Parallel Imaging: Techniques, Quality Control, and Applications

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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

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

General Description of Parallel Imaging

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

X-ray CT  Parallel MRI

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**

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, $j$. $\rho_j$ 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, $\rho$ can be determined.

**The Encoding Matrix**

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

**k-Space Representation**

- 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

**Auto-Calibration Methods**

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

GRAPPA

Image Aliasing in PI

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


The Geometry Factor in Parallel Imaging

The Acceleration Factor

$R$ (R-factor)

The Geometry Factor

$g$ (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:

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

where \( i, j \) is the index of the signal-producing voxel, \( \text{PI} = \) parallel imaging, \( \text{norm} = \) 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:

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

where \( r \) is the spatial location of the signal-producing voxel, \( \text{PI} = \) parallel imaging, \( \text{norm} = \) normal Fourier imaging & \( R \) is the acceleration factor.

SNR vs. Acceleration

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


Signal & Noise Propagation


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.


g-Facts

- \( g \geq 1 \) (typically \( 1.5 \geq g \geq 1 \) 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 \( \downarrow \) as \( g \uparrow \) because noise \( \uparrow \) with g
  - g is sometimes referred to as “noise amplification factor”
- g-factor changes with coil loading
g-Factor Maps from SENSE Imaging


Low-res Reference images
Maps of geometric noise-enhancement (g-factor)
a b c

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

Applications of Parallel Imaging

Reeder SB et al. MRM 54:748, 2005

R-L Phase Encoding A-P Phase Encoding

FSE Pulse Sequence

ETL = Echo Train Length
The greater the ETL, the lower the SNR

FSE Point Spread Function Depends on T2 and TEeff

G. Clarke - Parallel MR Imaging
**Improved FSE Resolution**

- With SENSE, ETL is reduced from 96 to 48.
- $T_{\text{eff}}$ is also reduced.
Results in:
- ↑ Spatial resolution in the phase-encoding direction
- ↑ Greater overall SNR


**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

Adaptive TSENSE
Time-Adaptive Filtered SENSE

Parallel MRI Terminology

<table>
<thead>
<tr>
<th>Name</th>
<th>Acronym</th>
<th>Method</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity Encoding</td>
<td>SENSE,</td>
<td>Image-based, reference scan</td>
<td>Philips</td>
</tr>
<tr>
<td>Array spatial sensitivity</td>
<td>ASSET</td>
<td>Image-based, reference scan</td>
<td>General Electric</td>
</tr>
<tr>
<td>Generalized auto-</td>
<td>GRAPPA</td>
<td>k-space based, auto-calibrated</td>
<td>Siemens, GE</td>
</tr>
<tr>
<td>Modified sensitivity</td>
<td>mSENSE</td>
<td>Image based, auto-calibrated</td>
<td>Siemens</td>
</tr>
<tr>
<td>Integrated parallel</td>
<td>PAT</td>
<td>used for all pMRI</td>
<td>Siemens</td>
</tr>
</tbody>
</table>

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.

Highly Accelerated MRI with 32-element array

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

TSENSE with 2D-Parallel Imaging & 32 channel coil

2D TSENSE

B = B0 (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


• 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 B0 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


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

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 3T and higher field strengths
- Parallel imaging and dedicated RF coil design are enabling technologies for high $B_0$ MRI

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

References

- Kellman P. Parallel imaging: the basics. (NIH white paper available at: mrel.usc.edu/class/articles/Kellman_Parallel.pdf)