Parallel Imaging: Techniques, Quality Control, and Applications

Geoffrey D. Clarke
Department of Radiology
University of Texas Health
Science Center at San Antonio

Overview

- General Description of Parallel Imaging
  - Basic Flavors of Parallel Imaging
- The Geometry Factor (g-factor)
- Applications of Parallel Imaging
- The Future of Parallel Imaging

General Description of Parallel Imaging

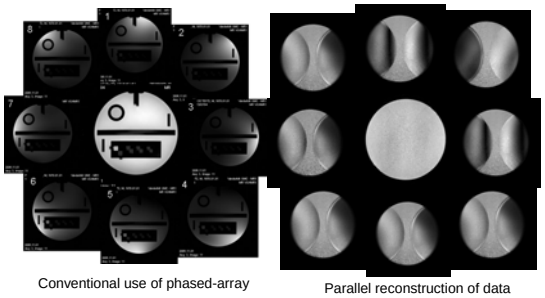
Parallel Imaging (pMRI)

- Uses spatial information obtained from arrays of RF coils sampling data in parallel
- Information is used to perform some portion of spatial encoding usually done by gradient fields (typically phase-encoding gradient)
- ***Speeds up MRI acquisition times***
  - without needing faster-switching gradients
  - without additional RF power deposited

Two Approaches

- Image based: Methods that reconstruct images from each coil element with reduced FOV and then merge the images using knowledge of individual coil sensitivities (SENSE)
- k-Space based: Methods that explicitly calculate missing k-space lines before Fourier transformation of the raw data (SMASH, GRAPPA)

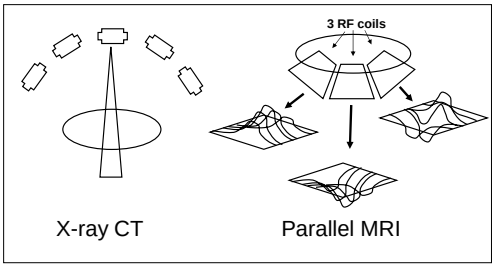
Use of Phased Array Coil in MRI



Conventional use of phased-array

Parallel reconstruction of data

Generalized Projections



Parallel imaging can be thought of as being analogous to x-ray CT…

pMRI Considerations

- There is no fixed geometry between the coils and the patient
- Coupling between the (conductive) patients and the coil array changes from study to study
- Surface coils receive MRI signals in an inherently non-uniform fashion

Additional Information Required

- Need information on the spatial distribution of the RF coils' sensitivity
- Electromagnetic modeling of coil properties or phantom measurements
  - Only practical for RF coil design
- Extra data collection to gain *a priori* knowledge of patient and coil together

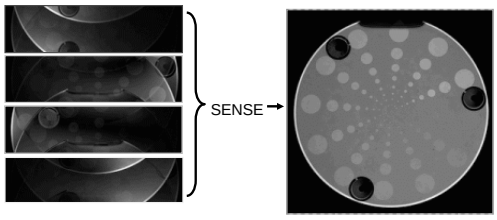
Coil Sensitivity Profiles

- Methods for parallel imaging differ in their approaches to solving the inverse problem that recovers spatial information from a set of radio frequency coils at different spatial positions
- The key information required to solve this problem is information on the spatial distribution of the RF coils' sensitivity

Image-Based pMRI (SENSE)

- Acquisition of reference images give *coil sensitivity profiles*
- Speeds up imaging by a factor as much as the maximum number of phased array coil elements (R: acceleration factor)
- Reduces SNR by at least the same factor as the speed is increased
- Field of view must be larger than the body part to avoid artifacts

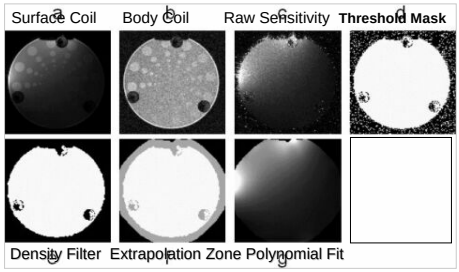
SENSE Imaging **(SENSitivity Encoding)**



Data acquired from each PA coil element goes into reconstruction of whole image – reduces imaging time, reduces SNR, reduces uniformity.

http://www.mr.ethz.ch/sense/

Determination of Sensitivity



http://www.mr.ethz.ch/sense/sense_method.html

The Encoding Matrix

$$S_p \approx \sum_j B_{pj} \rho_j$$

Here, S_p is the signal received by the coil, p.
B_{pj} is the encoding function for the coil, p at the pixel index, j. ρ_j is the proton density at the pixel index, j

In matrix notation: $S = B\rho$
or inverting: $\rho = B^{-1}S$

Thus if B^{-1} can be calculated, ρ can be determined.

k-Space Representation

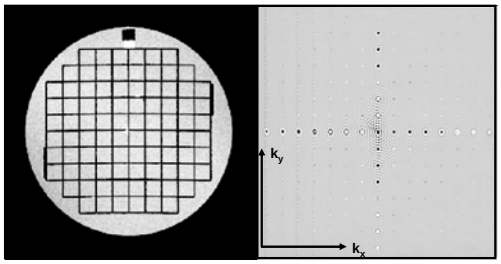


Image Data **Raw Data**

Auto-Calibration Methods

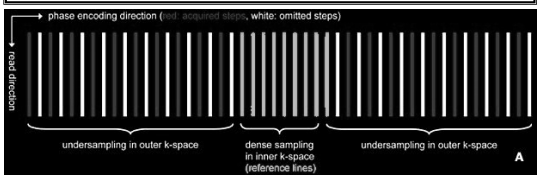
- Missing k-space lines are synthesized using linear least squares fitting between reference data and nearest neighbor lines of data
- Fitting determines the weighting factors for generating missing lines for each coil
- FT is then used to produce uncombined image for each coil

k-Space Based pMRI

- Assumes spatial harmonics of phase-encoding gradients can be omitted and emulated by a linear combination of coil sensitivities
- Acquire reference lines (ACS lines) in k-space rather than whole coil sensitivity images
- Acceleration achieved by omitting phase-encoding steps during acquisition and reconstructing missing data from the redundant information in the signals captured by different array elements

GRAPPA Imaging

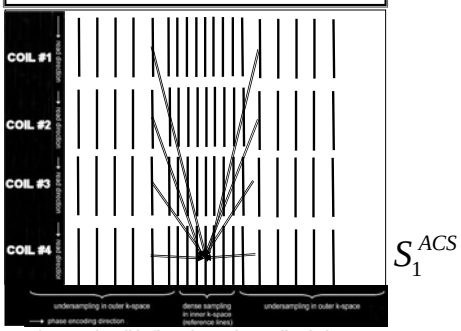
GeneRalized Auto-calibrating Partially Parallel Acquisition



- Acceleration is achieved by omitting phase encoding steps during acquisition and by reconstructing the missing data from the redundant information in the signals captured by different array elements

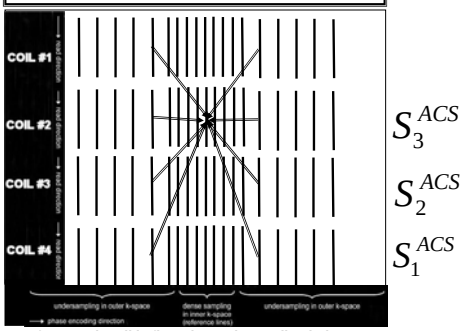
http://www.bruker-biospin.de/MRI/applications/bio62.html

GRAPPA



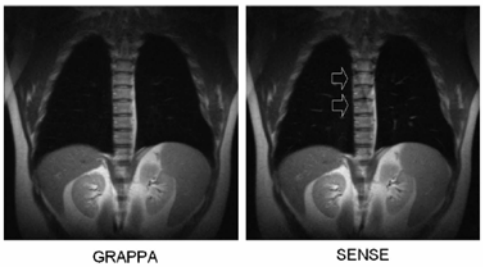
Data from each coil is fit to the each ACS line in k-space

GRAPPA



Data from each coil is fit to the each ACS line in k-space

Image Aliasing in PI



- Parallel imaging (HASTE) show wrap-around artifacts more prominent in SENSE than GRAPPA images

Bammer R, Schoenberg SO. Top Magn Reson Imag 2004; 15: 129-158

The Geometry Factor in Parallel Imaging

Key Parameters in Parallel Imaging

The Acceleration Factor

- (R-factor)

The Geometry Factor

- (g-factor)

Imaging Time Reduction

- Theoretically imaging time can be reduced by a factor (R-factor) equal to the number of phased-array coil elements
- Often, when full imaging acceleration is attempted, numerical instabilities result
- Typically, decreased SNR and increased image non-uniformities limit acceleration factors below the theoretical maximum R

SNR in Parallel Imaging

- In parallel imaging the number, size and orientation of the coil elements influences the SNR in an unusual manner compared to normal imaging:

$$SNR_{i,j,k}^{PI} = \frac{SNR_{i,j,k}^{norm}}{g_{i,j,k}\sqrt{R}}$$

where i, j is the index of the signal-producing voxel, PI= parallel imaging, norm = normal Fourier imaging g is the geometry factor & R is the acceleration factor

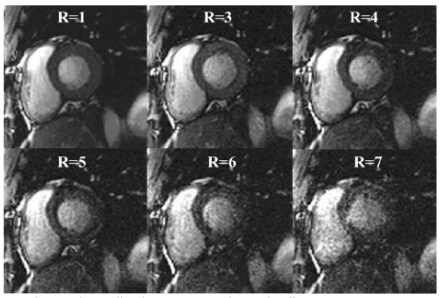
The Geometry Factor (g)

- "g" is the coil-dependent noise amplification factor across the image volume which results from the estimation process of the unwrapping algorithm

$$g(\vec{r},R) = R^{-1/2}\frac{SNR^{norm}}{SNR^{PI}(\vec{r})}$$

where r is the spatial location of the signal-producing voxel, PI= parallel imaging, norm = normal Fourier imaging & R is the acceleration factor

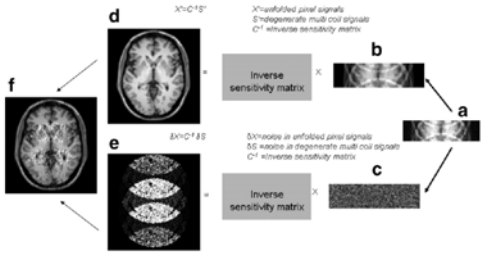
SNR vs. Acceleration



Short-axis cardiac images – 32-channel coil – 1.5 T magnet

Reeder SB et al. MRM 54:748, 2005

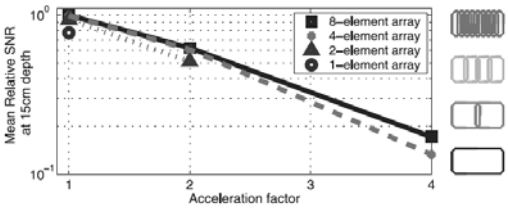
Signal & Noise Propagation



Larkman DJ et al. Magn Reson Med 2006; 55:153-160

g-Factor changes with R and number of elements

Comparison of mean relative SNR for one-, two- , four- and eight-element arrays with the same total extent but progressively smaller individual elements.

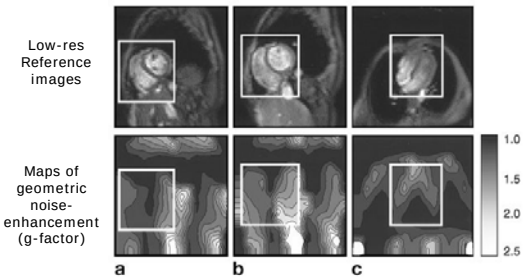


Sodickson DK et al. Acad Radiol 2005; 12:626-635

g-Facts

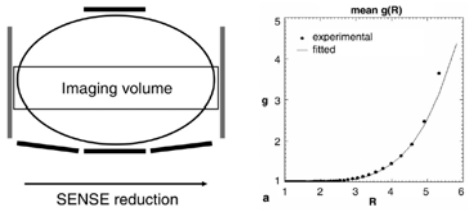
- g ≥ 1 (typically 1.5 ≥ g ≥ 1 allows for adequate image quality)
- g-factor varies with spatial position, so SNR varies with position, too
- g-factor typically increases as R increases
- SNR ↓ as g ↑ because noise ↑ with g
  - g is sometimes referred to as "noise amplification factor"
- g-factor changes with coil loading

g-Factor Maps from SENSE Imaging



Weiger et al. Magn Reson Med, 2000

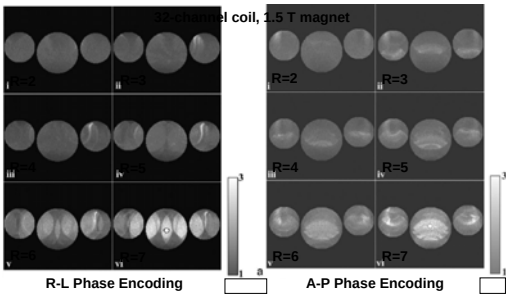
g-Factor changes with R



Increase of g-factor with increase in R shown for six-coil array in the left diagram.

Weiger M et al. Magn Reson Med 2005; 53: 177

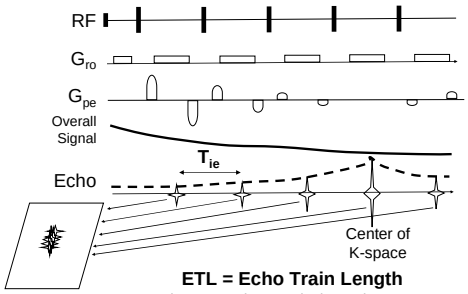
g-Factor Calculated Maps



Reeder SB et al. MRM 54:748, 2005

Applications of Parallel Imaging

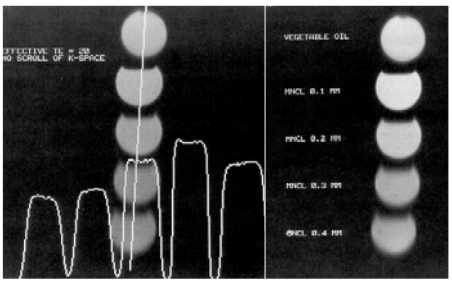
FSE Pulse Sequence



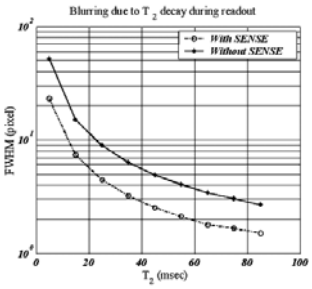
ETL = Echo Train Length

The greater the ETL, the lower the SNR

FSE Point Spread Function Depends on T_2 and TE_{eff}



Improved FSE Resolution



- With SENSE, ETL is reduced from 96 to 48.
- T_{eff} is also reduced

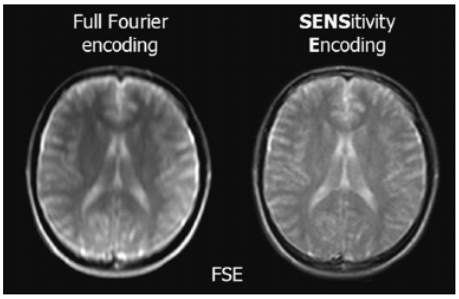
Results in:

↑ Spatial resolution in the phase-encoding direction

↑ Greater overall SNR

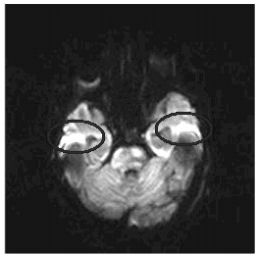
Chung & Muthupillai, Top Magn Reson Imag 2004; 15: 187-196

pMRI in FSE imaging of Brain



Augustin Me et al. Top Magn Reson Imag 2004; 15:207

Susceptibility Artifacts - Sphenoidal Air Sinuses



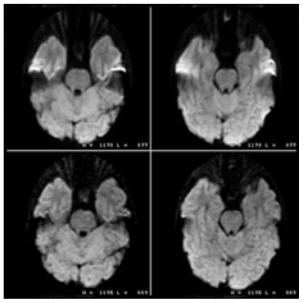
- Regions of air/bone/soft tissue causes local gradients due to differences in magnetic field susceptibility

Strategy to Minimize Susceptibility Artifacts

- Use technique less sensitive to magnetic susceptibility (more RF pulses/acquisition)
  - FSE → SE → GRE → EPI

    Increased sensitivity
- Shorten TE
  - Phase differences don't have as long to play out

Susceptibility Artifact Reduction with Parallel Imaging



- Parallel imaging reduces number of phase-encoding steps required per imaging time
  - Top – normal acquisition,
  - Bottom – R=2 acceleration

When Should You Use Parallel MR Imaging?

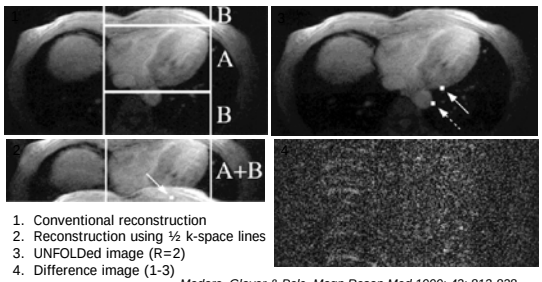
- To reduce total scan time
- To speed up single-shot MRI methods
- To reduce TE on long echo-train methods
- To mitigate susceptibility, chemical shift and other artifacts (may cause others)
- To decrease RF heating (SAR) by minimizing number of RF pulses

Future Directions

- pMRI in the temporal direction
- pMRI with massively parallel arrays
- pMRI in a second spatial direction
- pMRI at ultrahigh magnetic fields
- Transmit parallel imaging

UNFOLD Imaging

UNaliasing by Fourier encoding the OverLaps using the temporal Dimension



1. Conventional reconstruction
2. Reconstruction using ½ k-space lines
3. UNFOLDed image (R=2)
4. Difference image (1-3)

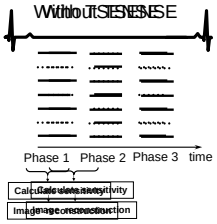
Madore, Glover & Pelc, Magn Reson Med 1999; 42: 813-828.

Adaptive TSENSE

Time-Adaptive Filtered SENSE

TSENSE

- Additional acquisition time is no additional k-space lines are required
- PAT factor gives the real acceleration value



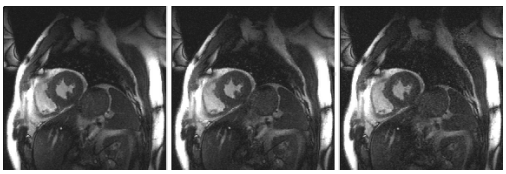
TSENSE sequences

- Function : cine_trufi, trufi_rt
- Perfusion : trufi, tfl

Peter Kellman et al MRM 45:846-852 (2001)

TSENSE

2D Cine TrueFISP



R = 2	R = 3	R = 4
6 heartbeats	4 heartbeats	3 heartbeats

36 msec true temporal resolution, 144 x 256 matrix

Peter Kellman, NHLBI, and Al Zhang, Siemens R&D, Chicago

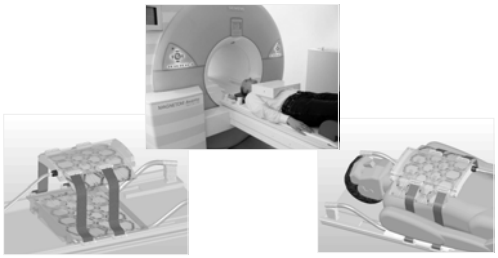
Parallel MRI Terminology

Name	Acronym	Method	Manufacturer
Sensitivity Encoding	SENSE, SPEEDER	Image-based, reference scan	Philips
Array spatial sensitivity encoding technique	ASSET	Image-based, reference scan	General Electric
Generalized auto-calibrating partially parallel acquisition	GRAPPA	k-space based, auto-calibrated	Siemens, GE
Modified sensitivity encoding	mSENSE	Image based, auto-calibrated	Siemens
Integrated parallel acquisition techniques	iPAT	used for all pMRI	Siemens

More Flavors of Parallel Imaging Coming Soon

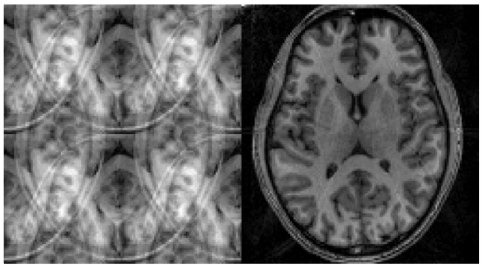
- Time Auto-Calibrated GRAPPA (TGRAPPA)
- Broad-use Linear Acquisition Speed-up Technique (BLAST)
- BLAST sparsely sampled in space and time (k-t BLAST)
- Self-Calibrating Non-Cartesian SENSE

32-Element Cardiac Array



MRI Devices Corporation, Gainesville, FL
Works-in-Progress

2D SENSE with 3DFT MRI



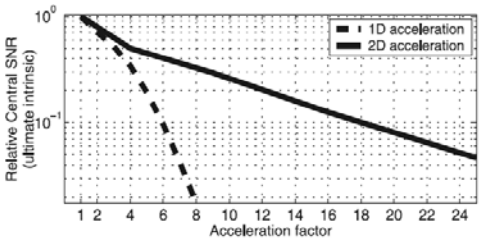
2D SENSE reconstruction (2X in L-R and 2X in A-P) from an 8-channel head array coil conjugated gradient iterative solver after 10 iterations .

http://www.nmr.mgh.harvard.edu/~fhlin/tool_sense.htm

2D SENSE

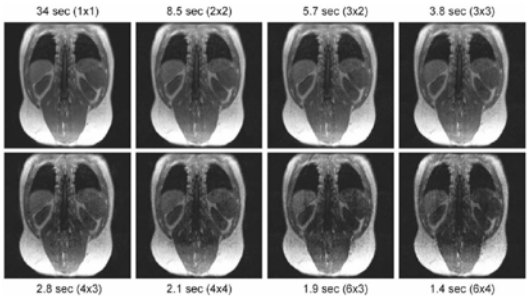
3DFT imaging with two phase-encoding directions

Maximum achievable SNR at center of elliptical volume of tissue as a function of acceleration factor (R) with 32-element coil.



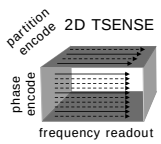
Sodickson DK et al. Acad Radiol 2005; 12:626-635

Highly Accelerated MRI with 32-element array



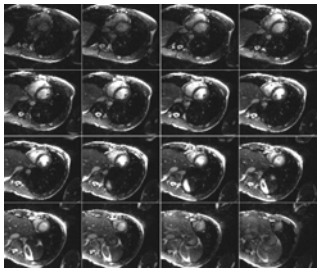
Sodickson DK et al. Acad Radiol 2005; 12:626-635

TSENSE with 2D-Parallel Imaging & 32 channel coil



R = 8 (4 X 2)
40 msec temp. resolution,
20 s breathhold,16 slices,
2.5mm x 2.6mm x 5mm,

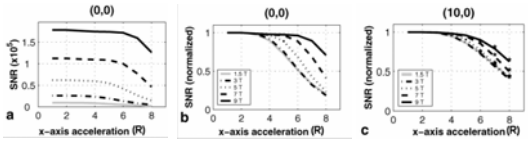
Peter Kellman, NHLBI



*prototype 32 channel cardiac array, *Rapid Biomedical*

High Field Parallel Imaging

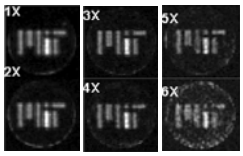
Ohlinger, Grant & Sodickson, Magn Reson Med 50:1018, 2003



- SNR values for a theoretical right elliptical cylinder with the electrical properties of liver, imaged using parallel technique.
- Graphs show the dependence of SNR on acceleration factor for B_0-fields ranging from 1.5T to 9T.

A) Raw SNR values at each field strength
B) (B) SNR values at point at center of sample, normalized so that SNR=1 when R=1
C) (C) SNR values at point 10cm from center of sample, normalized as in (B).

Transmit Phased Array Coils



- Have the potential to shorten the duration of complex RF pulses for use in short TR/TE sequences
- Independent current source amplifiers adjust current in each rung based on local impedance

Setsompop et al, Magn Reson Med 56: 1171, 2006

QC Problems with Parallel MRI

- Due to peculiarities of parallel processing, noise in pMRI images can vary with position
- Tends to be greater closer to RF coil elements
- Uniformity may depend on the type of parallel imaging procedure used

Importance of pMRI

- Increases MR imaging speed
- Is applicable to all MRI sequences
- Is complimentary to all existing MRI acceleration methods
- Can often reduce artifacts
- Alters SNR in MR images

g-Factor Summary

- The SNR in parallel images is dependent on the interaction of the R-factor and the g-Factor
- The g-factor is spatial dependent so SNR in parallel MRI is spatially dependent
- Acceleration factors beyond R= 4-5 are difficult to achieve with standard PI methods

Application of pMRI

- pMRI offers the promise of high resolution MR imaging at speeds as fast as MSCT
- Applications of parallel imaging include FSE, cardiac MR, diffusion and perfusion EPI brain imaging methods, 3D FT MRI (and MRA).
- Parallel imaging is tool for managing RF heating in the body at 3Tand higher field strengths
- Parallel imaging and dedicated RF coil design are enabling technologies for high B_o MRI

References

- Larkman DJ, Nunes RG. *Parallel magnetic resonance imaging.* Phys Med Biol 2007; 52: R15-R55.
- Kellman P. *Parallel imaging: the basics.* (NIH white paper available at: mrel.usc.edu/class/artices/Kellman_Parallel.pdf)
- Glockner JF et al. *Parallel MR imaging: a user's guide.* Radiographics 2005; 25: 1279-1297.