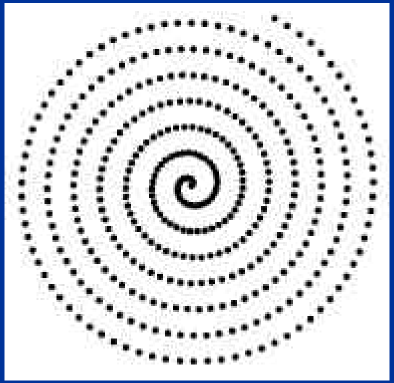
- Estimated Image is updated with each iteration

Spiral SENSE – An Example

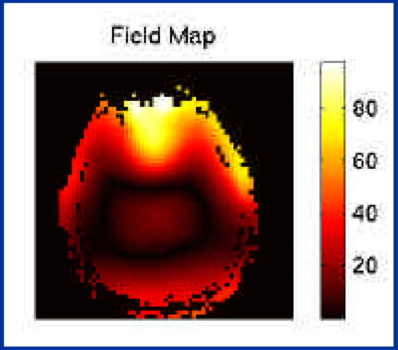
Prior Information Needed for Image Reconstruction



Coil Sensitivity Maps
(complex valued)

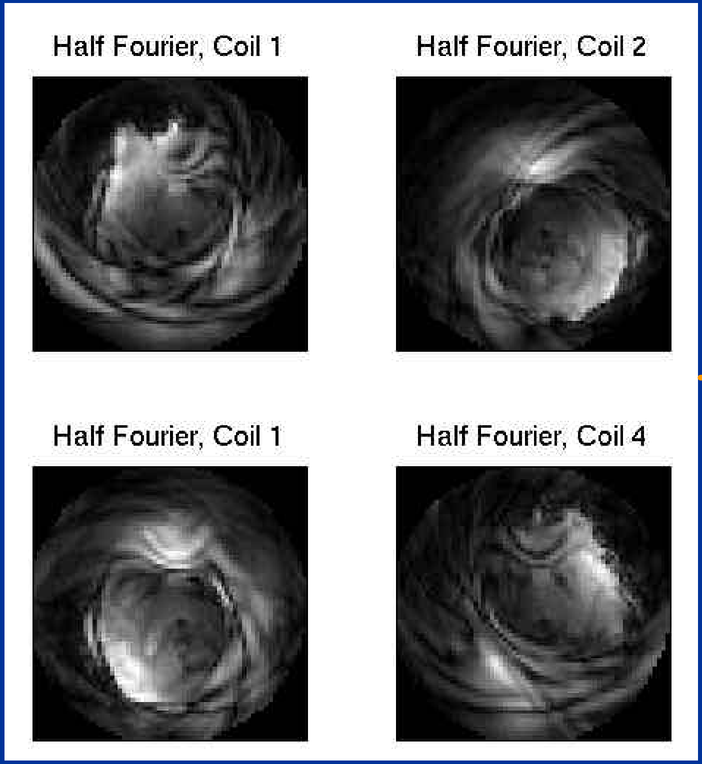


K-space Trajectory



Magnetic Field Maps
(optional)

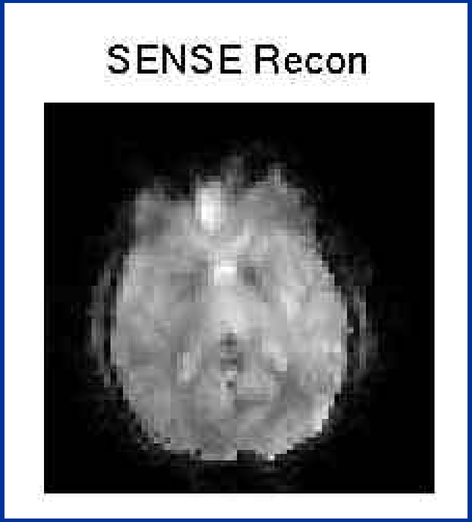
Spiral SENSE – An Example



Received Signal
For Coil *k*

Iterative
Image
Reconstruction

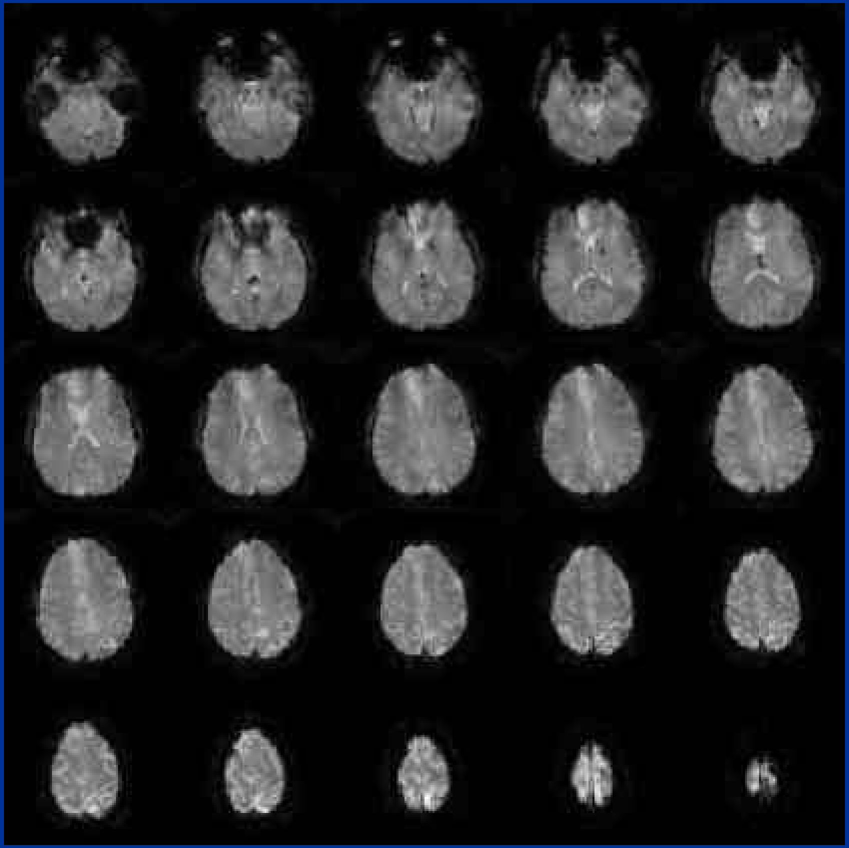
Prior
Information



Estimated
Object

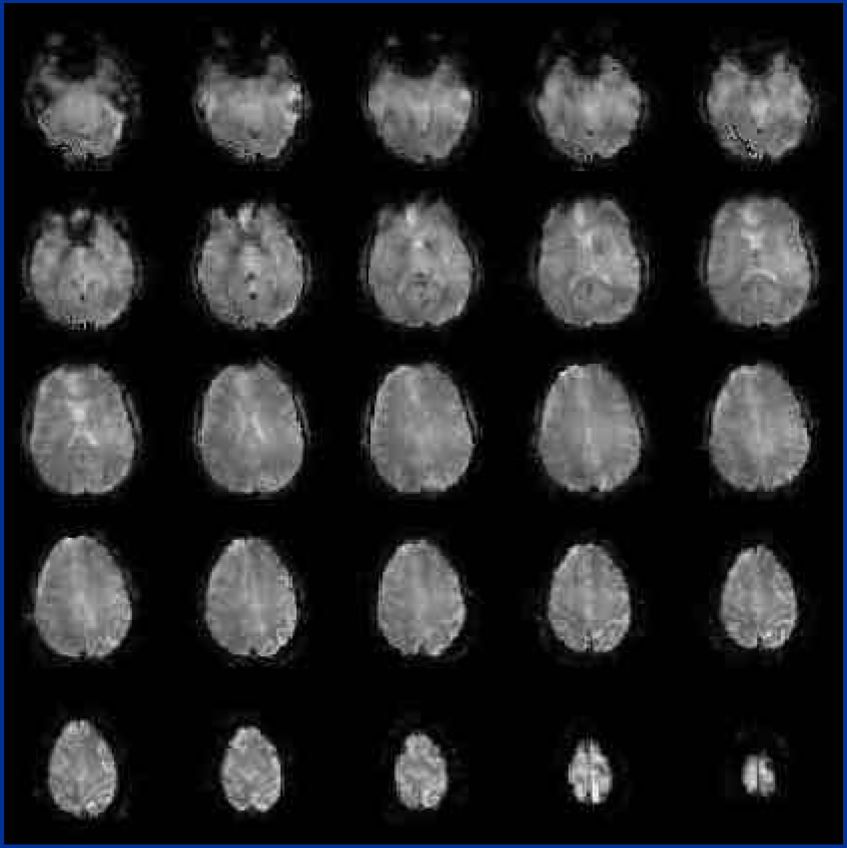
Spiral SENSE – Results

Head Coil



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

4-Channel SENSE Coil

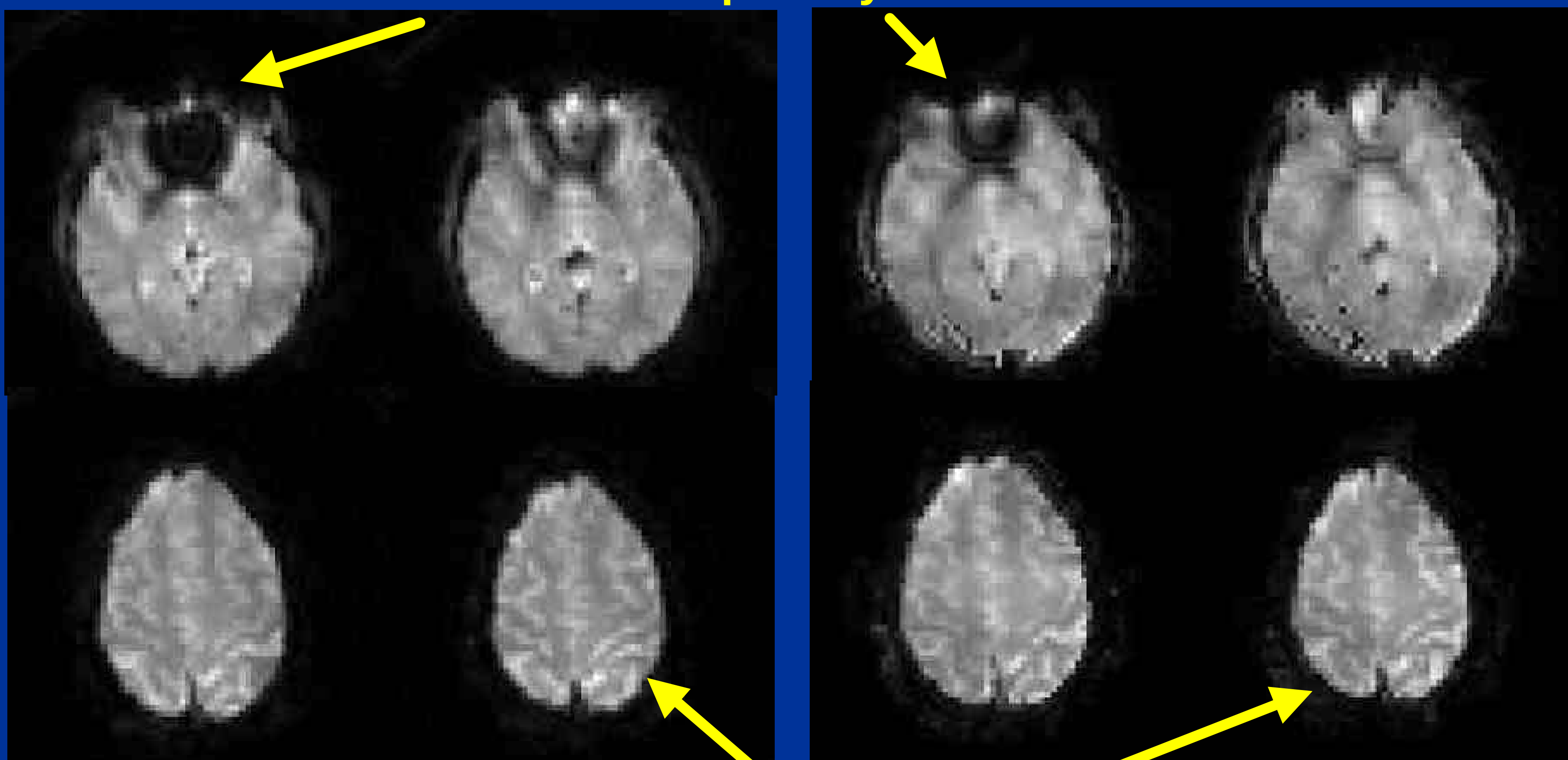


Single-shot spiral, TE = 25 ms, TR = 2 s
Readout = 10 ms – Half Fourier Acq

Spiral SENSE – Results

Head Coil **4-Channel SENSE Coil**

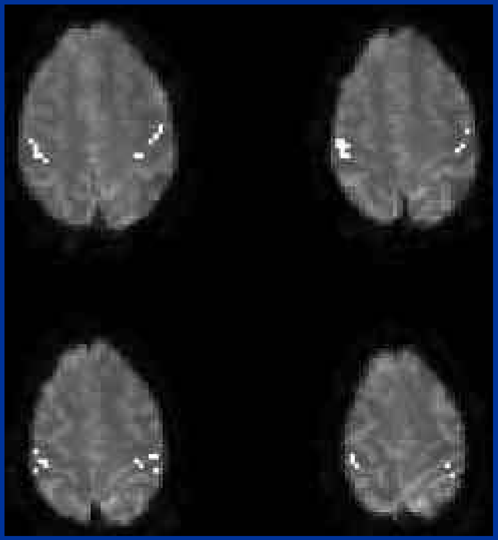
Reduced Susceptibility Artifact



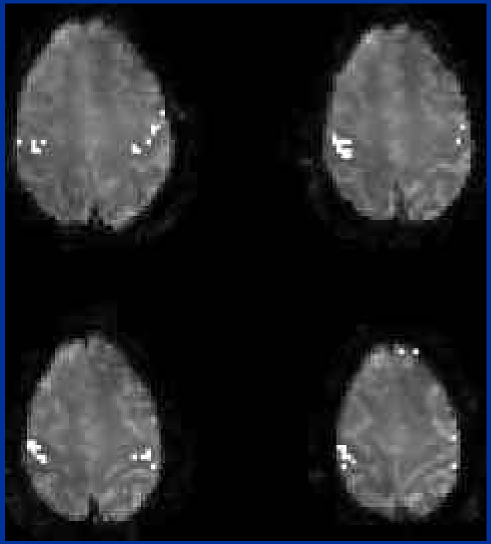
Excellent Detail

Spiral SENSE – Activation Results

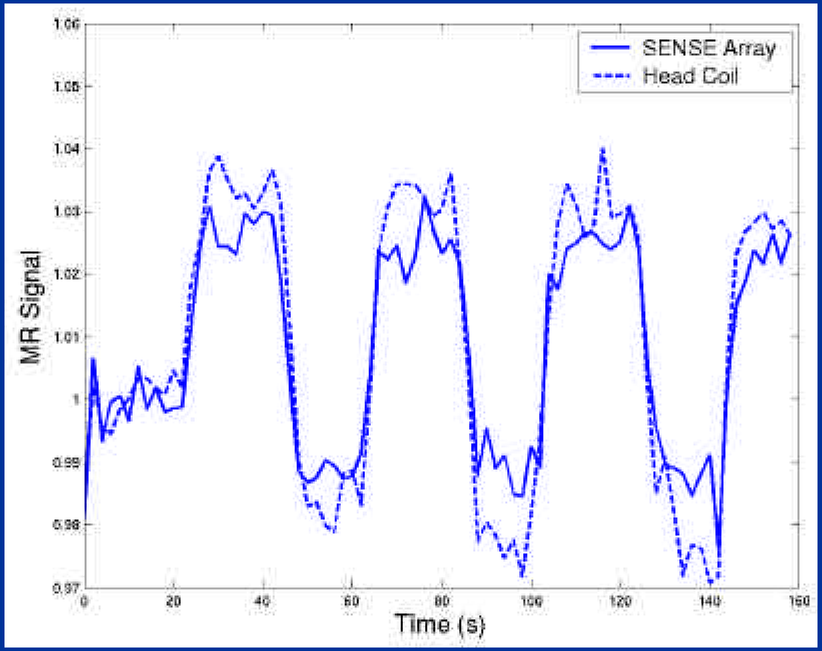
Head Coil



4-Channel SENSE



Time Courses



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

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