Diffusion and Functional MRI of the Spinal Cord
Methods and Clinical Applications

Susceptibility artifacts in DTI of the spinal cord
J. Cohen-Adad

Q-space imaging and axon diameter measurements
C. Wheeler-Kingshott

Functional MRI Potential for Clinical Assessment of the Injured Human Spinal Cord
P. Stroman

TSE / GE-EPI spinal cord fMRI and angiography of spinal vasculature
W. Backes

Physiological noise modelling in spinal cord fMRI
J. Brooks
Susceptibility artifacts in DTI of the spinal cord

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Spinal cord MRI is challenging

Physiological motions
- Aorta
- Spinal cord
- Kidney
- Lungs
- Heart

Small structure

Susceptibility artifacts
- Anatomic
- DTI sequence

~1 cm
DTI is challenging in the spinal cord

- In DTI we use echo-planar imaging (EPI)
- EPI sensitive to magnetic field inhomogeneities → distortions
- How does this work?

Susceptibility artifacts

DTI sequence
EPI acquisition

RF excitation

One slice
EPI acquisition

k-space

One slice

2DFT⁻¹

Image
Susceptibility artifacts

- Linear gradients are applied to spatially encode spin location
- If magnetic inhomogeneities are present, the linearity is corrupted
- In EPI, error accumulates in the X and Y directions
- Error proportional to the time spent filling the k-space
Susceptibility artifacts

- **Image reconstruction**
  - We assume the linear profile of X and Y gradients. Errors along $k_y$ translate into image shifts along Y.

![Diagram showing image reconstruction with and without errors](https://via.placeholder.com/150)
Susceptibility artifacts

Large field inhomogeneities in the spinal cord

- Cartilage
- Bones
- Fat
- Grey/White matter
- Water (CSF)
- Air (lungs)
Solutions?

- Better shim
Importance of shimming

GE-EPI, TE=36ms, matrix=128x40, voxel size=2x2x2mm³, R=1

Pfeuffer et al. “Zoomed EPI using 2D RF Excitation Pulses” (Siemens WIP #508A)
Solutions?

- Better shim
- Reduce echo spacing
  - Higher switching rate (gradient performance)
  - Skip k-space lines
Susceptibility artifacts

Multi-shot acquisition
Susceptibility artifacts

Multi-shot acquisition

- EPI-based (Fast, high SNR)
- Longer than single shot
- Phase errors induced by physiological motion → navigator echoes

TR~2800ms (cardiac gated), TE=74ms, matrix=124x138 (3 shots), resolution=1.7x1.7x1.7 mm³, R=2, b=800 s/mm², 30 dir.

D. Porter et al. “RESOLVE Multi-Shot Diffusion” (Siemens WIP #544A)
Susceptibility artifacts

Reduced FOV

Image space

$k_y = 1/\text{FOV}_y$

$k$-space

reduce effective echo spacing
Susceptibility artifacts

Reduced FOV

- Adapted to spinal cord geometry
- SNR $\propto \sqrt{N_\phi}$
- Aliasing
Susceptibility artifacts

Reduced FOV

- Adapted to spinal cord geometry
- SNR $\propto \sqrt{N_\phi}$
- Aliasing

$\rightarrow$ Outer volume suppression
Susceptibility artifacts

Reduced FOV

- Adapted to spinal cord geometry
- $\text{SNR} \propto \sqrt{N_\phi}$
- Aliasing

$\rightarrow$ Outer volume suppression
$\rightarrow$ Spatially selective excitation

Saritas, MRM 2007; Finsterbusch JMRI 2009; Dowell, JMRI 2009
Susceptibility artifacts

Reduced FOV

- Adapted to spinal cord geometry
- SNR $\propto \sqrt{N_\varphi}$
- Aliasing
  - Outer volume suppression
  - Spatially selective excitation
  - Parallel imaging
Susceptibility artifacts

Parallel imaging

Receive Coils

FOV

Griswold, MRM 2002; Pruessman, MRM 1999
Susceptibility artifacts

Parallel imaging

- EPI-based (Fast, High SNR)
- Reduce distortions by factor $R$
- Can be combined with multi-shot or rFOV methods
- Lower SNR ($\propto 1 / \sqrt{R} \cdot g$)
- Requires highly parallelized coils
Array coils

- Benefits of multiple array coils
  - Parallel imaging → Less susceptibility artifacts
  - Smaller coil elements → Higher SNR
SENSE Optimized Sixteen Element Receive Array for Cervical Spinal Cord Imaging at 3T

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Introduction:
High quality and high resolution anatomical and functional imaging of the human spinal cord remains a significant challenge in MRI [1,2]. The benefits of parallel imaging with surface coil arrays have been clearly shown particularly in the brain imaging for both anatomical and fMRI studies [3,4]. Here we demonstrate a custom design and build of a sixteen element receive-only surface coil array for spinal cord MRI imaging at 3 Tesla.

Material and Methods:
The spinal array has been develop and built with help of Nova Medical Inc. (Wakefield, MA USA). The array consisted of a 4x4 arrangement of coils placed upon a rigid curved former (Fig 1a). Each of the four columns comprised four elements overlapped in z. In order to improve axial Sensitivity Encoding (SENSE) g factors, gaps were placed between adjacent columns with a gap to element width ratio of 30%. Each coil element comprised an oval 8x6cm copper trace on flexible PC board and was tuned to 127.8 MHz with distributed capacitors. A lumped element balun matched the coil impedance to 50 ohm coaxial cable and in conjunction with a PIN diode functioned as an active detuning trap. Each element also had one passive detuning trap. The cables from each coil were routed to ultra low impedance preamplifiers (input impedance <1.2 ohm) through two sets of baluns to minimize any common mode cable currents. The preamplifier outputs were then fed to the 3Tesla General Electric HDx system connectors through two shielded cable bundles with integral triaxial baluns. MRI Imaging: Phantom: Gradient Echo with FOV/sl=300/4mm, matrix 256x256, TR/TE=34/1.2ms, flip=20deg, BW=31.25kHz. Human: Fast Spin Echo Sequence with flow compensation and fat suppression was used with: FOV/sl/gap=300/2/0.5 mm, matrix 512x512, TR/TE=2800/90ms, NEX=4, etl=16, BW=50kHz, 16 sagittal slices. Single shot EPI with SENSE (reduction factor=2 in the phase direction) was used with: FOV/sl/gap=120/4/0.5 mm, matrix 192x144, TR/TE=2000/30 ms, BW=250kHz, 10 axial slices.

Results:
Phantom results are shown on Figures 1c-1e. The sagittal reference image (Fig 1c, display level displev=0-1000) shows coronal imaging plane (red line) used for the array evaluation as well as individual coronal coils images (Fig 1d, displev=0-300) and resulting the combine image (Fig 1e, square root of sum of squares, displev=0-500) are shown. Individual images show an excellent isolation between coils. An example of T2-weighted FSE anatomical image (SNR image: displev=0-70) and of high-resolution SENSE EPI axial images (displev=0-2000) are shown on Figures 2a and 2b respectively.

Discussion and Conclusion:
The new 16-element spinal array offers excellent image quality for both anatomical and functional studies. The imaging coverage spans from brain visual cortex down to about the tenth cervical vertebra. The coil optimized parallel imaging design allowing high resolution SENSE EPI for functional studies – which may be critical for more meaningful fMRI results to be obtained from the spinal cord. With regard to anatomical imaging, the good SNR over a large range of the spine can open up a wide array of potential clinical applications.

References:

![C-spine former](1a)
![Elements layout](1b)
![Sagittal scan](1c)
![Individual coil images](1d)
![Combine image](1e)

**Array coils**

<table>
<thead>
<tr>
<th>16-channel</th>
<th>22-channel</th>
<th>32-channel</th>
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<tbody>
<tr>
<td>visual cortex ➔ T3</td>
<td>Lower brain ➔ T3</td>
<td>Full brain ➔ T3</td>
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Bodurka, ISMRM 2008

Courtesy of Jon Brooks, FMRIB

Cohen-Adad, MRM 2011
Array coils

SNR

➔ 2x more SNR in the brain, cerebellum and spinal cord

Cohen-Adad, MRM 2011
Array coils

Application in spinal cord injury

TR/TE = 900/20 ms, **300 µm in-plane resolution**, thickness = 3mm, 
R=3, BW = 227 Hz/pix, TA = 6:20 min

Cohen-Adad, ISMRM 2011
Array coils

TR=14280 ms, TE=80 ms, resolution = 1.7x1.7x1.7 mm³, nbDir=30, b-value=800 s/mm²
Susceptibility artifacts

Correct distortion *a posteriori*

1. Estimate the displacement map

2. Apply to DWI

- How to estimate displacement map?
  - Phase field map [Jezzard, *MRM* 1995]
  - Point Spread Function [Zaitsev, *MRM* 2004]
  - Reversed gradients [Holland, *Neuroimage* 2010]
Susceptibility artifacts

Correct distortion *a posteriori*

Cohen-Adad, Neuroimage 2011
Susceptibility artifacts

Correct distortion *a posteriori*

Human spinal cord tractography (brainstem-seeded)
Application in SCI
Methods

Aim

• Find biomarkers of degeneration in normal-appearing SC

Subjects

• Patients with chronic cervical SCI (N = 14) and age-matched controls (N=14)

Multi-parametric MRI (3T, head/neck coil)

• Anatomical $\rightarrow$ Atrophy
• DW EPI $\rightarrow$ DTI
• Magnetization transfer $\rightarrow$ MTR
Methods

Measure #2: DTI

single-shot EPI, cardiac gating, in-plane resolution = 1x1 mm, R=2, b=1000 s/mm², 60 dir.
Methods

Measure #2: DTI

Example of DW at $b=1000 \text{ s/mm}^2$

single-shot EPI, cardiac gating, in-plane resolution = 1x1 mm, $R=2$, $b=1000 \text{ s/mm}^2$, 60 dir.
Manually-defined ROI in normal appearing tissue
Results

**Significant difference for atrophy, DTI and MT**
Conclusion

- Susceptibility artifacts
  - Careful positioning of shim box
  - Multi-shot / rFOV / Parallel imaging (RF coils)
  - Phase map / reversed EPI ➔ only takes 1 min!

- **Multi-parametric MRI** provides more confidence and specificity for characterizing the pathological spinal cord

- See also at OHBM:
  - Multi-parametric MRI applied to ALS patients [El-Mendili, #2517]
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Bibliography

more technical


more clinical